CONSIDERATIONS REGARDING THE USE OF A.C. IN WARSHIPS

by

H. D. MacLaren, C.B., D.F.C., B.Sc.

This is an extract from a talk given by Mr. MacLaren, Director of Electrical Engineering, at the Controller's periodical Inter-Departmental Technical Discussion on the 16th April, 1946.

With the exception of Ferranti's efforts, all early developments in the practical application of electrical power used direct current. As consumers' load was built up the limitations of D.C. were soon felt due to the fact that, in the absence of an economical method of transforming the voltage, a limit was soon put to the distance at which consumers could be supplied without an unacceptable drop in voltage. This inability to transform voltage readily, and the progress in the development of the steam turbine, swung the balance to the advantage of A.C.

D.C., however, continues to hold the field for marine applications. The reasons for this are that it permits complete freedom of choice in electrical rotating machinery speeds, and easy speed control ; A.C. appearing to offer little counterbalancing attractions in a power consuming unit having the compactness of a ship installation. Furthermore, voltage for voltage, an A.C. installation for a warship would be heavier than a corresponding D.C. installation.

The foregoing seems to weigh the scales heavily in favour of D.C., and partly explains why, other than in the U.S. Navy, D.C. is still used as the basic supply on board ships, except where main propulsion is the objective.

Let us now see what can be said in favour of an A.C. installation. Then I shall review the objections to the use of A.C. and the means of dealing with them, thereby, I hope, opening up the way for discussion.

ADVANTAGES OF THE USE OF A.C. INSTALLATION

Briefly, the advantages of the use of an A.C. installation in order of importance are considered to be :—

(i) Greater reliability and reduced maintenance.
(ii) Economy in production of electrical equipment and ease of expansion of production in war-time.
(iii) Elimination of motor alternators for the supply of A.C. consuming equipment.
(iv) Makes available for Naval use the results of industrial research and development which are today largely confined to A.C.
(v) Gives latitude for selection of the most suitable voltage for lighting and minor power consuming apparatus.

While examining these items, I shall refer as may seem desirable to the features of A.C. apparatus.

Department under a Rear-Admiral (E.) and a number of air dockyards, air maintenance yards and an air training establishment for air artificers.

Training

As I stated earlier, our officers are trained at the R.N.E. College, Keyham, but the method of entry was altered in 1903 with the introduction of the Fisher-Selborne Scheme. The old title of Chief Inspector of Machinery changed to Engineer Captain, Fleet Engineer to Engineer Commander, and the new entries were known as the (E.) Officers. The last of the entries direct to Keyham was in 1906, and by next year (1947) none will remain on the active list.

The establishment at Keyham is too small and we are building a new College at Manadon, on the outskirts of Plymouth.

Our artificers are trained at the A.T.Es., Rosyth and Torpoint, and Arbroath (for Air). Our mechanicians are trained at the Mechanical Training Establishments at the three Home Ports, and our stokers at H.M.S. *Imperieuse* (two old battleships moored together). This is a vast training commitment. In war-time we have to expand more than a hundredfold, and to help to meet this commitment we maintain in peace-time an R.N.V.R., which we hope officers and men who served in the last war will join. Young men of the standard accepted by our Institutions are just the type we want to fill our officer posts should another war ever occur.

The Future

Having thus traced the evolution and development of British naval engineering from both the material and personnel aspect but in its very broadest sense, and though it is not within the title of my talk, you would perhaps like to know what the future holds for naval engineering.

We are at a most interesting stage in the engineering world ; the steam engine is likely to move into the fields of higher pressures and temperatures, but we must be careful to ensure that these are decided by marine requirements, which are more arduous than those of shore plant.

The Diesel engine is also very much alive and in the range below, say, 2,000 or 3,000 h.p. is likely to be required for some time to come. I feel sure that there will be considerable developments in this field. The gas turbine is on the threshold. Here our marine problem is very different and much more difficult than the air one, as we have to maintain efficiency over a range of power, and we must have a larger life than the 300 odd hours required for aircraft.

