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SILICON DIODES IN HIGH-VOLTAGE RECTIFIERS

INTRODUCTION

BEFORE THE ADVENT of the silicon diode the choice of a rectifier, for use in the high-voltage rectifiers for broadcast transmitters, was limited to a variety of mercury arc and thermionic devices. These had been developed to an acceptable standard of reliability and efficiency but they had the disadvantage of a finite life.

Silicon diodes, with economic cost and adequate rating, are now available to satisfy the requirements of the largest equipments. High a.c. to d.c. conversion efficiency and long-life expectancy enhance their use in high-voltage rectifiers.

These devices are incorporated in the high-voltage rectifiers used in Marconi transmitters up to 750 kW carrier rating. Their introduction by The Marconi Company has been progressive in terms of power rating and extensive development work has been necessary to assure reliability in service.

Silicon diodes have been in use for several years in low-power Marconi transmitters. Their record in service of many millions of hours of trouble-free operation is proof of the application techniques developed for high-voltage equipment. These techniques have been extended to the use of higher powers and the diodes have been selected with reliability as a prime requisite.

The silicon diodes employed in the high-power transmitters were primarily developed for use in traction equipment. In this application very high reliability has been achieved under the adverse operating conditions experienced in railway locomotives.

TYPES OF HIGH-VOLTAGE RECTIFIERS

The high-voltage rectifiers used in broadcast transmitters must withstand fault condition overloads, must have a high a.c. to d.c. conversion efficiency and a relatively low impedance. These considerations preclude the use of high-vacuum thermonic diodes. Though these can be built to withstand extremely high peak-inverse voltage at high ambient temperatures, their high impedance gives poor regulation and power conversion efficiency.

The requisite regulation and efficiency can be achieved with mercury-vapour rectifiers. Two disadvantages, however, are the limited temperature range of condensed mercury, usually quoted as 25°C to 50°C, and the effect of temperature on the permissible peak-inverse volts.

Xenon-filled rectifiers operable over the range −55°C to +75°C overcome the foregoing shortcomings but are limited in power-handling capacity and peak-inverse volts and life is dependent on gas pressure.

Grid-controlled mercury-vapour thyratrons have the advantage that the d.c. output can be controlled by a low-level voltage but still retain the drawbacks inherent in all mercury vapour tubes.

High-tension supplies for broadcast transmitters have successfully employed mercury-arc rectifiers. Initially multi-anode tubes, these developed into 'Excitrons' comprising a single anode unit, a mercury-pool cathode, means for initiating excitation and a control grid. The latter electrodes offered a successful means of arc suppression and the ability of the device to withstand short-circuit currents made it sufficiently rugged for high-tension rectifier applications. Despite these advantages the 'Excitron' like the 'Ignitron', also used successfully, still fall within the category of components having finite life.

Semi-conductor rectifiers are relatively low-voltage devices which have to be series operated in high-tension power-conversion equipment. The current rating of silicon diodes has been progressively increased and diodes are now available with current ratings up to 600 A and peak-inverse voltage ratings up to 1500 V.

Avalanche diodes have desirable characteristics which have been successfully exploited in lower-power high-voltage rectifiers. Higher-current avalanche diodes are becoming available but more development work is necessary to ensure long life and reliability before introducing them into the high-power applications.

Silicon diodes should have a life of the same order as the equipment when they are employed within their specified operating conditions.

CHOICE OF SILICON DIODES FOR HIGH-POWER VOLTAGE RECTIFIERS

During the life of a broadcast transmitter it is probable that the maximum diode current may be determined by a short circuit across the rectifier. It is this current which must be used as a basis for diode selection and not the mean (thermal) current. The magnitude of the diode fault current under short-circuit conditions is largely determined by the impedance of the main high-tension transformer which determines also the voltage regulation. Design compromise may thus be necessary to protect the diode and also meet the transmitter performance. The ambient temperature, and the loss within the rectifier, determine the junction temperatures and thus the overload surge rating.

Marconi high-power broadcasting transmitters, with carrier powers between 100 kW and 750kW employ silicon diodes in the main h.t. rectifier. The diodes used in these rectifiers are supplied in identical packaging for current ratings of 70, 150 and 200 A (mean forward current averaged over whole cycle). The voltage rating of the diodes covers the range of 100 to 1500 V maximum peak-reverse transient voltage. The cost of the diodes is naturally related to their current and voltage rating and the single-size device makes it economically possible to produce a very wide range of power outputs using a modular construction.

