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Energy Conversion

A REVOLUTION IN ELECTRIC POWER IS IN THE MAKING, WITH SILENT GENERATORS FED BY RADIANT ENERGY

by KENYON KILBON

For future generations, the cough of the gasoline-driven compressor, the roar of the diesel generator, and even the hum of the great dynamo may exist only as curious echos ringing through the vast gallery of mankind's forgotten sounds.

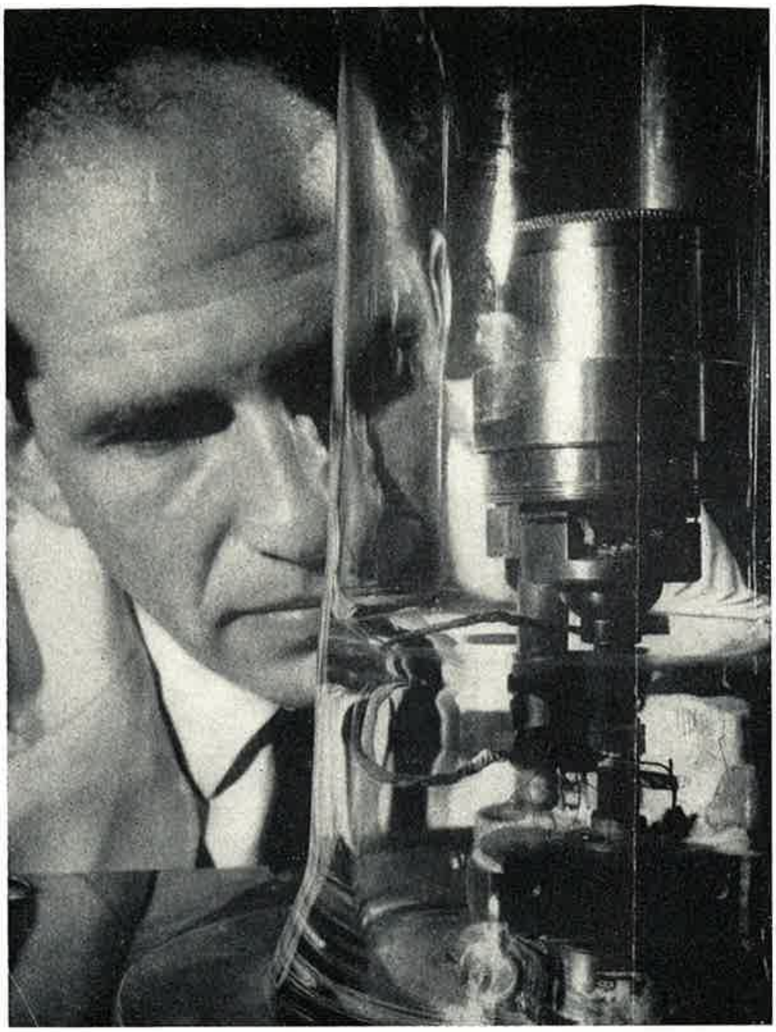
New electronic technology, founded upon painstaking research, is preparing a future era of noiseless generators that function without moving parts to transform heat, light, and chemical energy directly and simply to abundant electric power—first in handy packages for use anywhere on earth or in space, and eventually in great central stations serving urban industrial complexes across the continent.

Except for our yet-limited use of atomic energy fueled with materials that make up the earth, all of our power comes from the immense outpouring of light and heat radiation from the thermonuclear furnace of the sun. Some of the solar energy has been captured and stored for millions of years in the fossilized remains that form our deposits of coal and oil. Some is spent in the great pumping cycle that raises moisture into the atmosphere to fall on heights from which it runs downward in swiftly flowing streams.

Whatever the original form of the energy, we have contrived involved and standardized mechanical methods for converting it to useful electric power. Fossil fuels are burned in steam boilers and internal combustion engines—to turn rotating generators. Rushing water is intercepted by great turbines—to turn rotating generators. Atomic energy has been worked into the same pattern, producing heat for steam — to turn rotating generators.

Now a revolutionary break is in the making, with new techniques that bypass the rotating generator and proceed from heat or light or chemical energy directly to electrical energy without mechanical aid. In one case—that of the solar cell familiar in satellite and space vehicle design—no intermediary other than the small device itself stands between the radiated light energy of the sun and the output of useful electricity. In every case, the results are a potentially great saving in initial cost and maintenance of machinery and major dividends in the form of far greater simplicity, flexibility, compactness, and long-term reliability in power production.

These bright prospects have sparked a major research and engineering effort that has carried electronic science well beyond its traditional activities in communications and information handling, into the power generating field that was once the exclusive preserve of the older established electrical industry. The trend, as described recently by Dr. E. W. Engstrom, President of the Radio Corporation of America, is toward "a wedding of many electrical and electronic techniques in both the production and use of energy, forming a unified advanced technology that will be our principal building block for the future."



An RCA scientist tests a powerful new alloy that produces electrical energy directly from heat.

There is sound logic in such a combined approach to new methods of direct energy conversion. The effects, materials, and fabrication processes involved in some of the most promising techniques are precisely those in which electronics has accumulated substantial know-how during years of vacuum valve and solid-state (e.g., transistor) development.

Two of the conversion methods, in fact, employ a semiconductor effect akin to that which occurs in transistors. One is the *photovoltaic* process by which a thin layer of sensitive material in a solar cell converts light to electrical energy in a manner resembling—but with greater punch—the conversion of light to sufficient electrical energy to move the needle on a photographer's light meter.

The other, the *thermoelectric* effect, produces useful electricity directly from any type of heat source up to about 1800°F as a result of heat-stimulated electron action in small blocks of specially tailored alloys. Yet a third fruitful approach, known as *thermionic* conversion, generates electricity directly from heat in the 2000° to 4000° range by means of a gas-filled tube that is similar in principle to the high-power electron valves used in broadcast transmitters.

To complete the pattern, electronics has a vital supporting role in two further energy conversion techniques that have evolved from a background of electrical engineering and applied physics. Experiments in the tongue-twisting art of *magnetohydrodynamics*—happily abbreviated to MHD—now point toward supplementary and even complete central power stations generating electricity directly from the energy of hot plasma, or ionized gas, flowing at high speed through a magnetic field. Finally, extensive development is under way, largely in the chemical and electric power industries, on *fuel cells* that deliver electrical energy directly from the continuous chemical reaction of air or oxygen with various liquid or gas fuels fed into packaged devices that bear a general family resemblance to ordinary storage batteries.

While there is likely to be some competitive overlapping in ultimate applications, the various methods complement one another to a considerable extent. The result will be a broad choice from which tomorrow's planners may select one or a combination of energy conversion techniques best suited to a given task, whether the job is lighting a city or operating an air pump at an astronauts' base on Venus.

Electronic science, spurred by the urgent needs of a growing space technology, has concentrated with dramatic effect upon the thermionic, thermoelectric, and photovoltaic methods that stem directly from established electron valve and solid-state skills. As satellites and space vehicles advance in size and complexity, the demand mounts for more reliable and powerful electrical generating techniques to operate their more elaborate electronic systems through weeks and months of travel far beyond the earth. The ideal solution is direct conversion of energy in devices free of mechanical parts or fuel supply problems, drawing upon continuously available radiant light, heat, or nuclear energy.

The simplest device, still the most widely used to supply power in space, is the solar cell—a thin rectangular wafer of semiconductor material (e.g., silicon or gallium arsenide) treated to form a junction in which light energy excites electrons to produce a flow of current in a circuit. All that is needed is a supply of sunlight—a commodity freely available almost anywhere in the solar system. Present types of cells, available in quantity from several manufacturers, operate at a conversion efficiency of up to 15 per cent—i.e., about 15 per cent of the light energy is converted to electrical energy.

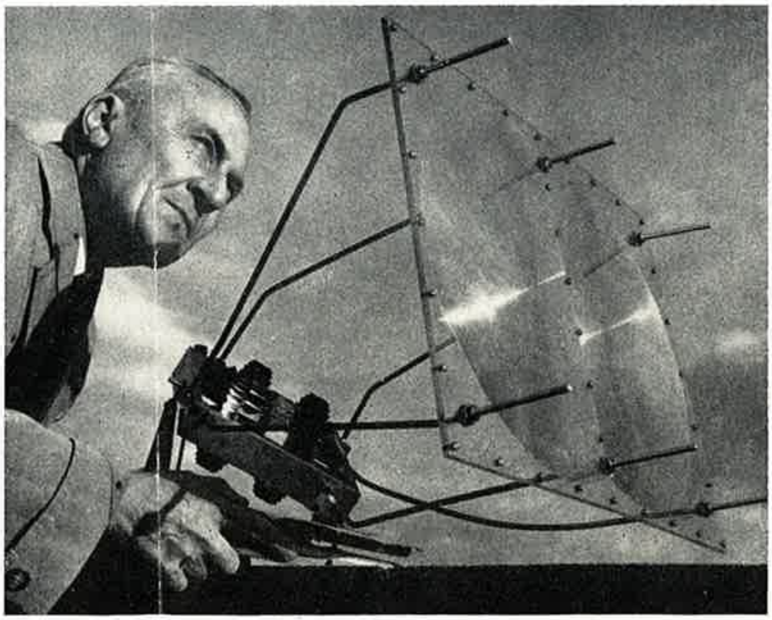
Yet the cells have several drawbacks that have inspired intensive research. The crystal semiconductor is expensive, and large numbers of cells are needed in order to obtain an appreciable amount of electricity. Furthermore, present standard solar cells are highly susceptible to damage from radiation, especially in the extensive Van Allen belts surrounding the earth.

Recent research has been changing the picture substantially, however. Studies of radiation effects, conducted largely at the U.S. Army Signal Corps laboratories and at RCA's David Sarnoff Research Center, have led to increases of ten to one-hundred times in the radiation resistance of silicon solar cells, promising substantially longer operating life in the Van Allen belts and other possible regions of high radiation in space.