Atomic energy is not so far away and no one can say definitely if and when it will be a practical proposition. I think it is more likely to be of use to marine and land applications than to the aircraft or motor car industry. We must be ready to develop it as soon as it passes the fundamental and scientific research stage.

In the meantime, we must not sit back and wait till it is developed, but press on with the other means which we have at hand at present.

To what extent and at what rate we will progress will depend not so much on the willingness of the Naval Engineers, but on the active interest of people and Parliament in the maintenance and development of the Royal Navy. And always we must bear in mind the man who has to control the machinery. Entry of the right sort of young men, training to meet the special needs of the Service, and a guided career in the Navy ; these matters are receiving special consideration at the present time.

Greater reliability and reduced maintenance

With the increasing number of electric motors used on board ship and the inaccessible positions in which many have to be installed to get the best layout of equipment as a whole, this is a factor of ever increasing importance. In fact, it is in the possibility of reduced maintenance and increased reliability by the use of the induction motor that the preponderant advantage of A.C. lies.

This is due to the fact that in the majority of cases the squirrel cage motor of constant speed characteristic can be accepted. The squirrel cage motor has no competitor in the field of electrical rotating machinery so far as simplicity and robustness are concerned. It has no commutator and no brush gear. The rotating winding has no insulation, and in fact consists of solid conductors driven or cast into slots in the stampings and short-circuited by solid uninsulated end-rings. No spare armatures are required. The only insulated winding is stationary. With modern methods of insulation the risk of failure of this winding is very remote, and maintenance on such motors should be merely lubrication.

Starting is accomplished by switching direct on the line in all cases where the peak starting current, which is in the neighbourhood of 6 to 8 times full load current, is not large enough to cause overload protective devices in the supply system to operate.

The squirrel cage induction motor has a characteristic comparable with that of the constant speed shunt wound D.C. motor, but its speed depends on the frequency of the supply and the design of the winding. Thus, on a 60-cycle system a motor can be designed to run at speeds of just under 3,600, 1,800, 1,200, 900, and so on, r.p.m. We have not, therefore, the unfettered selection of speed which is possible with D.C.

Selected speeds should be as high as possible to obtain the maximum power for weight. Another reason for emphasising the desirability of using as high speeds as possible is that it is an inherent characteristic of the induction motor that the power factor is higher for a high speed motor. Speed variation in a motor, in steps corresponding to the speeds I have just mentioned, can be obtained at the cost of slightly complicating the winding, and the supply of a pole-changing switch. It is desirable, however, to restrict this means of speed control to two or at most three speeds.

If speed variations are required which cannot be met by pole changing, it is necessary to go to the wound rotor variety of the induction motor. With this type of motor, speed control can be obtained down to about 60% of full speed, but the method is inefficient as a proportion of the power input is dissipated in heat—an objectionable feature, especially in confined spaces. If speed control of greater flexibility is required, it is necessary to select one of the relatively complicated designs of A.C. commutator motors or Ward Leonard control.

Before passing on from the induction motor, the effect of power factor on the selection of motor horse-power must be mentioned. As the load on an A.C. motor decreases, the current does not fall in anything like the same proportion but merely becomes more out of phase with the voltage. This means that if motors are selected on the generous side, and are, therefore, run underloaded, the generators will have to provide more current in proportion to motor load. Thus, generators, cables and switchgear will have to be larger, heavier and occupy more space than necessary. It will therefore be appreciated that it is of the utmost importance that motor horse powers are most carefully selected if the overall power factor is to be confined to acceptable limits.

Economy in production of Electrical Equipment and ease of expansion of production in war-time.

