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MINE SUBSTATIONS
Motor-Generator Sets vs. Synchronous Converters

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ABSTRACT OF PAPER

The number of mines which use electrical power supplied by transmission lines carrying high-voltage alternating current is constantly increasing. Low-voltage direct current is usually required for underground work in all coal mines. These conditions require the installation of motor-generators or synchronous converters. The extent and location of the mine workings will determine the voltage of the direct-current supply. Improper application of the transforming apparatus may result in great variation of voltage in the direct-current network, with its attendant disadvantages.

The operating characteristics of the induction and synchronous motor-generator sets and synchronous converters are considered with regard to starting conditions, d-c. regulation and the effect on the a-c. transmission lines, a-c. voltage regulation, and power factor correction.

Mine conditions and the nature of the power supply will determine the type of transforming apparatus which will give the most efficient and satisfactory operating conditions. Each of the several types of apparatus has a field where the best results will be obtained.

DURING the past few years there has been a great increase in the number of mines, especially coal mines, using power supplied from the mining company's central power plant, or by central stations. Several central stations have recently built, and others have greatly extended their distribution, with the main object of serving mining districts. These conditions are making economical power possible for all kinds of mines. To provide economical transmission, this power is generally distributed at a voltage which requires transformation before it can be utilized in rotating machinery. Operating conditions at the average mine are such that direct current is required, and this requires the installation, as part of the mine equipment, of a motor-generator set, or a synchronous converter. The object of this paper is to show the adaptability and field of each type as applied to mine service.

In the small coal mine, where power for haulage service will be a chief requirement, it is generally necessary, because of the mine location and layout, to feed power from the extreme end of the feeder system. Under these conditions, to avoid installing an excessive amount of copper and in order to maintain a reasonable voltage in the region of the maximum load, an increase in the terminal voltage of the d-c. generator becomes necessary with the increase in load.

However, when the mine workings become extensive, the low voltage generally used makes it desirable to feed into the feeder system at its load center, or even into two or more such places. This is sometimes accomplished by installing a substation underground, or in shallow mines, which are in favorable locations, on the surface, feeding the low-voltage current underground through boreholes. Under these conditions, an economical feeder system can be installed, so that the drop is low, and an increase of terminal voltage with an increase in load is not so necessary or desirable. As the mine system becomes larger, the amount and size of the apparatus will increase so that motors in constant load service, such as pumps and mining machines, will be distributed throughout the mine, to whose successful operation an excessive variation of voltage will be detrimental.

A direct-current motor, when subjected to an excessive increase in voltage, will have its shunt coils overheated, and its speed will increase, which will, with certain characteristic loads, overload the motor.

An excessive reduction in voltage will cause over-heating of the armature, reduced speed and reduced output. Series motors are generally used for intermittent service, and, as the torque is a function of the current, lower voltage will mean a greatly reduced speed and an increase in the time for any particular cycle of operation. This will invariably result in overheating of the motor windings.

Power for mine service is nearly always purchased on a unit basis and is easily and accurately measured. The actual cost of power is, therefore, accurately known, which is quite different from the former conditions, where each mine was usually served by an individual power plant where the actual cost of power was very indefinite. Due to the ease of ascertaining the actual cost, the mine operator is vitally interested in the over-all efficiency of the transforming apparatus.

The average mine is served with three-phase, 60-cycle power, at a voltage which is rarely higher than 11,000. Expert attendance is not available or desirable. The first cost must be kept at a minimum, with the operating efficiency at a maximum. Direct current is required at a voltage generally under 300, but never exceeding 550. The selection of the proper apparatus lies between a motor-generator set, of the induction or synchronous type, and a synchronous converter. The starting characteristics of the last two types of machines have been very greatly improved, and the operation of the starting greatly simplified, within the last few years. The starting conditions of these machines in the order of their desirability follow:

1. Induction motor-generator.
2. Synchronous motor-generator.
3. Synchronous converter.

The induction and synchronous motor-generator sets consist of two machines, a motor and a generator, each electrically and magnetically independent. The generator can be given any reasonable characteristics, but standard practise is to flat-compound for 500 or 250 volts, or to over-compound not to exceed 10 per cent. The operating characteristics of the direct-current generator are understood by the average mine attendant, as its operation is similar to engine-driven generators with which he may be familiar.

The induction motor-generator set is exceedingly easy to start, but has the disadvantage of a small air gap and a lagging current characteristic, which causes the transmission line to carry an additional current above the required load current. This means an increase in the transmission line and power station generator capacity.

The synchronous motor-generator set of the present day is no more difficult to start than the induction motor set. It has the advantage of a large air gap and the power factor of the machine is under the control of the operator. This latter feature, if properly applied, is of great benefit to the transmission line regulation. If induction motors are in use at the same mine, operating the synchronous motor at a leading power factor will greatly offset the lagging wattless component. It requires judgment to secure the best results from this feature. While the corrective effects apparently only benefit the power company, they may be detrimental as well as beneficial, and in order that the power company may secure the greatest benefit, it would be necessary for the attendant to be under the control of the power company, as far as power factor adjustment is concerned. Standard machines are usually built for operating at unity power factor at full load, and under average load conditions it is possible to operate them at slightly leading power factor without detrimental results.