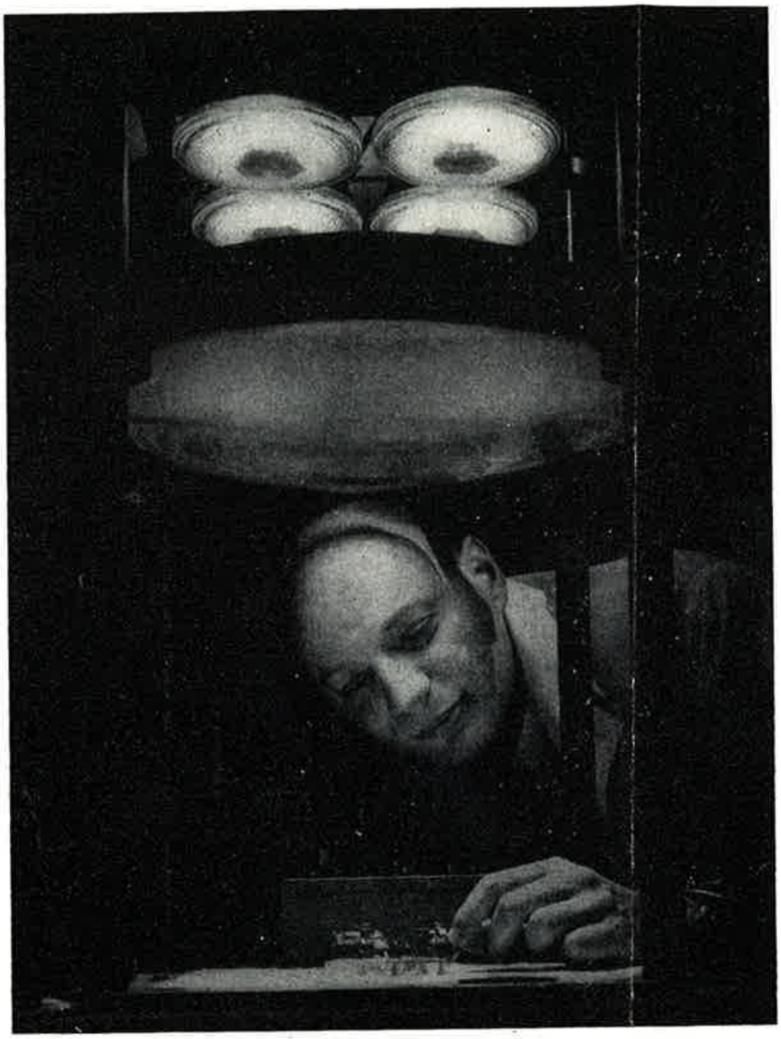
Even more significant, perhaps, is the recent achievement by RCA scientists of an entirely new photovoltaic device—a thin-film solar cell made by depositing photosensitive cadmium sulfide on a lightweight surface by techniques that are adaptable to quantity production. So far the laboratory device has achieved efficiencies of only 4 to 5 per cent, but it has proven at the same time to be more resistant to radiation damage and lighter in weight than are the best present semiconductor solar cells.

In the meantime, the virtual monopoly enjoyed by solar cells in the nation's space program is on the verge of being broken by more powerful, compact and versatile thermoelectric and thermionic heat-to-electricity devices.

The two thermal energy conversion techniques are based upon physical effects long known to electronic science. The thermoelectric effect goes back nearly 150 years to the discovery that application of heat to a junction of dissimilar materials in a circuit can start a flow of current through the circuit. The thermionic converter is



RCA's N. E. Lindenblad tests the behaviour of thermoelectric materials by focusing solar heat through a special lens on a small test motor.



Paul Rappaport, RCA Laboratories technical staff, tests solar cell power output under a simulated solar source.

based on the emission of electrons from a hot cathode and their collection by an anode—a principle that is fundamental to electron valves.

The sudden leap to prominence and practical application of these thermal energy conversion techniques reflects the happy coincidence of two factors: a widespread basic research program that has achieved drastic improvement in electronic materials, and the encouragement provided by government funds to support energy conversion research and development projects in many laboratories.

Successful materials research has been the key especially in the case of thermoelectric progress. Until recently, the most effective thermoelectric devices have operated only with relatively low-temperature heat sources—up to about 900°F—at conversion efficiencies of less than 10 per cent. While this has been adequate for certain military and space needs, the inability to operate practically at higher temperatures has ruled out the effective use of thermoelectric devices with a full range of heat sources, including most nuclear reactors.

Now a major breakthrough has come from RCA Laboratories in a series of advances that have raised the efficiencies of the lower-temperature thermoelectric materials to 12 per cent or more, and at the same time provided a brand-new material of astonishingly high performance in a temperature range of about 1800°F. This new upper limit effectively brackets the temperature spectrum of heat-producing nuclear reactors as well as the majority of common fossil fuel heat sources.

The new high-performance material is an alloy of germanium and silicon, two semiconductor materials familiar in transistor application. Developed by RCA scientists in a Navy-supported program, the alloy is stronger and lighter in weight than previous thermoelectric materials. Even more striking is its power density at high temperatures. Laboratory measurements have indicated that a square-foot panel arrangement of germanium-silicon units operating from an 1800° heat source could generate up to ten kilowatts of power—about three times the power consumed at any given time in an average home.

Rapid progress in thermoelectrics is matched by recent advances in thermionic energy conversion—but with an odd reverse of objective. Since they are vacuum devices in which electrons are "boiled" out of a hot electrode into free space, thermionic converters have required very high operating temperatures, in the range of 3000° to 4000°F. Because only a few costly materials are suitable for operation at such high heat, a major goal in thermionic research is to push down the lower limit of temperatures at which the converters can operate efficiently.

When they compare this effort to the upward temperature push in thermoelectric research, workers in the field see an analogy to the construction of the first transcontinental railroad by groups racing from opposite directions to meet somewhere around the halfway mark. If electronics should pursue the analogy to the extent of driving a golden spike, it will probably be placed near 2000°F—a point that is being rapidly approached from below by thermoelectrics and from above by thermionics.

Today, government and industry together are spending about $10 million a year in research on thermionic converters. This compares to virtually nothing seven years or so ago, when thermionic power generation was little more than a laboratory curiosity dating back to observations by Thomas A. Edison in 1883. Edison's observation, confirmed and fully described later in theoretical work by Dr. Irving Langmuir, disclosed a physical process that is far simpler in principle than in practical execution: the emission of electrons from a hot cathode, and their accumulation at a lower temperature anode in sufficient quantity to build up a charge that can drive electric current through a circuit connecting the two.

A number of electronic tricks have been ingeniously applied to enhance the effect in order to maintain a steady high-power output, including the use of cesium gas in the vacuum to expedite the flow of electrons from the hot emitter to the cooler collector. Coupled with research has been the development of successively better thermionic converters at several major laboratories.

Intensive research has continued at the same time in the quest for thermionic devices that will operate at lower temperatures. A long and dramatic stride in this direction has now been taken by RCA scientists with the invention of a new type of three-element thermionic converter that can generate electricity directly from a heat source of about 2000°F at better than 10 per cent efficiency. Among its major advantages are a non-critical design that lends itself to quantity production by techniques long familiar in tube technology, as well as probable longer operating life in the lower temperature environment.

As it masters these new techniques of energy conversion, electronic science has started to probe more deeply into the emerging art of MHD power generation. Here, too, the principle is an old one, known to electrical engineering since the days of Michael Faraday. In practice, it involves the heating of a gas to temperatures in the 4000° to 5000° range, where electrons are stripped from atoms in an ionization process that turns the gas into a conductor of electricity. Forcing the gas in rocket-like fashion through a magnetic field creates an electrical interaction that can be harnessed to provide electric current in a circuit. The effect is, in fact, analogous to the operation of a conventional rotating generator, but without moving mechanical parts.

Initially, MHD has been studied intensively and with important experimental results by major electrical companies, drawing upon electronics primarily for the design and supply of certain equipment. Recently, RCA has undertaken original study and development, with partial government support, of what may be the first MHD generator for alternating current—an advance that is regarded as essential to simplifying and reducing the cost of equipment to the point where the new technique may be adopted by the power industry for ultimate use in central stations.

Every survey of the accelerating progress in direct energy conversion points unerringly to the conclusion that a remarkable new era is dawning with the discovery of far simpler and more practical methods than man has ever known, to harness the enormous energy pouring from the sun or locked from the beginning of time in the atoms that make up the earth.

The prospect is especially stimulating today for electronic science, which has grown with unprecedented switfness through recent decades by supplying the urgent need for radically improved methods for handling information in all its forms. Now electronics is turning increasingly to the development, with electrical science, of the energy sources for which it has previously been a consumer only.

The promise was recently expressed in these terms by a leading scientist of RCA: "If in time the electronics industry we know should pass from its present dynamic phase to reach a plateau, the potential revolution in power conversion may well give rise to another period of equally extraordinary growth."

(With acknowledgements to RCA.)

"GREAT OAKS . . ."

The Story behind the Formation of the B.B.C.

Forty years ago, on 14th November 1922, the Marconi Company formally handed over its London sound broadcasting station, 2LO (with which the Company had been transmitting programmes since the previous May), to the newly formed British Broadcasting Company Ltd., an organisation formed by six large radio manufacturers* with a share capital of £100,000.

Today, the British Broadcasting Corporation has an annual income of over £40 millions, possesses nearly 400 transmitters and employs a staff of over 17,500. A daily audience of 25 millions is claimed for its sound programmes and 20 millions for BBC television.

The seed sown by the Marconi Company in the years 1919-22, when techniques developed during the Great War were used to originate entertainment broadcasting in this country, have thus borne remarkable fruit. The story behind those pioneering years is a curious one in terms of evolution and one not generally known to the public.