A rectifier module, mounting five diodes connected in series, is shown in Fig. 1. Each diode is shunted by a capacitor and resistor to equalize the applied diode voltage under both normal operating and fault conditions. The diodes are maintained in thermal contact with the heat sinks by a compression spring at the end of the module. This pressure can be released to enable the diodes to be removed from the module.

A glass-fibre frame, illustrated in Fig. 2, which normally supports and electrically insulates the modules also evenly distributes the cooling air stream.

Typical examples of the use of these rectifiers are in the 100-kW h.f transmitter B6123 and the 750-kW m.f transmitter B6026. The main h.t rectifier for the 100-kW h.f transmitter provides a nominal output of 10 kV at 25 A d.c using a three-phase full-wave rectifier. The peak fault current through one leg of the bridge is 700 A and diodes, rated at 70 A thermal current, have adequate safety factor at this fault level.

The 750-kW transmitter employs two rectifiers in parallel with their commutation phased. Each rectifier has a nominal rating of 12 kV 55 A d.c. The peak fault current through one leg of the bridge is 1400 A and in this example the thermal rating of the diodes is 150 A.

A high overall safety factor and inbuilt redundancy, to allow for the unlikely failure of one device, determines the number of series diodes. Typically, the

Fig. 1. Module mounting five high-power silicon diodes.

rectifier for the 750-kW transmitter has 35 diodes (7 modules) in series in each limb of the three-phase full-wave bridge circuit. Each diode is rated at 1·0 KV maximum peak-reverse transient voltage and 0·8 kV maximum recurrent reverse voltage. Thus the total peak-reverse transient voltage rating is 35·0 kV compared with the open-circuit voltage of 13·0 kV.

THE PROTECTION OF SILICON DIODES IN HIGH-VOLTAGE RECTIFIERS

As already stated, the amplitude of a fault current through the diodes is limited to a safe value by building the requisite impedance into the associated rectifier transformer.

The duration of the fault current is normally determined by the interruption time of the high-speed vacuum switches connected between the transformer and rectifier diode assembly. This time is usually less than one cycle of mains frequency (20 msec). In the unlikely event of vacuum switch failure to operate, protection is by a circuit breaker in the primary of the rectifier transformer. The breaker, of normal construction, has an interrupt time of several cycles of the mains frequency and the diodes are chosen to withstand the fault current for this period.

The series-connected diodes have been selected to give adequate voltage rating but additional precautions are taken. Voltage spikes produced at commutation are restricted to low amplitudes by resistor/capacitor combinations connected across the transformer secondary windings and the smoothing reactors. The values of resistor and capacitor are chosen effectively to damp the internal resonances of these components. In addition, surge diverters are connected to the secondary windings of the transformer to limit the peak surge voltage to a level well below the rating of the series-connected silicon elements. Typically for a rectifier rated at 12-kV d.c output the diodes in each limb would have a maximum peak-reverse transient voltage of 35 kV and the surge divertor would limit the actual voltage to 28-kV peak.

Equal voltage across each diode for both normal working and fault conditions is ensured by capacitors connected in shunt with each diode.

The transformers used with high-voltage high-power silicon rectifiers are designed with high insulation levels. Whilst there are a limited number of faults which present effective short circuits to the secondary of the transformer the mechanical design must cater for this contingency. This means special construction techniques to give the mechanical strength to both core and windings to avoid distortion when