It is now recognized that a low power factor load is detrimental to the power company, so that such loads are sometimes penalized, the power rate being based on the power factor. Under such conditions it is advisable for the mine operator to utilize the corrective effect of a synchronous machine, so as to offset the lagging effect of any induction motors. It is not always economical to attempt to raise the power factor too high, as the corrective effect obtained from a given wattless component is much less in the regions of unity power factor than elsewhere. Generally speaking a power factor of 90 per cent would be considered good. The efficiency of a synchronous motor will be materially affected

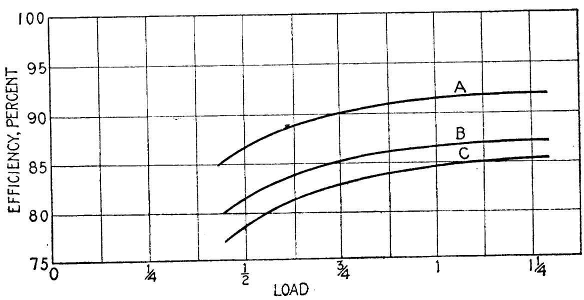

FIG. 1

by over-excitation. Reference to Fig. 1 will show the efficiency curve of a standard synchronous motor-generator set, as built by one manufacturer, when operating at unity and 80 per cent leading power factor.

Synchronous converters are nearly always started from the alternating-current end, and are no more difficult to start than in the preceding cases, except that it is necessary to close the field break-up switch, so that the direct-current polarity will be correct. They have the advantage of large air gaps, and each unit consists of one machine instead of two. The machine itself is much lighter, and requires less energy to bring it up to speed. The 60-cycle converter of today is quite a different piece of apparatus from that of only a few years ago.

Referring again to Fig. 1, curve *A* is the efficiency curve of a standard synchronous converter of the same rating as the motor-generator set, with transformer losses included. A converter does not lend itself to power factor correction to the same extent as the synchronous motor. The disadvantage of using transformers will be offset by giving the machine a large decree of protection from grounds which might be caused by surges on the high-tension line. It is much easier to run, temporarily, on two transformers than to repair a high-voltage coil in either an induction or a synchronous motor.

A synchronous converter necessarily requires transformers, while both the induction and synchronous motors can be wound for moderately high voltages. Standard mine sets of less than 300 kw. are not wound for voltages in excess of 2200. Therefore, if the voltage is above 2200 transformers will be required in either case, or the machine can sometimes be wound for a higher voltage at an increased cost and reduced efficiency.

In contrast to a motor-generator set, the alternating-current and direct-current sides of a synchronous converter are connected together. The direct-current voltage bears an approximately constant ratio to the impressed alternating-current voltage. In a direct current generator, an increase in voltage with an increase in load is obtained by placing series coils on the field poles, which coils carry all or a portion of the load current. In the converter the same method is used, but the accompanying results are obtained quite differently. Standard synchronous converters are built so as to give flat compounding, maintaining approximately constant terminal voltage. As the direct-current voltage bears a definite ratio to the alternating-current voltage, it is necessary to maintain constant voltage at the collector rings. This is accomplished by having a suitable reactance and a certain minimum resistance in the alternating-current circuit. This reactance may be introduced separately or be in the transformer, line and generator. To maintain constant voltage, the line drop, due to resistance, must not be in excess of 10 per cent. Maintaining constant voltage with varying load by changing the series field excitation will change the power factor. The effect on the line, therefore, is quite different from that caused by a synchronous motor without compounding, as usually built. This results in the difference in corrective effect of the two types of machines. Over-compounded synchronous converters are not standard, because certain limitations peculiar to the type of machine make it undesirable.

In a synchronous converter, part of the alternating current passes directly to the direct-current end, without circulating through the entire converter windings. The heating capacity of a direct-current generator will depend upon the average heating, while in a synchronous converter it depends upon the heating of the so-called tap coils. Low power factor at full load will cause heavy currents to circulate in the converter winding. As the tap coils must carry this heavy current in addition to the current passing through them, the heating will be above the average of the rest of the winding.

The average mine load, referring particularly to the direct-current load, is usually of a very fluctuating character. Assuming that the field of a synchronous motor is adjusted for unity power factor, say at $\frac{3}{4}$ load with constant excitation, the power factor will be leading at lighter loads and lagging at the heavier loads. A synchronous converter, as generally constructed with varying excitation caused by compounding, will act quite differently, provided, of course, that the line conditions are suitable. As the load falls below the $\frac{3}{4}$ value, the power factor will be lagging, and at full loads, and overloads, slightly leading. Where power is received at high voltages from large transmission lines, the capacity effect may make it more desirable to have a lagging component at light loads and leading at maximum loads. Under these conditions the synchronous converter will give the most desirable performance. However, where large corrective effects are required there is no doubt but that the synchronous motor is the type to be employed. When the synchronous motor receives its excitation from an over-compounded generator the exciting current will increase with the load, thus tending to hold the power factor up on overloads. The synchronous motor-generator set can be successfully operated on a line whose characteristics are such that the operation of a synchronous converter would be unsuccessful. Parallel operation between machines of the same type is practically on the same basis for each of the three types. Parallel operation between machines of the different types is not advisable, as considerable adjustment will be necessary to obtain equal division of the loads.

Cost. A comparison in prices between the induction, or synchronous, motor-generator set, and the synchronous converter, including transformers for the latter, will show that the costs are approximately the same when transformers are not required by the motor-generator set. It is the usual practise for the central station to supply power at 2200 volts, so that it is seldom necessary for the coal company to purchase transformers. In smaller sizes the synchronous converter with its transformers will cost a little more than the motor-generator set, while with the larger sizes, the reverse is true. For the sizes most common for mine work, the motor-generator set will cost less than the synchronous converter with transformers.

The foregoing comparisons show that where the line characteristics are suitable, the operating efficiency and automatic alternating-current line regulation are in favor of the synchronous converter. Where large corrective effects are required on the alternating-current line, compounding is desired on the direct-current machines, and the transmission line characteristics are not of the best, the synchronous motor will prove the most reliable. When the voltage and frequency variations are such as to preclude the successful operation of synchronous apparatus, the induction motor-generator set should be used.