To a Canadian must go the honour of being the first to broadcast speech and music. This was as long ago as 1906, when Professor R. A. Fessenden, working in the U.S.A. transmitted a short programme on Christmas Eve of that year from Brant Rock, Massachusetts. His transmitter was a 50 Kc alternator, modulated by a watercooled microphone.

Others followed suit, notably Dr. Lee de Forest in 1907, 1908 and 1910, the 1908 experiments being carried out from the Eiffel Tower. Another American, E. W. Alexanderson, succeeded in building a 100 Kc alternator with a power of 1½ Kw and made a decisive step forward in 1912, when he devised a means of coupling the microphone indirectly to the alternator.

De Forest used a modulated arc for his tests and both this and the alternator systems had serious practical disadvantages. Nevertheless, it must have been a puzzling experience for the few ships' operators who chanced to tune their receivers to the transmissions, to hear distorted music and speech instead of morse. As for the experimenters, they were carrying out serious tests and there was no thought of mass-entertainment in their minds at the time.

Oddly enough, de Forest had the key to successful radio-telephony transmission right to hand in his own invention which he called the "Audion." This was the triode thermionic valve; but unfortunately the early Audions were very inefficient as amplifiers and it was not until after Dr. Langmuir's introduction of high-vacuum triodes in 1912 that they were found to be capable of generating oscillations.

Thereafter, events moved swiftly; the high-vacuum technique gave the thermionic valve a significant amplification factor and the almost simultaneous discovery in 1913 by Meissner (Germany), Armstrong, Langmuir and de Forest (America) and Round (Britain) of the valve's ability to generate oscillations opened the door to practical radio-telephony.

The 1914-18 war gave great impetus to the triode's development in the military field, and in particular the work of Round and Prince of Marconi's established radio-telephony's value as a means of controlling fighter aircraft. The coming of peace found the thermionic valve vastly improved both as an amplifier and a generator,

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*The Marconi Company; the Metropolitan-Vickers Co; the Western Electric Co; the British Thomson-Houston Co; the Radio Communication Co and the General Electric Co.

and designs for radio-telephony transmitters and receivers were by that time well established.

But with the war ended, civil uses for such equipments had to be found and evaluated. As one aspect of this, the Marconi Company in 1919 installed a radio-telephony transmitter at Ballybunion, Ireland, and it was via this station that the voice of W. T. Ditcham, a Company engineer, made history as being the first to span the Atlantic from East to West, being received clearly in Louisberg (Novia Scotia). The transmission was carried out on a wavelength of 3,300 metres.

Later in the year a 6 Kw experimental radio-telephony station was built at Marconi's Chelmsford works but this was replaced early in 1920 by a 15 Kw transmitter with which a series of public telephony range tests were carried out by Round and Ditcham. Purely to offset the monotony of reading "railway time-table" material at the microphone for test purposes, the engineers introduced the occasional musical item. To their surprise, reports and letters of appreciation came in from all over Britain and the Continent, and it was obvious that the amateurs wanted more.

Thus the real beginning of broadcast entertainment in this country was accidental; a mere side-effect to the main business of range-testing.

On February 23rd 1920, the Chelmsford transmitter again made history by broadcasting the world's first telephony news service. The further interest shown by listeners was another straw in the wind to indicate that there might be possibilities in the broadcasting of speech and music for entertainment purposes alone, and plans were laid for an ambitious essay—no less than the transmission of a recital by Dame Nellie Melba herself.

This, the world's first advertised programme of broadcast entertainment, took place on June 15th 1920, when Melba, under the sponsorship of the "Daily Mail," visited the Marconi works. At 7.10 p.m. on that summer evening the golden notes of the famous prima donna thrilled amateurs all over Europe — the privileged few hundreds who owned receiving equipment at that time.

The spate of congratulatory messages which came in as a result convinced the Marconi Company that here was a vast potential civil market in transmitting equipment, domestic receivers and components, if only the public at large could be made aware of the fascination and the entertainment value inherent in broadcasting.

There was, unfortunately, a snag, and a big one at that. The Marconi transmissions were licensed by the Postmaster General for experimental purposes only, and although the occasional special demonstration was tolerated, a regular entertainment service would most certainly be vetoed. Nevertheless, some further broadcasts were carried out.

The blow, when it fell, was none the less heavy for being anticipated. The worst happened; the PMG withdrew the Company's licence to transmit items of entertainment on the ground of interference with legitimate services. The situation was crucial because although the Company had a clear lead at that moment, there was every indication that American business interests were hot on the trail and were shortly about to make a big drive to popularize broadcasting and to go all-out for world receiver markets.

The situation in America, in fact, parallelled British experience. In 1919, Dr. Frank Conrad of the Westinghouse Company had built an experimental radio-telephony station, and, like Round and Ditcham, transmitted music to avoid the tedium of continuous speech. He, too, was inundated with requests for more and more gramophone record transmissions and soon, largely as a result of newspaper publicity, the number of listeners multiplied, and Dr. Conrad's Company experienced a minor boom in the demand for receiver components.

There was, however, one important difference between England and the USA in that in America there was comparatively little restriction in the matter of licensing radio stations. As a consequence, when Westinghouse decided to build a station in Pittsburg and operate it on an advertised entertainment basis, their way was clear. Their station KDKA went on the air officially on November 2nd 1920, causing an immediate sensation by broadcasting the results of an American Presidential Election.

In the meantime, in Britain, Marconi's had to endure the chagrin of having established a lead and being unable to follow it up officially. Westinghouse, on the other hand, were reaping a rich harvest in terms of domestic receiver and component sales. It was not until 63 Wireless Societies in the country petitioned the PMG asking for official permission to have the Chelmsford transmissions resumed, that the ban was lifted. By that time nearly two precious years had gone by.

It was not until January 13th 1922, that Marconi's were authorized to establish another station. Even at that, there were restrictions. The power must not exceed 250 watts and transmission time must not extend beyond one half-hour per week; the station was to shut down for three minutes in every ten to listen for instructions to stop, should interference be experienced by other services. It was the man with the red flag in front of the motor car all over again.

The task of building the transmitter was undertaken by the Development Section of Marconi's Aircraft Division, who also undertook to provide the weekly half-hour transmission each Tuesday evening between 8.00 and 8.30 p.m. Captain P. P. Eckersley who was in charge of the project, acted as compere, singer and actor-manager in addition to his technical responsibilities.

That station, 2MT, Writtle, or 'Two Emma-Tock' as it was soon affectionately known, rapidly endeared itself to all amateurs within listening range. Capt. Eckersley proved himself a master of spontaneous humour and the programmes, mostly consisting of items by Marconi employees, ran with a joyous abandon that has never again been recaptured. At the same time much valuable data accrued.

First on 700 metres wavelength but soon changing to 400 metres, Two Emma-Tock continued for almost a year, making an ever-increasing army of friends throughout its career. It is of interest to note that among the young engineers who ran it, P. P. Eckersley became the first Chief Engineer of the BBC, N. Ashbridge (now Sir Noel) was the BBC's Technical Director when he retired in 1952 and is now on the Marconi Board of Directors, R. T. B. Wynn became the Chief Engineer of the Corporation, H. L. Kirke an Assistant Chief Engineer and B. N. MacLarty became Head of the BBC's Design and Installation Department before returning to Marconi's in 1947. He is now the Company's Engineer-in-Chief.

Soon after Writtle began operation the Marconi Company received another permit—this time for the establishment of an experimental station at Marconi House, London. Again there were restrictions; a power of only 100 watts was permitted; no music was to be transmitted, and broadcasting was allowed only between 11.00 am and 12.00 noon and from 2.00 pm to 5.00 pm daily. The weekly half-hour from Writtle had been a few crumbs; the new permit constituted half a loaf, and the Company set to work without delay. After a while the 'no music' restriction was removed and approval given to increase the power to 1½ Kw.

This was the original station '2LO' which began operations on May 11th 1922, the first broadcast being the Lewis-Carpentier fight. At the start, transmissions were not advertised, but concerts were arranged for the benefit of special audiences at some institution, hospital, private garden party, fête or wireless society at which the receiving apparatus was installed and operated by the Company's own engineers. Each concert was the subject of a special GPO authorization, and listeners who were registered on a Marconi mailing list were notified by post of forthcoming broadcasts. Later, newspapers began to announce some of the programmes editorially, but mention of the Marconi House station was forbidden.

The 2LO station transmitter was designed by Captain H. J. Round and installed, together with the aerial system, by C. S. Franklin of short wave beam fame. It operated on a wavelength of 360 metres. In charge of activities was the late A. R. Burrows who eventually became the well-loved "Uncle Arthur" of the BBC. He it was who introduced the concept of a professional announcer (they were called Masters of Ceremonies in those days) and who laid the foundations of today's studio management techniques.

In contrast to 2MT, the London station was self-conscious to a degree. As befitted its responsibility it was careful to give offence to none and its programmes were typical of the 'musical evenings at home' which were still in vogue everywhere. The 2MT Writtle engineers were quick to sieze upon this and lost no opportunity in lampooning 2LO's sobriety. It added nothing to the London station's self-confidence to receive requests not to transmit on Tuesday evenings so that listeners could give the Writtle boys' parodies their undivided attention!

Nevertheless, many notable broadcasts were carried out. In addition to the Lewis-Carpentier fight mentioned, Carpentier himself spoke on behalf of the British Legion; reports on the King's Cup Air Race were given; and the Prince of Wales broadcast to the Boy Scouts—all before the Marconi Company relinquished the station.

The radio broadcasting boom was on with a vengeance; aerials with varying degrees of aesthetic appeal were rapidly becoming a feature of the London landscape and a nightly hush fell on the suburban living-room as father fiddled with the cat's whisker. Marconi's were experiencing a healthy demand for their domestic receivers (manufacture of these ceased in 1926) and other manufacturers were pressing their claims to stimulate similar interest for their products by installing stations of their own.