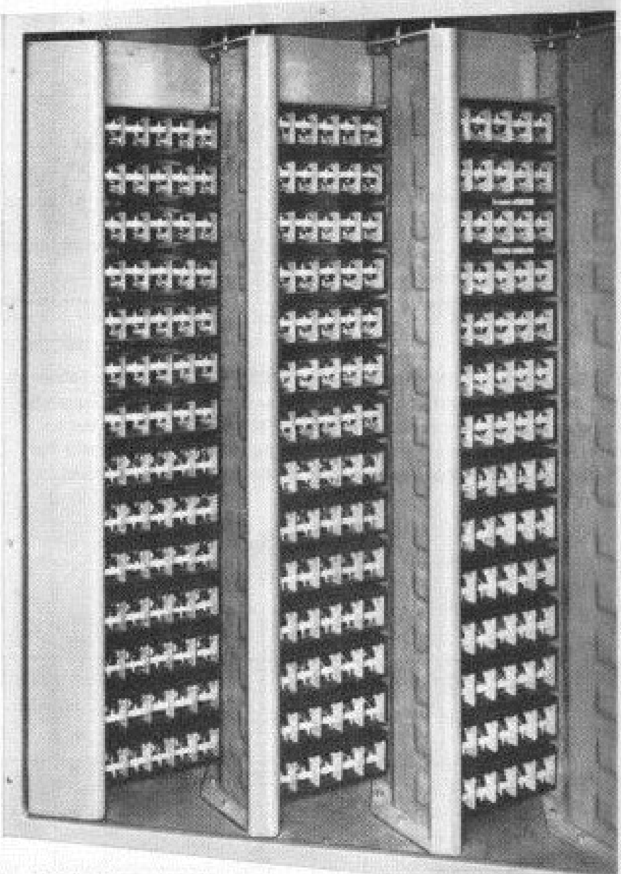

Fig. 2. Rectifier assembly.

they are subjected to the mechanical forces experienced under short-circuit conditions.

The silicon diodes in these rectifiers operate under favourable cooling conditions with heat sinks in fin form which couple thermally to the filtered cooling air. Effective cooling is essential under fault conditions so that the resulting rectifier junction temperature can be reduced to a safe level before power is reapplied. The transmitters include a device which automatically restores power after an intermittent fault. The cooling of the diodes permits power to be reapplied twice before a 'lock-out' is effected to clear a persistent fault. The intervals between reapplication of power are of 1 sec.

During the period when power is first applied to these high-power rectifiers, a resistance in series with the smoothing capacitors limits the peak charging current to approximately three times the nominal d.c current. A vacuum switch is used to short circuit the resistance for normal operation. An additional benefit is obtained from this starting sequence since the peak surge voltage across the capacitors is also limited.

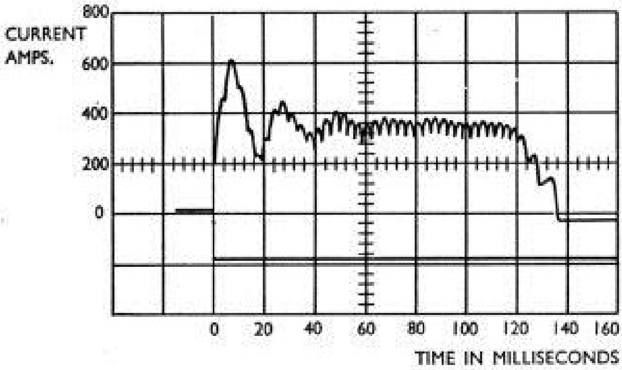

Fig. 3. Rectifier for 100 kW transmitter B6123. The fault current through the silicon diodes with the high-speed vacuum switches deliberately inoperative. The primary circuit breaker (400 V 3 phase) was set to clear in 7 cycles against the normal setting of 5 cycles. Normally the fault current would have been restricted by the vacuum switches to the first half cycle.

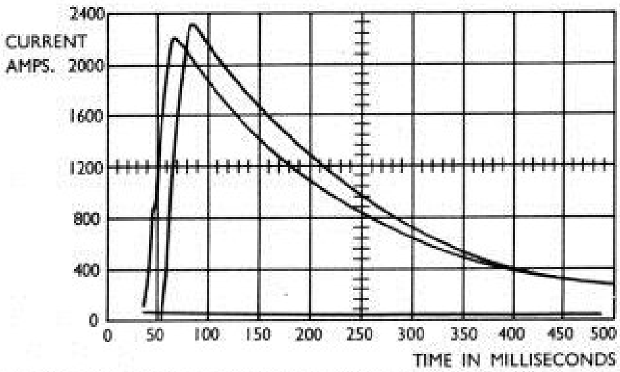

Fig. 4. Rectifier for 750 kW transmitter B6026. The total rectifier current when a short circuit is applied across the output of the smoothing filter, with two 'shots' are shown. Individual diode currents are half those depicted.