This was considered to be an important factor by the Americans in deciding to change from D.C. to A.C. as they did in 1932. There is little doubt that, so far as they were concerned, the late war proved the wisdom of their decision. It does not, however, follow that this factor has the same weight in this country as in the U.S.A. In fact, at no time during the late war were we unable to provide all the D.C. equipment required. The British Electrical Manufacturing Industry is very flexible as compared with that of America, and there is still in this country, apart from naval requirements, a relatively large demand for D.C. plant.

There are, however, two points which have to be taken into consideration in spite of the general comment I have just made. These are :—

(i) The man hours required to manufacture D.C. rotating machinery and control gear are considerably greater than for equivalent A.C. equipment —up to twice. There is no justification therefore, for using D.C. machines where A.C. machines will serve the purpose.

(ii) It may well be that, before the Navy is faced with another world crisis, the potential capacity for the manufacture of D.C. equipment will not be as great as it is now.

Elimination of rotating machinery for the supply of A.C. consuming equipment

Where by the use of an A.C. system loads can be supplied directly off the system which with a D.C. system necessitate conversion from D.C. to A.C., we have a direct gain of the weight, space, and maintenance of the conversion plant concerned. In the case of a modern cruiser this is estimated at about 400 k.V.A. This may sound small in relation to the total k.V.A. generated, but the elimination of the converting plant which would otherwise be required gives a saving of 20 tons and 1,000 cubic feet. Furthermore, it is not unlikely that the services requiring A.C. will continue to increase.

I should here like to take the liberty of reminding you that with A.C. you can, by the efficient and reliable static transformer, step the voltage up or down to suit requirements : but you cannot, without the introduction of rotating machinery, alter the frequency.

Unfortunately, there is a requirement in warships for A.C. supplies at frequencies other than the basic frequency selected. These are required for fire control systems, and other special services. The most suitable subsidiary frequencies appear to be 400 cycles and 1,600 cycles per second. Each of these subsidiary frequencies requires motor alternators, and furthermore, where very close speed control is asked for, as is the case of the 400 cycles system, there is at present no way of achieving the close degree of governing required by D.N.O. by the use of an A.C. motor, so that we are forced to face up to the conversion of A.C. to D.C. with which to supply a closely governed D.C. motor driven alternator set.

Makes available for Naval use the results of industrial research and development which are to-day largely confined to A.C.

It may be said that, while in the past there has been rather scanty justification for this being put forward as a strong argument for the use of A.C., the present day industrial applications of thyratrons and ignitrons to the solution of industrial control problems indicates that in future there may well be increasingly strong reasons for the use of A.C. to exploit this field to full advantage.

Departure from the Ring Main System

The main reasons for this being necessary when A.C. is used are *that alternators are not so easily paralleled as dynamos*, and *the weight of the A.C. switchgear* which would be required to reproduce, using A.C., the present ring main arrangements.

When paralleling an incoming dynamo to a system it is only necessary to adjust the voltage of the incoming machine approximately to that of the busbars or ring main and close the supply breaker. To perform the same operation with A.C., there are two additional factors to be taken into account :—

(i) The speed of the incoming machine must be adjusted so as to be exactly the same as that of the alternator or alternators to which the incoming machine is being paralleled.

(ii) The incoming machine must be brought into phase with the system, *i.e.*, the voltage wave of the incoming machine must be such that at the moment of closing the supply breaker, it exactly coincides with the wave of the system.

These two factors mean that during the paralleling operation the operator must be in actual control of the speed of the prime mover or be able to signal clearly to the driver.

To reduce the necessity for paralleling to a minimum, it is proposed to adopt a four switchboard system for the cruiser. This arrangement should provide adequate flexibility of supply and indeed certain advantages can be claimed for it over a ring main.

The adoption of a switchboard system does, however, involve the provision for each switchboard of a fairly large space, as the units forming a switchboard must be grouped together. They cannot be disposed round the ship as in a ring main system, and I fear D.N.C. will, in this respect, think he is having the worst of the bargain, especially when I add that another inherent disadvantage from his point of view of the switchboard system is that a greater number of bulkhead glands is involved.