Over-cautious as the GPO undoubtedly was at the onset of the experimental work, its attitude was to some extent justified in the light of conditions across the Atlantic, where no right of refusal to establish stations existed, and as a consequence the wavebands were choked with the outpourings of rival transmitters, each interfering unmercifully with its neighbours. The GPO having granted a licence to the Marconi Company, could not in fairness refuse other manufacturers, yet to follow the American example unreservedly would be to create chaos in Britain also.

In April 1922, the matter was considered by the Wireless Sub-Committee of the Imperial Communications Committee, which made certain recommendations to the Postmaster General. As a result of these, the PMG called a conference of radio manufacturers and it was decided that they should consolidate their interests by forming a single Company which, subject to certain conditions, should have complete control of broadcasting in this country.

In this fashion the British Broadcasting Company Ltd. was born, with a capital of £100,000 in £1 shares subscribed by the six radio manufacturers mentioned earlier. Any bona-fide radio manufacturer was eligible to join the Company by depositing £50 and taking up one or more shares. On November 14th a Broadcasting Committee of the founder members took over responsibility for transmissions from 2LO (although official registration of the British Broadcasting Company did not take place until December 15th) and the Marconi Company was officially freed from the onus of providing programmes.

While the two-year lag in obtaining authorization to broadcast entertainment programmes was regrettable, there was satisfaction in knowing that, in spite of it, the situation had been contained and the British radio industry was well able to supply all home requirements in the boom years of the 1920's. Overseas, too, the Marconi Company was able to safeguard its interest in the capital goods field (transmitting stations, etc.) thanks to the extensive amount of technical know-how acquired in the war and immediate post-war years. The USA did, however, capture a considerable slice of the world market in domestic receivers and components.

In the intervening forty years Marconi's have been in close association with the BBC as a major supplier of transmitting and studio equipment, both sound and television, on a competitive basis with other manufacturers. As two typical instances—in 1936 Marconi-EMI television equipment was selected to carry the first public television service in the world, and, when, twenty years later, the BBC's Crystal Palace station came into service, Marconi transmitters were chosen to carry the service. In 1954 Marconi's gave the first public demonstration of compatible colour television in the United Kingdom; the Company's colour cameras have been used by the BBC for their subsequent experimental transmissions.

(Courtesy, Marconi's Wireless Telegraph Co. Ltd.)

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PEAK CURRENT CONSIDERATIONS FOR SILICON RECTIFIER APPLICATIONS

By J. NEILSON

Introduction

This article describes the peak current considerations involved in the design of various rectifier circuits. In rectifier applications, conditions may develop to cause momentarily higher than normal operating current. These increases (current surges) may occur from time to time during normal circuit operation (due to normal load variations), or they may be due to abnormal conditions or faults in the circuit.

In normal operation, a rectifier can absorb a limited amount of additional heat without any effects other than a momentary rise in junction temperature. However, a sufficiently high surge can drive the junction temperature high enough to destroy the rectifier.

The amount of current overload or surge a device can survive has been carefully investigated for each of the silicon rectifier families listed in Table 1. Surge ratings based on these findings have been established to guide the user in his applications of the devices. In the following text, these data, and information on fusing are presented and their use in rectifier design applications is discussed.

Surge Ratings Sinusoidal Circuit Applications

Surge rating curves for typical single-phase, 50-cycle rectifier applications are shown in Fig. 1. These ratings can also be used to find approximate surge current ratings in multi-phase circuits as well as single-phase circuits. The heat generated by a one-cycle surge in a three phase circuit, either half-wave or full-wave, will be within 10 per cent of that of a single cycle surge of the same peak current in a single-phase circuit. The peak surge current rating in six-phase will be approximately 1.3 times the corresponding rating in single-phase. The Universal Ratings should be used for multi-phase circuits whenever the surge duration is one cycle or less and whenever more accurate ratings are required.

CURRENT RATINGS	RECTIFIERS
40 amp.	1N1183A, 1N1184A, 1N1186A
35 amp.	1N1187, 1N1188, 1N1189, 1N1190
20 amp.	1N248C, 1N249C, 1N250C, 1N1195A 1N1196A, 1N1197A, 1N1198A
12 amp.	1N1199A, 1N1200A, 1N1202A, 1N1203A, 1N1204A, 1N1205A, 1N1206A
5 amp.	1N1612, 1N1613, 1N1614, 1N1615, 1N1616
0.5 amp.	1N440B, 1N441B, 1N442B, 1N443B, 1N444B, 1N445B, 1N536, 1N537, 1N538, 1N539, 1N540, 1N1095, 1N547, CR101–CR110

Table I.
Surge current ratings for typical single-phase rectifier applications.

In such operation, a surge may be defined as a chain of equal amplitude half-sine-wave current pulses. This is shown in Fig. 2 for the RCA 1N248C, 1N249C, 1N1195A, 1N1197A, and 1N1198A 20-ampere rectifiers.

The applications engineer when designing a rectifier circuit must determine the surge currents the circuit can deliver in terms of number of half-sine-wave pulses and their peak values. If any conditions can cause a surge over the ratings of the rectifier, appropriate circuit modifications must

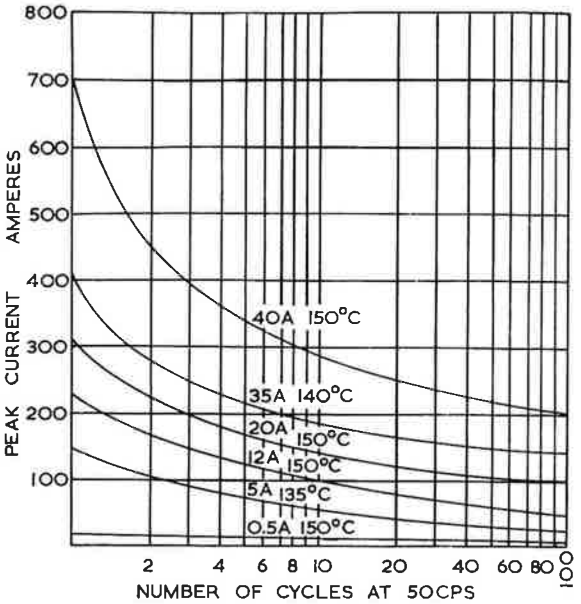


Fig. 1—Allowable peak surge current as a function of the surge duration in cycles, taken for single-phase, 50-cycle sinusoidal surges. For other frequencies, temperatures and wave shapes, see Figs. 5 and 6. These curves assume that the device is suitably mounted for continuous operation at the maximum ratings.

be made, such as adding impedance in the case of a capacitive load, or a fuse or circuit breaker for a variable load.

A convenient way to determine the fusing requirements of a given circuit is to make up a coordination chart as shown in Fig. 3. The coordination chart consists of a graph of current versus time on which are plotted the surge rating curve of the rectifier, the maximum surge (fault current) and steady-state current of the circuit, and the opening characteristics of the circuit protective elements.

The circuit to be considered is shown in Fig. 4. Assume the circuit is subject to overload conditions where the load resistance can go as low as four ohms. Peak surge current which can flow under these conditions would be

$$I_{peak} = \frac{V_{peak}}{R_{L}min} = \frac{600}{4} = 150A$$

To set up a coordination chart (using the 20-ampere unit as an example), first plot the surge rating curve for the rectifier, then, plot both the steady-state peak current (62.8 amperes) and the maximum peak surge current (150-amperes) the circuit can deliver. Both of these are shown as horizontal straight lines. From this it can be seen that the device is capable of passing 150-amperes peak surge currents for no more than seven cycles, approximately.

Because of this limitation, a protective element must be added to open-circuit in seven cycles. This requires the selection of a fusing element with an operating characteristic which will fall below the surge rating curve for the 20-ampere rectifier for all times greater than seven cycles.

Opening characteristics of fuses or circuit breakers are generally given in terms of time required to open as a function of rms current. In a half-sine-wave current, the rms value is one-half the peak value, and at 50 cycles per second one cycle corresponds to 20 milli-seconds.

In the circuit shown in Fig. 4, for periods less than seven cycles, surge current is limited by the circuit resistance. For periods greater than seven cycles, current is limited by the protective element. This results in a maximum surge current as indicated by the dashed line of Fig. 3.

If the circuit of Fig. 4 is subject to overloading such that the total circuit resistance can drop to 1.7 ohms, the maximum available current is:

$$I_{peak} = \frac{V_{peak}}{R\,min} = \frac{600}{1.7} = 350A$$

The surge rating curve indicates that the rectifier can take 300 amperes for one cycle only. Therefore, the protective element must be selected to open in one cycle or less with a half-sine-wave peak of 300 amperes or less. When the current can go higher than 300 amperes peak, the protective element must open in less than one

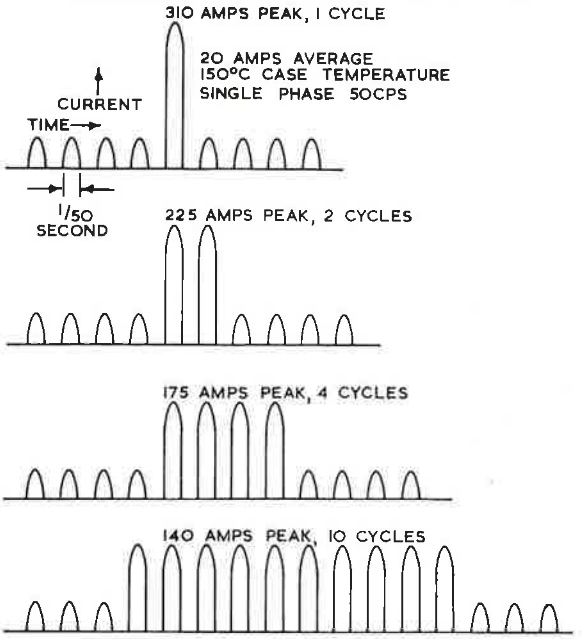


Fig. 2—Examples of half-cycle sine-wave surge currents specified by the rating curve for the 20-ampere rectifier.