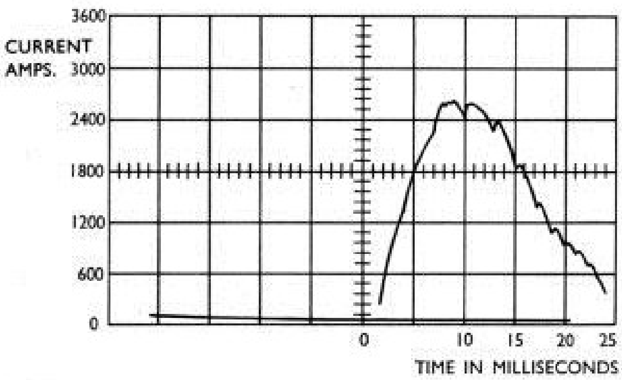

Fig. 5. Rectifier for 500 kW transmitter B6021. The total current to the two rectifiers when a direct short-circuit is applied. Individual diode currents are half those depicted.

SHORT-CIRCUIT TESTING OF SILICON DIODES

Whilst calculations of fault current under short-circuit conditions can be made with adequate accuracy it is essential to prove both the calculations and the transformer behaviour by actual tests.

The tests involve a large number of short circuits applied at various points in the rectifier and the associated filter system whilst the equipment is delivering power. In addition, the equipment must be started with the rectifier operating into a short circuit.

Illustrations of typical waveforms obtained on the 100-kW, 500-kW and 750-kW transmitters during such test programmes are shown in Figs. 3 to 7. These results agree closely with calculated values.

Figs. 5 and 6 make an interesting comparison. The former shows the total rectifier current when the high-speed vacuum switches are operative. The safety factors built into the rectifier are illustrated by the

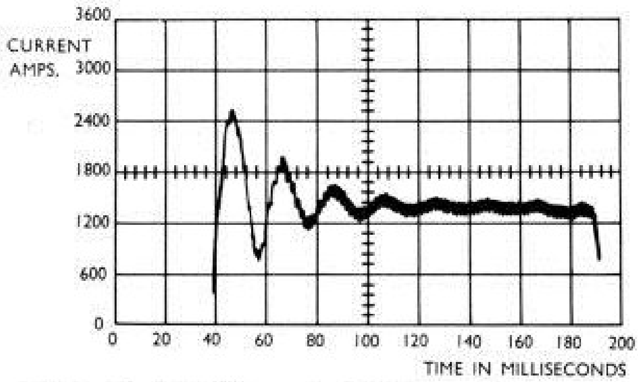

Fig. 6. Rectifier for 500 kW transmitter B6021. Taken with conditions as for Fig. 5 but with the high-speed vacuum switches inoperative. The primary circuit breaker (11 kV 3 phase) was set to clear in 7 cycles.

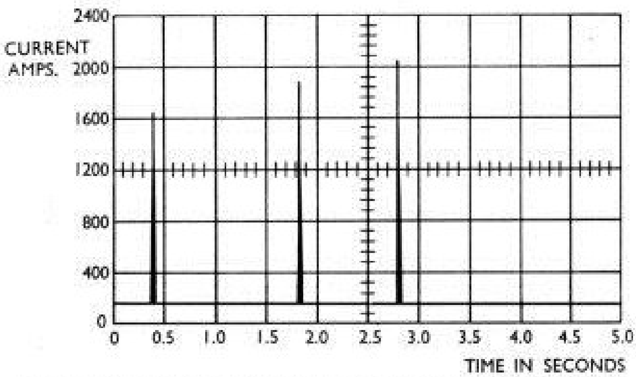

Fig. 7. Rectifier for 500 kW transmitter B6021. The fault current through the silicon diodes with the reclosure device in operation.

latter photograph. This was taken with the vacuum switch inoperative and the fault-current duration some seven times that shown in Fig. 5.

Identical diodes are used in the rectifiers of the 500-kW and 750-kW transmitters. The fault currents are kept to the same level in the two equipments by the impedance of the particular associated rectifier transformer.

HARMONIC DISTORTION IN SUPPLY SYSTEMS CAUSED BY RECTIFIERS

A rectifier connected to an a.c supply system having a sinusoidal voltage waveform will take from that supply a current whose waveform will have a mixed harmonic content. For a given number of rectifier phases the amplitudes of the harmonics are not affected by the internal connections of the rectifier transformer.