The emergency supply system is more complicated

Many of you are familiar with the very flexible emergency supply arrangements in present use. To reproduce as flexible a system, with the danger from 440 volts A.C., will need more elaborate cable terminal arrangements than with 220 volts D.C.

Three leads are necessary instead of two. Also the direction of rotation of A.C. motors depends on the phase sequence of the supply. Thus for safety some type of shrouded plug and socket must be designed, and either they must be fool-proof against wrong connection or suitably marked to facilitate preservation of correct phase rotation.

The adoption of a frequency higher than the British standard

The necessity for adopting a frequency higher than 50 cycles arises from the fact that an analysis of the speeds required by motor drives on a cruiser and destroyer indicates that a 50 cycles system would be severely handicapped from the weight point of view as compared with a 60 cycle system. The 4 pole 50 cycle motor runs at about 1,450 r.p.m., whereas a speed around 1,750, which is that of a 4 pole 60 cycle motor, is much more generally used in the ships under consideration. Acceptance of the lower speed would result, not only in heavier motors, but heavier driven plant as well. 60 cycle transformers are also appreciably lighter than 50 cycle transformers.

The objections to adopting a frequency differing from the British standard are more apparent than real. To begin with the mechanical design of electrical machinery for warships necessarily departs from industrial practice. Furthermore, in an emergency, standard British motors could be used if necessary with only a slight drop in efficiency. The only objection to 60 cycles is that arrangements for shore supply are not so straightforward as with 50 cycles ; but the selection of the optimum frequency from the point of view of warship design should not be unduly influenced by the shore supply factor. The difficulty of taking a shore supply at 50 cycles by a 60 cycle ship is not insurmountable. A 50 cycle supply can be used for all services excepting certain rotating machinery the use of which would necessitate running one of the ships Diesel sets on the auxiliary bus-bars.

I need not enlarge on the possible advantages of adopting a system common to the U.S. Navy. It means that all U.S. equipment, e.g. fire control and radar, could be used in our ships without any adaptation at all.

D.E.E. investigated the same question in 1932 and recommended against the change. His main reasons for so doing were :—

(i) The greater danger to personnel from the use of 400 or 440 volts A.C.
(ii) The number of motors in the ships and the ratio of motor load to other loads were not high enough to give advantages which would outweigh the disadvantages.

The experience of the U.S. Navy has shown that, with proper design and adequate training, 440 volts A.C. need not be objectionable. The applications of electricity in warships have enormously increased since 1932, and where the balance of advantage now lies I should not, at this stage of the investigation, venture to predict ; but I hope that it will be found such as will make it possible to recommend at least a trial installation in say one cruiser and two " *Daring* " Class destroyers.

Gives latitude for selection of the most suitable voltage for lighting and minor power consuming apparatus.

This results from the use of the static transformer which is a highly efficient and very reliable piece of apparatus with no moving parts. Were it not for this feature and its application to such an item as lighting, it would not be possible to use as high a pressure as 440 volts for power generation and distribution, and an A.C. installation would not be practicable.

Although at this stage of the application of fluorescent lighting to warships I cannot fairly add the advantages of A.C. in this respect, I must just mention that the full efficiency obtainable with this form of lighting can only be achieved with A.C.

OBJECTIONS TO THE USE OF ALTERNATING CURRENT

What then are the objections to the use of A.C. and the steps required to dispose of them where possible ?

First the objections :—

(i) Restriction in the selection of speeds at which prime movers and motor driven plant can be run.

(ii) To show a saving in weight it is necessary to adopt a higher voltage for generating, distributing, and motor drives, with possibly, higher risk of fatal accidents.

(iii) Alternators under short circuit fault conditions supply higher currents than equivalent D.C. generators.

(iv) Necessity for use of automatic voltage regulators.

(v) The problem of power factor.

(vi) It is necessary to depart from the well-tried ring main system of distribution.