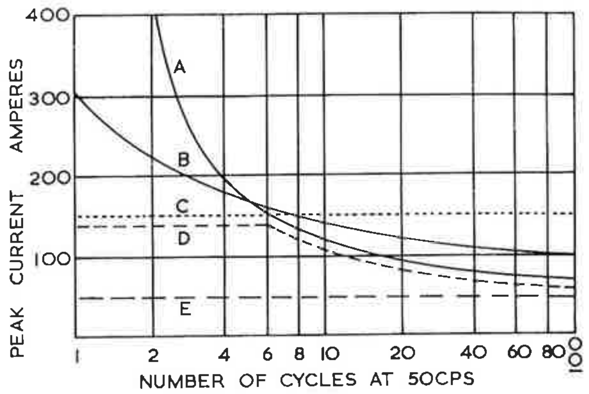


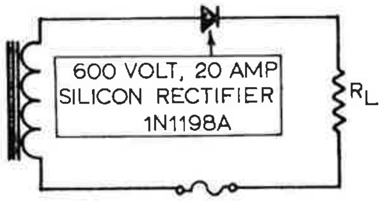
Fig. 3—Co-ordination chart. A represents the opening characteristic of the fuse or circuit breaker, B the surge rating, C the maximum available from the circuit, D the maximum fault current line, and E the steady-state load current of the circuit.

cycle. Such circuits must be evaluated with the universal surge rating charts of the following section.

Universal Surge Ratings

The Universal Surge Rating charts shown in Figs. 5 and 6 are for rectifier circuits where non-sinusoidal shaped current surges may be encountered, either as part of normal operation or in circuit fault conditions.

There are certain differences between the universal surge rating curves shown in Figs. 5 and 6 and the half-sine-wave rating curves shown in Fig. 1: (1) The time base on the universal curve is given in seconds rather than number of cycles, (2) the current in the universal chart is given in rms amperes rather than peak amperes of a half-sine-wave, and (3) the universal rating curve also approaches zero current as time approaches infinity, while the half-sine-wave rating curve approaches the normal peak repetitive current. This difference is due to basic differences in the method of using the curves.



$$V_{peak} = 600 \text{ volts}$$

$$R_L = 9.5 \text{ ohms}$$

$$I_{peak} = \frac{600 \text{ volts}}{9.5 \text{ ohms}} = 62.8 \text{ amps}$$

$$I_{average} = \frac{I_{peak}}{\pi} = 20 \text{ amps}$$

Fig. 4—Sample circuit for the co-ordination chart.

The half-sine-wave rating curve specifies a current which replaces the peak forward current for the duration of the surge. The universal curve however, shows a current which is added to the normal forward current to determine the maximum current which may occur during the surge.

Definitions for the terms used in the following text are illustrated in Fig. 7. For the reason previously stated, the current specified by the universal curve is referred to as the incremental surge current rating. The total surge current rating is then the sum of the incremental surge current plus the steady-state operating current.

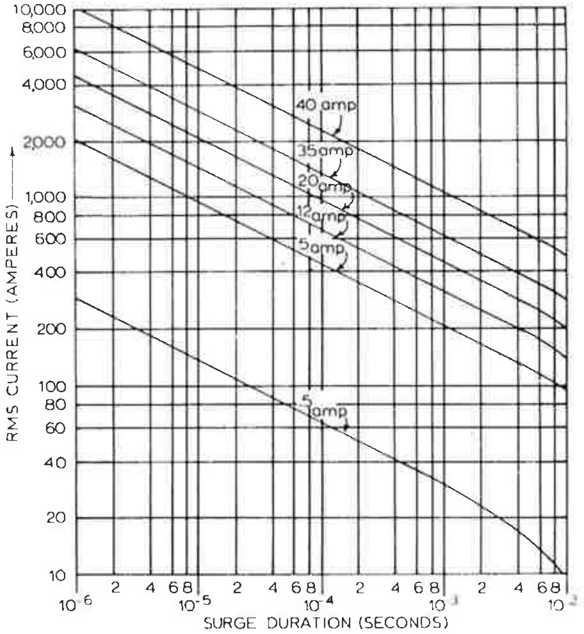


Fig. 5—Universal surge rating chart for rectifiers. The rms current given by this curve is a partial surge rating, and should be added to the normal rms current to determine the total surge rating.

Therefore, the actual surge current rating for long-time duration surges approaches the steady-state or continuous current rating for the particular application in which the device is being used. Conditions such as heat sink size and ambient temperature will determine the maximum continuous current rating.

Each point on the universal rating curve defines a specific incremental surge current in terms of the maximum length of time for which any given rms current can be allowed to flow. For example, consider a rectangular current pulse. The rms current is the same as peak and same as average

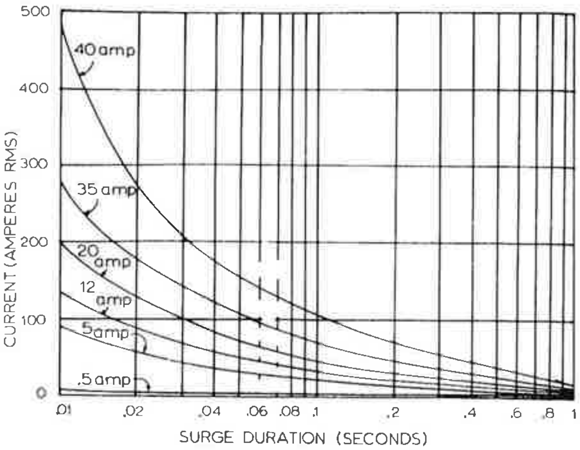


Fig. 6—Universal surge rating chart for rectifiers. The rms current given by this curve is a partial surge rating, and should be added to the normal rms current to determine the total surge rating.

while the pulse is flowing. Therefore, the full load surge rating curve (for the 20-ampere rectifier) shows that a rectangular pulse of 320 amperes can be applied for three milliseconds, or that a 1600-ampere pulse can be applied for 20 microseconds, or that a 4500-ampere pulse can be applied for one micro-second. This, of course, is in addition to the normal operating current.

When using these curves for a surge shape other than rectangular, the rms value of the surge may be calculated by use of the following equation:

$$I_{rms} = \left[\frac{\int_{t_1}^{t_2} I^2 \, dt}{\int_{t_1}^{t_2} dt} \right]^{1/2} \qquad \text{---------} 1$$

The rms value of the surge must be within the current rating given by the curve for a time interval equal to that used in the rms calculation, i.e., the time given by:

$$\int_{t_1}^{t_2} dt$$

The rms value of any portion of the surge, as well as the rms value of the entire surge, must be within the ratings given by the curve. This restriction must be placed on the surge since the rms value calculated for any given surge will depend on the time interval used in the calculation. For example, consider a current surge such as shown in Fig. 8.

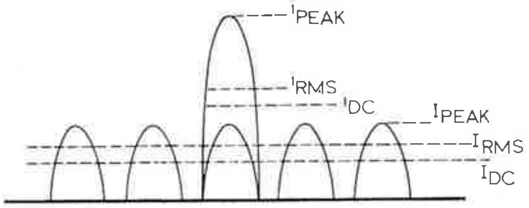
Calculating the rms current on the basis of the full 10 milliseconds of the surge gives:

$$I_{rms} = \left[\frac{100\text{A}^2 \times 9.98\text{MS} + 2000\text{A}^2 \times 0.02\text{MS}}{10\text{MS}} \right]^{1/2}$$

$$= \left[\frac{99800\text{A}^2\text{MS} + 40000\text{A}^2\text{MS}}{10\text{MS}} \right]^{1/2}$$

$$= (13980\text{A}^2)^{1/2} = 118\text{A}$$

Referring to the surge rating for 10 milliseconds (time used in calculation) it is seen that the device is rated for up to 200 amperes rms for this period of time. However, if the rms current during the highest portion of this surge is calculated, the current is 2000 amperes rms for a time interval of 20 microseconds. Referring to the 20 microsecond surge rating, the maximum rated current for this period is 1600 amperes, indicating that this portion of the surge is over the ratings although calculation of the basis of time of the entire surge indicates it to be within ratings. Therefore, either the time duration or the height of this current spike must be decreased to bring the rms current within the ratings.



I = Steady-state current
i = Transient surge current
Δi = Incremental surge current
I_{DC} = Steady-state current

Fig. 7

As an example of using the universal ratings for one cycle, half-sine-wave surge ratings for the 20-ampere rectifier, refer again to Fig. 5. At 50-cycles per second, a half-sine-wave lasts for 10 milliseconds. In Fig. 5 it is found that a time of 10 milliseconds corresponds to an rms incremental surge current of 200 amperes. If the normal operating conditions are 150°C case temperature and 20 amperes average forward current for a sine-wave input, the rms value of the steady-state current is:

$$I_{steady\ state\ rms} = 1\ 57\text{AVG.} \cong 32\text{A}$$

Then the total rating for a 10 millisecond surge in this application is: *

---

* *It is recognized that rms currents can only be added vectorially, however, the universal curves presented here have been adjusted to allow algebraic addition.*

$$
\begin{aligned}
I_{\text{total rms}} &= I_{\text{incremental rms}} + I_{\text{steady state rms}} \\
&= 200 + 32 = 232\text{A}
\end{aligned}
$$

For a half-cycle sine-wave surge, the peak current is 1.4 times the rms current so:

$$I_{\text{peak}} = 1.4\, I_{\text{total rms}} = 315\text{A}$$

Referring back to Fig. 1, it is seen that the one cycle surge rating determined in this way is the same as that given by the half-sine-wave rating curve.