In flowing through the supply system the harmonic currents will cause voltage drops. These harmonic voltages will be propagated through the system and may cause interference to other customers. Typically, static capacitors may be overloaded, fluorescent lighting may not operate satisfactorily, errors may be caused to metering and the operation of other rectifiers and electronic equipmay be affected.

Whilst the percentage harmonic content of the current drawn by the rectifier is essentially a function of the rectifier itself, the harmonic voltage drop is also a function of the supply system impedance. Since most supply systems have a predominantly inductive impedance it is approximately proportional to frequency. The supply-system impedance can therefore be expressed in terms of short-circuit level and can be related to the system short-circuit MVA.

The effects of harmonic voltages in supply systems have been thoroughly investigated by the British central electricity authority and a *Recommendation* has been published relating the size of the rectifier to the system short-circuit MVA. This relationship is shown graphically in Fig. 8 where it can be seen that for a given system short-circuit MVA increases in rectifier load can only be accomplished by increasing the number of effective phases.

The 750-kW transmitter demands 1·6 MW of rectified power at 100% modulation. Reference to Fig. 8 shows that for this rectifier load the system short-circuit MVA should be 350 if a 6-effective phase rectifier is used. The 750-kW and 500-kW transmitters use two rectifiers connected to have a 30° phase shift. This gives a 12-effective phase rectifier and reduces the system short-circuit MVA to some 85. If two of these transmitters are installed on one site, the

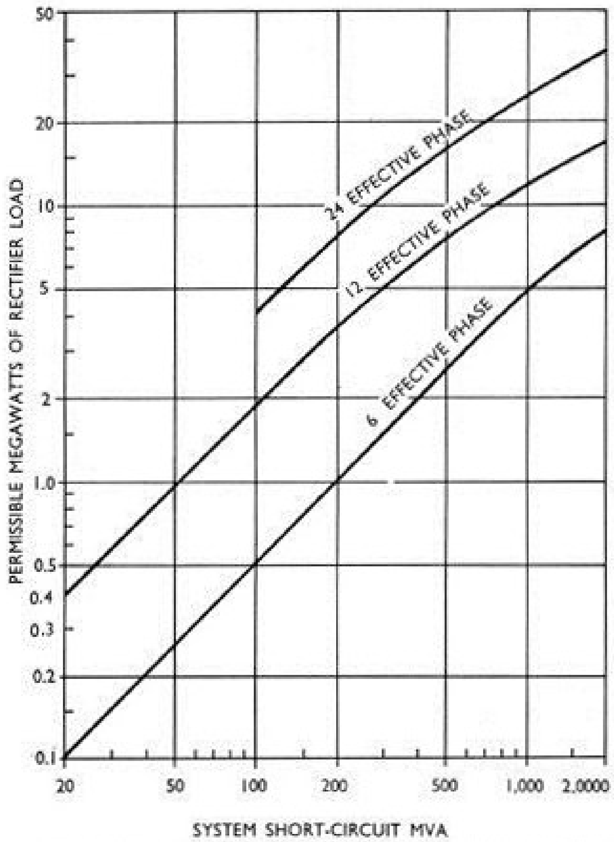

Fig. 8. Graph relating size of rectifier installation to the system short-circuit MVA.

phasing of the rectifier transformers of the second transmitter can be shifted by 15° to give a 24-effective phase rectifier and to maintain the system short-circuit MVA at 85.

If 750-kW or 500-kW transmitters are supplied with power-generating equipment which is used for no other equipment, then it is not necessary to employ the pair of dephased rectifiers since interference is not a criterion of performance. Silicon diodes with adequate fault-current rating are now available for use in a single rectifier rated at 1·6 MW d.c output.

CONCLUSIONS

Silicon diodes of adequate rating and the techniques for employing numbers in series with effective fault protection have now been developed to the state when reliability in service is assured.

In assessing the overall cost of an equipment the silicon diodes can be placed in the category of non-consumable items. Any comparison with thermionic or mercury arc rectifiers must take into account the finite lives of these devices and replacement costs must be calculated on the basis of the guaranteed lives.