(vii) The emergency supply system is more complicated.

To these 7 may be added an 8th, viz. :—

(viii) It is necessary to adopt a basic frequency higher than the British standard of 50 cycles per second to get an installation approximating towards the maximum possible saving in weight, and at least comparable in weight with installations in U.S.A. warships.

This list at first sight appears rather formidable, but some of the items sound more formidable than they are, as we shall see as I discuss them.

Restriction in the selection of speeds at which prime movers and motor driven plant can be run

I have already referred to this speed restriction where motor drives are concerned.

As A.C. generators must run at one of the synchronous speeds which depends on the selected frequency, the freedom allowed by D.C. is precluded. This is of little or no importance where turbo alternators are concerned, but it does restrict the choice of speed of the Diesel engine. If 60 cycles be adopted the direct drive speeds must be 900, 720, or 600 r.p.m.

To show a saving in weight it is necessary to adopt a higher voltage for generating, distributing, and motor drives, with possibly, higher risk of fatal accidents.

An investigation has shown that in order to achieve a worth while saving in weight with an A.C. system, as compared with the use of 220v. D.C. it is necessary to exceed this voltage. The most suitable voltage is 440, at which pressure an A.C. installation should give a considerable saving in weight, and it is not

too high for the operation under sea-going conditions for all but the smallest motors. For lighting and minor power applications the 440 volts would be transformed down to 115 volts, a pressure which is eminently suitable for lighting as it allows very robust filament lamps to be used.

Voltage for voltage A.C. is, however, more dangerous than D.C., mainly because when we speak of an A.C. voltage of say 440 this means the actual effective voltage from the point of view of power production and it is the root mean square value of the voltage wave of the system. The peak voltage, however, which is the effective pressure so far as danger to life is concerned, is 1.41 times greater.

On the other hand, A.C. plant can be designed so that there is much less risk of coming into contact with live metal than in the case of D.C. plant. So far as rotating machinery is concerned this is because, there are no commutator and brush gear, in fact, there is no metal alive at 440 volts which is not completely insulated and enclosed. Switch and control gear, must be of the dead front type permitting no access to unauthorised persons.

Alternators on short circuit supply higher currents than equivalent D.C. generators

This is an inherent characteristic of alternators. In D.C. generators the current on a dead short circuit quickly settles down to 2 or 3 times full load current. Such machines have a no load to full load voltage regulation of $12\frac{1}{2}\%$, which means that hand control of voltage is all that is required. With alternators designed for such voltage regulation, the current on a short circuit fault would achieve tremendous proportions, and very heavy and bulky switchgear would be required to deal with it. It can, however, be controlled in design within limits, but only to the detriment of voltage regulation. As usual in such cases a compromise has to be made by designing the alternators so that the current on short circuit is confined to acceptable limits and an automatic voltage regulator incorporated to look after the voltage.

Necessity for use of Automatic Voltage Regulators

Without such a device the voltage would fall by 45% from no load to full load, which is far beyond the possibility of the hand-controlled rheostat successfully used for existing dynamos.

Voltage regulators have been in use for many years on all except the smallest shore generating stations, but when we come to apply them to warship installations, two completely new features have to be incorporated :—

(i) Ability to withstand shock.
(ii) Speed of response.

I need not stress the need for a robust instrument to withstand conditions on board ship, including shock. The necessity for the " speed of response " feature arises because in a warship installation the motor starting currents which have to be supplied are *large* relative to the output of the generating sets. Voltage regulators will have to be developed to meet these requirements.

The problem of Power Factor

In an A.C. supply system the voltage and current are rarely in phase. Resolving the current into two components, one in phase with the voltage and the other lagging 90°, it is only the former which supplies power. The other component may be looked on as a parasite, but the generating and supply system must be designed to carry this useless current as well as the useful component. Provided motor drives are carefully selected, the overall power factor of the system will not be such as to worry us, as an overall power factor of 80% should result.