The reason for using the universal rating curve is seen if the surge rating for operation at something other than 20-amperes and 150°C case temperature is calculated. For example, if the device is operating at a case temperature of 100°C, it may carry up to 30-amperes average forward current (See Fig. 9). The rms value of this current is:

$$I_{\text{steady state rms}} = 1.57 \times 30 = 47\text{A}$$

The 10 millisecond total surge rating is:

$$I_{\text{total rms}} = 200 + 47 = 247\text{A}$$

and the peak current of a half-cycle sine-wave surge may be:

$$I_{\text{peak}} = 1.4 \times 247 = 346\text{A}$$

As another example, if the device is operating in a blocking application where the case temperature is 175°C and the steady-state current is zero, it may be subjected to a half-cycle sine-wave surge with a peak of:

$$
\begin{aligned}
I_{\text{peak}} &= 1.4 \times (\text{incremental rms} + 0) \\
&= 1.4 \times 200 = 280\text{A}
\end{aligned}
$$

The procedure for using the universal surge ratings for circuit evaluation is basically the same as that outlined in the previous section. A coordination chart is made up by plotting steady-state currents, incremental currents, surge current ratings and opening characteristics of the protective elements, all on the same graph of current versus time. Of course, all currents in this case are plotted in terms of the rms values rather than peak. The surge current ratings must be plotted by adding the incremental surge rating (from the curves of Figs. 5 and 6) to the steady-state current of the circuit.

Capacitor "inrush" surge is another problem the designer must consider when selecting a diode rectifier for a circuit such as that shown in Fig. 10.

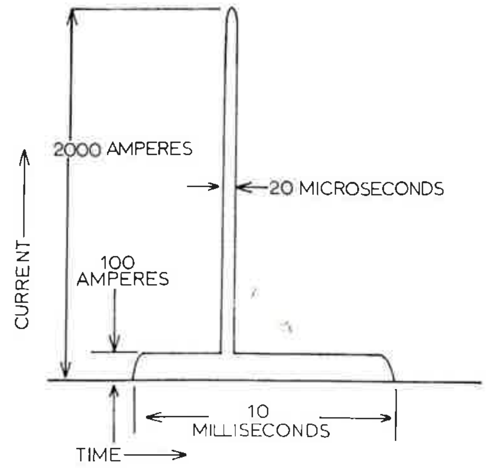


Fig. 8—Hypothetical surge current.

In such a circuit the main concerns are: (1) is the capacitor inrush surge within the surge ratings of the rectifier, and (2) if not, how much limiting resistance must be added to bring the inrush surge within ratings?

During the first cycle of a sinusoidal input, the capacitor is essentially a short circuit, since during initial energizing, the current is only limited by the transformer winding and other circuit elements in series with the capacitor. Most of the current would flow in one time constant (See Fig. 11). Therefore, the duration of this surge would be determined by the RC time constant. The "worst-case" condition for such a circuit would be when the circuit is energized at the peak (V_p) of the sinusoidal input.

If the time constant of the circuit is short compared to one cycle of applied sinusoidal voltage, there will be little change in the applied voltage during the "inrush" surge.

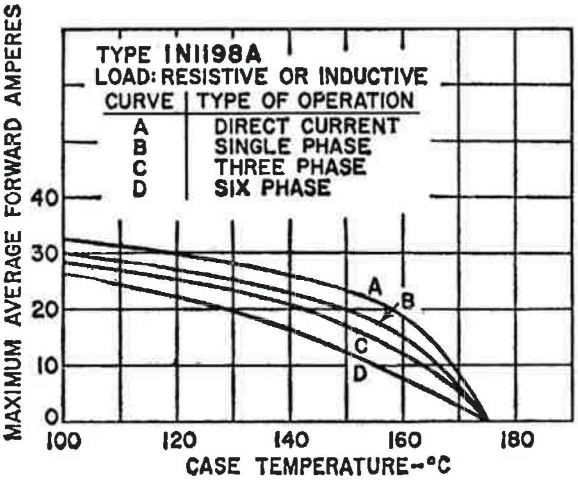


Fig. 9—Average forward current rating chart for 20-ampere rectifier.

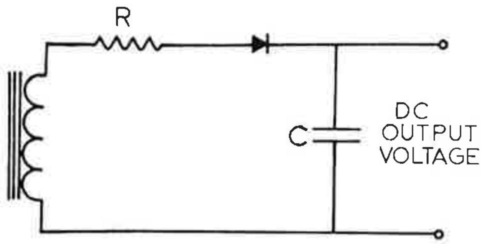


Fig. 10—Capacitor input circuit.

Since most of the surge occurs between 0 and time equals one time constant, this portion may be considered the time duration of the surge when referring to the rating charts of Figs. 5 and 6.

The choice of RC as the time base surge calculations is somewhat arbitrary since a somewhat longer or shorter time would also give an equally valid approximation to the surge. The time RC will be used here since it simplifies calculating the rms value of the 0 to time equals one constant portion of the surge. This may be calculated by equation (1) and is found to be given approximately by:

$$I_{rms} = 0.7I_p = 0.7\frac{V_o}{R} = 0.7\frac{V_p}{R} \quad \text{-----}\ 2$$

If the current from equation (2) is below that of the rating curve at one time constant, the inrush surge may be considered safe for the rectifier. If otherwise, additional resistance must be added in series with the capacitor.

If the latter is necessary, the amount of resistance required can be determined by recalculating the RC time constant and current of equation (2) with higher values of resistance until one is found to give a current and time which are below the rating curve.

A more exact method for finding limiting resistance is to substitute in equation (2) as follows. From the time constant, t = RC, write:

$$R = \frac{t}{C} \quad \text{-------------}\ 3$$

Using this equation (2) gives:

$$I_{rms} = 0.7\frac{V_pC}{t} \quad \text{-----------}\ 4$$

Equation (4) gives surge current as a function of surge duration for the load capacitance (C) and peak voltage (V_p) in the circuit. The curve of current time of equation (4) will be a straight line on a log-log plot such as that of the rating chart of Fig. 5. It will have a slope of –1. If this curve is plotted on the rating chart there will be some point at which it crosses the rating curve. The time given by this crossover point is the minimum time constant the circuit may have and still give a surge within ratings. The minimum value which the limiting resistance may have is then given by using this minimum time constant in equation (3).

The preceding analysis was developed for circuits where changes in input voltage are slow compared to the time constant of the circuit. Similar methods can also be applied to more rapidly changing voltages. For instance, if the time constant is several cycles long, the charging current will be approximately equal to a series of half-sine-wave pulses if a sinusoidal input voltage is applied. Since the rms value of a series of half-sine-wave pulses is just one-half the peak current, a good approximation may be obtained by using the same equations as those used previously by simply replacing the factor .7 by factor .5. Rewriting equations (2) and (4) for long time constants gives:

$$I_{rms} = 0.5I_p = 0.5\frac{V_p}{R} = 0.5\frac{V_pC}{t} \quad \text{----}\ 5$$

The methods presented are rough approximations for determining whether the device will operate within its ratings. They are usually adequate, but for cases where more exact analysis is needed, the actual surge currents occurring in the circuit may be measured and compared with the rating curves.

As an example of the use of this analysis, assume the following values for the circuit shown in Fig. 10.

Transformer output voltage =

$$\left[\begin{array}{l} V_{rms} = 210V \\ V_p = 300V \\ V_{inst} = V_p \sin(\omega t) \end{array}\right.$$

DC OUTPUT = V_p = 300V

PIV = $2V_p$ = 600V

C_{load} = 50 mfd

$R_{circuit}$ = 5Ω

TC (t) = RC = 250 μsec

$$\text{SURGE } I_{rms} = 0.7\frac{V_p}{R} = \frac{0.7 \times 300}{5} = 42A$$

Referring to the 0.5 ampere rectifier rating curve on Fig. 5, it is seen that this device will take a current of 44 amperes for a time of 250 microseconds. Therefore, the surge calculated above is within the device rating.

Surge Currents and Commutation

Because of the forward and reverse recovery, a certain amount of caution must be exercised when surge currents occur near commutation. Commutation is used here to mean the instant of time at which the current through the device changes its direction of flow.

Forward recovery appears as a forward voltage which is higher than normal when forward current first begins to flow, following the reverse blocking condition. If the rate of increase of forward current (d I_F/dt) is limited to a maximum of 10 to 100 amperes per microsecond, there will be little or no chance of damage to the device. Generally, the forward recovery does not present any circuit problems because in most cases, the self-inductance of the circuit will assure that the rate of rise of forward current will be far below that which might damage the rectifier.

The reverse recovery phenomenon appears as a reverse current which is higher than normal, immediately following forward conduction. The time duration of recovery current can vary considerably since it is a function of the magnitude of forward current just before commutation, the rate of change of forward current just before commutation, and flow of reverse current through the device immediately after commutation.

During the time when recovery current is flowing, the source voltage will drop across the other circuit components, thus limiting the magnitude of the reverse current. When the rectifier recovers to a high reverse impedance, this voltage drop will transfer from the other components to the rectifier. If the circuit contains inductance L, an additional transient reverse voltage equal to L di/dt will occur across the rectifier due to the sudden decrease in reverse current. This sudden increase in reverse voltage as the rectifier turns off, could exceed the rated PIV and also could result in a high surge of power being dissipated in the rectifier, possibly high enough to destroy it. For this reason, there are limits on the rate of rise of reverse voltage which a device can tolerate following forward current, and especially following a forward surge.

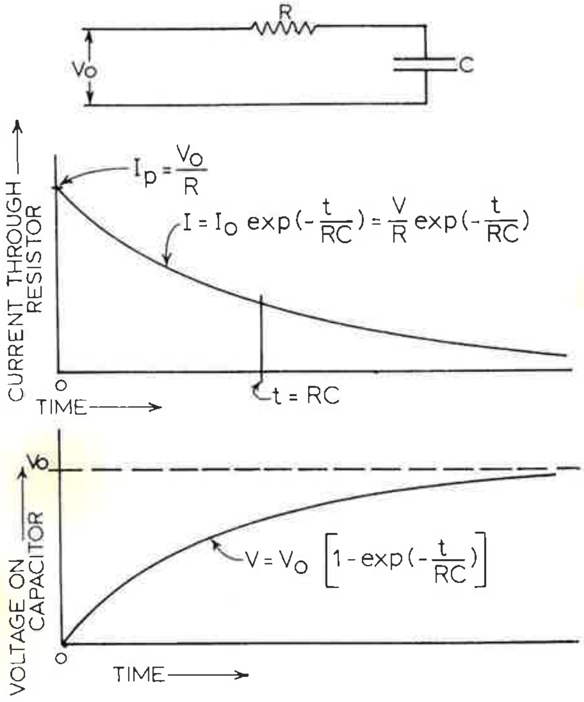


Fig. 11—Resistor-capacitor network with steady voltage applied.

The rate of rise which might cause damage would be of the order of magnitude of greater than 1 to 10 volts per microsecond. This will depend on a number of factors, such as forward current just before commutation, circuit inductance, device turn-off characteristics, etc. This danger to the rectifier exists only during the recovery phase which might last as long as several hundred microseconds after commutation. After the recovery phase is over, there is no need for limits on the rate of rise of reverse voltage.

The reverse voltage transient induced as the rectifier recovers is equal to L di/dt where L is the circuit inductance and di/dt is the rate of decrease of reverse current as the device recovers from a low to a high reverse impedance. To keep this transient voltage to a minimum, both of these quantities should be kept to a minimum. The circuit inductance can be minimized by appropriate circuit design. The di/dt can be minimized by placing a capacitor in parallel with the diode.

The ratings and figures given in this Note are meant to act as general guidance figures which can apply to the devices for all applications. There are, however, many instances in which a device can take a surge which is higher than that specified, or where unusually high rates of rise in reverse voltage or in forward current may be tolerated. In any application where unusual requirements are involved, the manufacturer should be consulted. Special requirements can very often be met by the standard product or by devices which have been specially selected for the application.

(With acknowledgements to RCA. Figs. 1, 2 and 3 have been redrawn on the basis of 50-cycle operation to coincide with Australian conditions.)

Continued

SINGLE SIDEBAND

by B. J. Simpson

In this fourth and last instalment of a simple exposition of single sideband communication, we will deal finally with the reception of the transmitted wave at the receiving station, and the recovery of the intelligence transmitted. Readers will recall that earlier instalments deal with a discussion of just what SSB is, and its advantages, and the various methods of producing SSB transmissions.

We now have a situation where we have transmitted certain intelligence by amplitude modulating the data onto a radio frequency carrier; we have then removed one of the two sidebands produced as a result of the modulating process, and have also removed the carrier, or at least severly attenuated it. What we have left is one sideband, with a trace of a carrier, and this is all that is actually transmitted.

Receivers

It is possible to receive SSB transmissions on an ordinary AM receiver, but in general this method is not satisfactory, largely due to lack of frequency stability. In AM communication, the channel width for voice transmission is generally several kilocycles, and frequency stability in the receiver, particularly of course in the local oscillator, need not be better than a few hundred cycles per second if intelligibility only is required.

An SSB transmission, on the other hand, has a very narrow channel width, and stability of a much higher order is required. In fact, a frequency drift of only 20 cps can easily be noticed, and by the time the drift has reached 50 cps, the transmission is completely unintelligible.

The problem of stability is also increased by the fact that the insertion of a locally-generated carrier, to replace the transmitter carrier component, is necessary in the receiver demodulator. High stability is required therefore, both in the signal tuning circuits and the local carrier generator section, if satisfactory reception is to be obtained.

There are two basic approaches to the design of a receiver for SSB work, and they are shown in the accompanying Fig. 25. Before going further, it will be necessary to examine the two arrangements.

In Fig. 25A, the input signal is applied to a tuned rf amplifier, and thence to the first mixer, where it is mixed with the output from a crystal-controlled oscillator. The crystal oscillator frequency is fixed, but the frequency is so chosen that the output signal from the first mixer falls within the tuning range of the first if amplifier which follows in the circuit.

The output signal from the first mixer usually has a frequency between 1.5 and 4.0 megacycles per second, and after passing through the first if amplifier is applied to the second mixer. The other input to this mixer is the output of a variable frequency oscillator, the frequency of which is so adjusted as to give an output from the second mixer at 455 Kc, or other convenient frequency.

The signal at the new low frequency is then amplified in the second if amplifier, which is a fixed frequency circuit, and which incorporates a sideband filter. Thence the signal passes to a product demodulator and the audio amplifier stages.

In the alternative arrangement shown in Fig. 25B, the rf amplifier of the receiver is tunable. The signal passes through the rf amplifier and then to the first mixer, where it is mixed with the output of a high-frequency oscillator. The oscillator frequency is variable, and is adjusted so the output of the first mixer is at 455 Kc or other convenient frequency. The next stage of the receiver is the first if amplifier, the operating frequency of which is fixed.

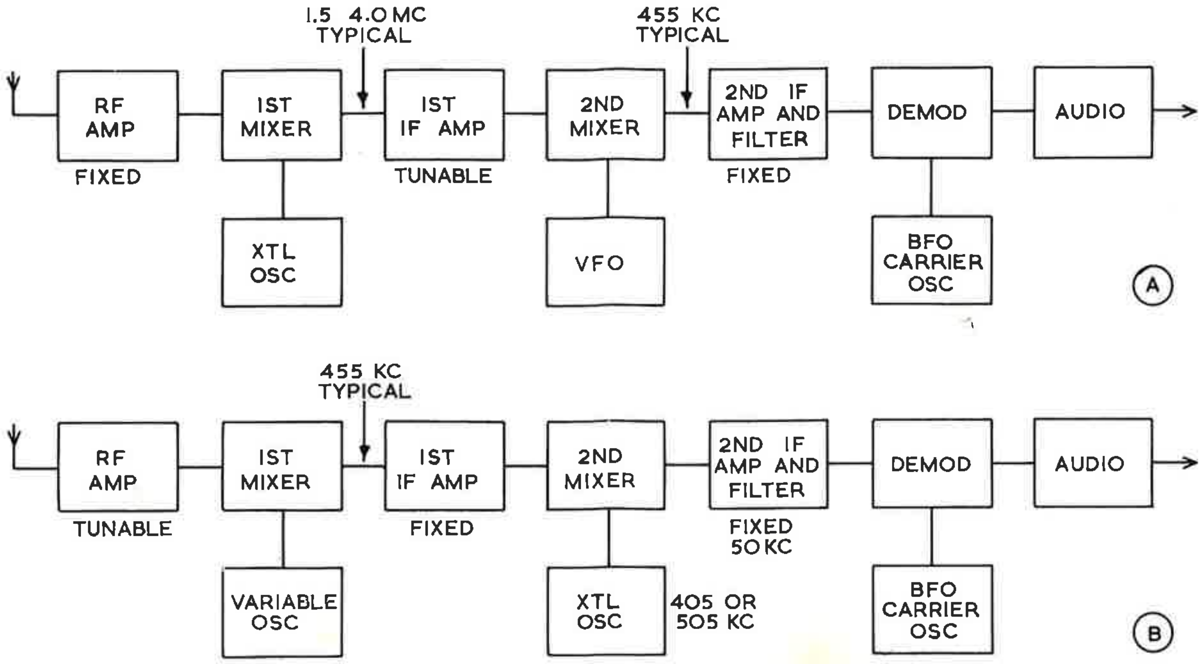


Fig. 25

The signal then goes to the second mixer, where it is mixed with the output from a crystal-controlled oscillator to form the second intermediate frequency. The crystal oscillator frequency is typically 405 or 505 Kc, so that the second intermediate frequency will be 50 Kc. The second if amplifier is fixed tuned to this frequency, and the bandpass characteristic of the amplifier is so arranged as to form a rejection filter for one of the sidebands of a conventional AM transmission. By arranging that the crystal oscillator is equipped with crystals of both 405 and 505 Kc, which can be switched as required, the bandpass characteristic of the following amplifier can be used to select either the upper or the lower sideband as required. The rest of the receiver follows the previous scheme already described.

The first of the two alternatives, shown in Fig. 25A, usually has the better frequency stability because the variable frequency oscillators all operate at relatively low frequencies. This arrangement is popular with amateur stations, and commercial stations operating on fixed frequency channels. The second of the arrangements, shown in Fig. 25B, is used where it is desired to cover a wide range of input frequencies.

Product Detectors

The two basic types of receiver just described will vary a great deal in detail from one maker to the other, whilst still following the same general plans. Apart from these matters, and the question of stability, there is only one other notable difference between these receivers and a conventional unit, and that is in the use of a product detector. It will be necessary to examine the operation of this circuit in detail in order to appreciate how the transmitted intelligence is recovered.

A typical arrangement of a product detector is shown in Fig. 26, and the valve used may be either half of a 12AU7 or the triode section of a 6U8A. The essential operation of this circuit is that it mixes the sideband signal with the local carrier oscillator, and the audio output from the detector is the product of the two rf input signals, hence the name. This arrangement is necessary because the envelope of an SSB signal contains a completely different set of components from those present in a conventional AM signal. This means that a suppressed-carrier signal cannot be detected in the ordinary AM diode detector; the output would be a very distorted and unintelligible audio signal which would be useless.

In the circuit being discussed here, the sideband signal is applied to the grid of the triode, and the local carrier oscillator output to the cathode of the valve. The injected carrier should have the same frequency relationship to the sideband signal as the carrier which was suppressed at the transmitter, and the relative levels of the sideband and carrier signals at the detector should be such as to produce minimum distortion. This will in general mean that the level of the injected carrier will be several times that of the sideband signal.

The low-pass filter at the output of the detector is the customary arrangement at the output of a detector.

It will now be seen that whereas at the transmitter, a carrier is modulated, and one of the sidebands and the carrier are then removed, at the receiver the sideband is mixed with a local carrier oscillator so that the original modulation can be recovered. The two processes are very similar, except that at the transmitter, the sideband is the product, whereas at the receiver, the audio modulation is the product.

More Vectors

The simplest way to explain the operation of the product detector is by the use of vectors. A vector diagram of a product detector is shown in Fig. 27, in which the carrier, and the upper and lower sidebands, are represented vectorially and indicated respectively by C, US and LS. The combination of the three signals represent the input to the grid of the product detector, consisting of a double-sideband suppressed carrier intermediate frequency signal.

As in the case of the previous vectors shown in this article, it is assumed that the carrier signal C is rotating about its origin, whilst the sideband signals, which are of different frequencies, rotate in opposite directions about the carrier vector. The carrier in this case is the injected carrier at the receiver. The actual frequencies of the sideband vectors will vary with the modulating frequency.

We can now turn to the sequence of events shown in Fig. 27, and commence with time A. At this point, the sideband signals are in antiphase, and therefore cancel, leaving only the carrier signal. Only the carrier signal will therefore affect the plate current of the detector, and it is assumed arbitrarily that the value of plate current is one unit, as shown in the lower part of the diagram.

At time B, we see that all three signals are adding. It has been assumed in the diagram that the amplitudes of each of the sideband signals is exactly half that of the carrier signal. This gives us a convenient basis, and we now have the condition where the signal applied to the valve has twice the previous amplitude; we can therefore assume for this argument that the new value of average plate current is twice that in the former case, and is now two units, as shown.

The rest of the diagram follows logically from this, because at time C, the two sideband vectors have rotated through 180 degrees, and are again opposing and cancelling. Average plate current value is therefore once again one unit.

Proceeding now to time D, we now have the condition where both of the sideband vectors are in phase, and are in opposition to the carrier vector. The resultant signal is therefore zero, and we take the average value of plate current as zero also. The last condition, shown at time E, is the same as that at time A, and completes the cycle of operation.

It will now be seen that the average value of plate current in the product detector follows the modulation applied to the carrier at the transmitter. In the case of this example, the modulation was assumed to be a sine wave of constant frequency, as shown in the plot of values of plate current.

Plate Current

The average value of plate current discussed here is in fact not an average value, but the average of the instantaneous values of plate current. Because the product detector is essentially

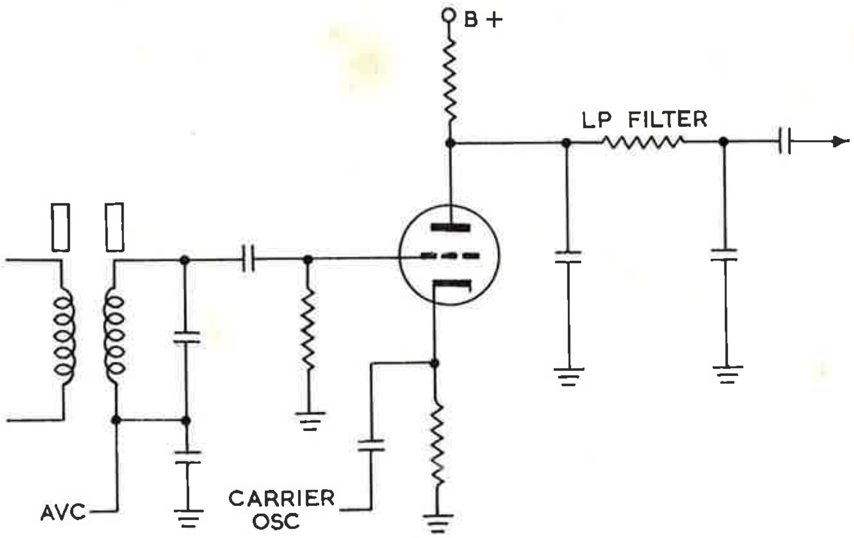


Fig. 26

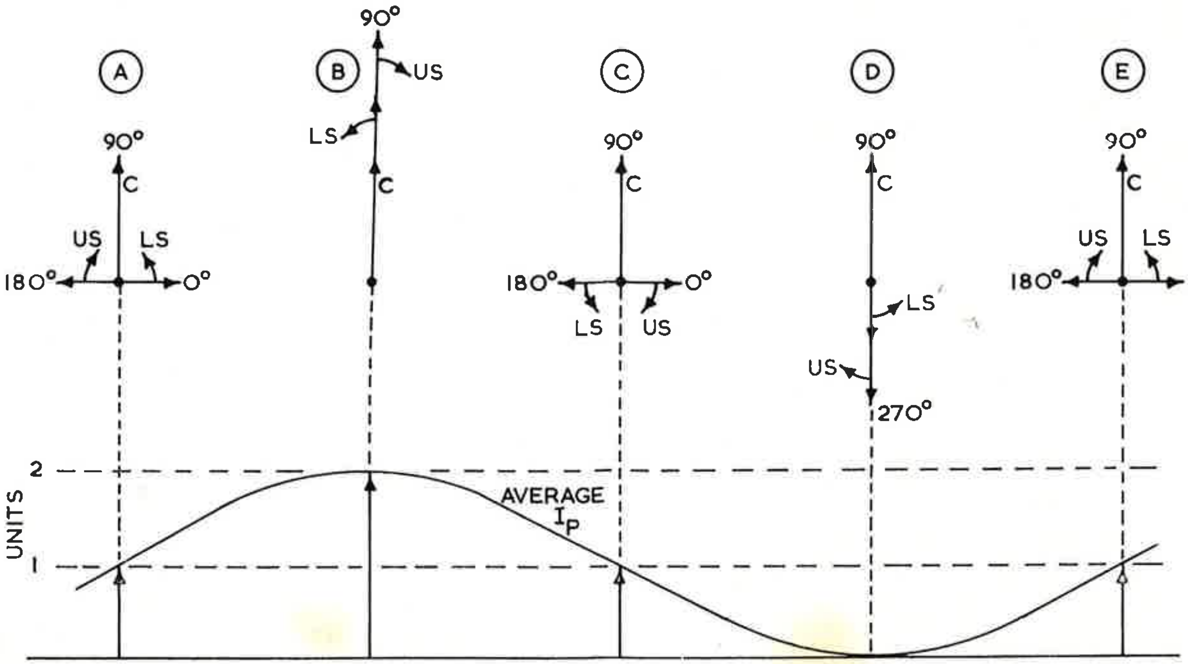


Fig. 27

a mixer, there will be many signals present in the plate current of the valve. The main ones will of course be those we have just been discussing, the two sideband signals and the injected carrier. The carrier will add to each of the sideband signals and produce sum signals in the plate current, which will appear as two sidebands above and below the second harmonic frequency of the injected carrier, and displaced from the harmonic frequency by the original modulating frequency.

Difference signals will also appear in the plate current. Their values will be the carrier minus the lower sideband, and the upper sideband minus the carrier. It is the difference plate current component that produces the original audio modulation, and this is the component plotted in Fig. 27. The higher-frequency components in the plate current are removed by the low-pass filter at the output of the detector.

Stability

A good deal of the discussion presented here surrounds the case of a double-sideband, suppressed carrier system, and this has been done to show more fully just what takes place. Where the reception of an SSB signal is concerned, the basic explanation is the same, except that one of the sideband signals is not present.

For those familar only with Standard AM receivers, who know how much the local oscillator frequency can be "off tune" whilst still preserving intelligible reproduction, even though the quality suffers, it may be interesting to conclude by an examination of the statement made earlier on regarding the extreme stability and closeness of tuning required in SSB and DSB receiver circuits.

Let us assume that the receiver if strip is designed for operation at 50 Kc, but the bandwidth is such as to provide good quality on speech, say up to 3.5 Kc. If now a 3 Kc tone is applied to the transmitter, then, assuming DSB transmission, if sidebands will appear in the receiver at 47 and 53 Kc. The carrier input to the product detector must be precisely at 50 Kc if the tone is to be recovered satisfactorily. If this is the case, then the two audio difference signals (50 minus 47, and 53 minus 50) will add in the product detector and emerge as one signal, their frequencies being identical.

If now we assume the carrier frequency to be 49 Kc instead of 50 Kc, then the two audio difference signals will not coincide. That due to the lower sideband signal will be at 2 Kc, and that due to the upper sideband will be at 4 Kc. The two signals do not represent the original modulation, and the effect can perhaps be imagined rather than described. Further, as the bandwidth of the if strip is only 3.5 Kc, it is reasonable to assume that the 4 Kc signal will be further affected by the low-pass filter at the output of the detector, as this filter would probably have the same cut off frequency.

In practice, DSB signals are generally handled by removing one of the sidebands in the if strip by a suitable adjustment of the bandpass characteristic. This eases the problem considerably. In this case, and in the SSB case also of course, the production of double tones will be avoided, but any departure of the carrier oscillator from the precise frequency required will result in a shifting of all tones in the modulation by the same amount. That is, a departure of 50 cps at 50 Kc will result in all the audio modulation being raised (or lowered) in frequency by 50 cps. The effect will be similar to that of operating a gramophone with the turntable speed wrong. Very little of this is required to ruin the quality and make the whole thing completely unintelligible.

Summary

This completes this very brief and basic description of SSB transmission and reception. There are many aspects of great interest but beyond the scope of this article. Several points have of necessity had to be passed over quickly, and a great amount of detail has had to be omitted. It is hoped, however, that the basic object has been achieved, to render a picture and an outline covering the main facts.

Editor .... **Bernard J. Simpson**

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