Lease Electrical Distribution Systems

By DAVID P. INWOOD & WM. J. SHIELDS
General Electric Co.

INTRODUCTION

The function of any electrical distribution system is to deliver electric energy at a satisfactory voltage level. Therefore, regardless of the system voltage classification — be it 13,200 volts or 240 volts — the fundamental criteria for good system design is good voltages.

It has been more or less generally accepted that the voltage limits allowable on lease electric systems have a wider spread than, for example, the recommended voltage spread for industrial plant power systems. From the standpoint of first cost for the distribution system, it is imperative that advantage be taken of the maximum allowable voltage spread. However, from the standpoint of operating costs, it is just as important to minimize the voltage spread to whatever extent possible. It is obvious, therefore, that an optimum voltage spread exists which will result in minimum total cost. Most electrical apparatus is designed to operate satisfactorily over a range of voltage. Therefore, the limits of voltage spread are established by the voltage limitations of the apparatus used on the electrical system. For example, the usual statement with regard to motors is that "Motors will operate successfully where the variation in voltage does not exceed ten percent above or below normal, but not necessarily in accordance with the standards established for operation at normal rating."

One of the more beneficial tools for bailing a distribution system out of low voltage troubles is the power factor correcting capacitor. Actually, the greatest benefit derived from the use of capacitors is probably the reduction in KVA loading, a reduction which results in added capacity in the system for carrying electric power. The benefit of improved voltage is also of great economic value, as is the reduction in power loss and KVA demand charges.

How to properly allocate voltage drops, along with an understanding of the benefits to be derived from the proper application of capacitors, can be most beneficial in the design of lease electrical distribution systems.

VOLTAGE CLASSIFICATIONS, AND FUNCTIONS OF PARTS OF A COMPLETE ELECTRIC SYSTEM:

To fully appreciate the magnitude of the problem of providing a satisfactory utilization voltage, one must have some feeling for operating conditions on all parts of the electrical system. This feeling would include a knowledge of conditions at the generating source, through the high voltage transmission system, at the distribution substation and through the primary distribution system, the distribution transformer, and the secondary circuit.

There are a number of basic factors which determine the magnitude of voltage employed in the different parts of the entire electric system. For example, some of the more important factors are (1) the amount of power to be transmitted (2) the distance over which power is to be transmitted (3) practical limitations on the magnitude of voltage which may be used in the design of certain types of electrical apparatus (4) considerations of safety. And, finally, all these factors and others combine to form the predominant controlling force — economics.

Thus, we find certain classifications of voltage levels — classifications based on usage, and magnitude of voltage. Control devices, which require very small amounts of power and which usually involve no consideration of distance over which the power is to be transmitted, are most frequently operated at 110 volts and almost without exception are in the "low voltage" classification of 600 volts and below. Power consuming devices, such as electric motors, are also generally in the low voltage classification, until the amount of power involved exceeds a generally accepted limitation of the order of 150 to 200 hp. Above approximately 200 hp, power consuming apparatus invades the "medium voltage" classification. This so-called medium voltage range is from 601 volts to 15,000 volts. The usual voltages are 2400 volts, the 4000 to 5000 volt range; the 6600 to 8700 volt range, and the 11,000 to 13,800 volt range. The reasons for so many different utilization voltage ranges are many and varied, but most of them have had a quite logical sequence of events leading up to their usage. In recent years, the oil production industry has seen the successful transition to a new and useful voltage level. This is the motor voltage of 762 volts, which is the wye of 440, or $\sqrt{3}$ times 440 volts. This, of course, has initiated a new secondary voltage, the wye of 480, or $\sqrt{3}$ times 480, which is 831 volts. I have called these voltages new, for although they have actually been in use for many years,[1] relatively speaking, they are new voltages.

"Secondary distribution" is the distribution of electrical energy at utilization voltage levels, usually in the "low voltage" classification. However, rated secondary distribution voltages are not the same as rated utilization voltages. For example, a common rated secondary distribution voltage — 480 volts — serves utilization devices rated at 440 volts. This distinction is important primarily because it is important that there be a difference in voltage. This difference in voltage is utilized in the voltage drops which occur in the various parts of the electric system.

"Primary distribution" is the distribution of electrical energy at a voltage level above normal utilization voltages and therefore requires a voltage transformation in order to supply utilization equipment. These voltages — primary distribution voltages — are generally in the "medium voltage" classification mentioned earlier. But primary distribution voltages also have gone beyond their usual classification. For example, there are primary distribution systems using voltages of 22 kv and 25 kv. In years past, voltages of this magnitude were considered transmission voltages. In fact, many transmission systems are operated at voltages such as 13.2 kv.

In general, however, when the voltage exceeds 15 kv, it is considered to be above the "medium voltage" classification, and in the "high voltage" class. Transmission systems generally employ voltages in the high voltage classification.

All of us have probably heard the term "sub transmission", a term which it is somewhat difficult to give an exact definition. Usually it is used to convey the impression that a higher voltage transmission system exists, and that the particular portion of the system designated as sub-transmission does not serve the function of primary distribution.

Still another portion of the electric system is the source of power, or the electric generating station. In the early days of growth in the use of electricity, there was a definite tie between the generated voltage and the utilication voltage. Much of the load was served directly from the generator terminals. This is still true in the case of many definite purpose power plants. For example, in an oil field the generated voltage may be 480 volts to conform to the utilization voltage of 440 volts. In general, however, there is no such relationship between the generated voltage and the utilization voltage. Since most of the generated power is transmitted to the utilization point via transmission and distribution systems, a transformation of voltage is almost always required at the power plant. Therefore, the rated voltage of the generator may very well be left to the discretion of the generator design engineer.

Obviously, there is considerable overlapping in the use of the voltage classifications — low, medium, and high — in the various portions of the electric system — utilization, distribution, transmission, and generation. These voltage classifications are merely relative terms and in no way restrict the use or function of a particular magnitude of voltage. On the other hand, the terms "utilization", "secondary" and "primary distribution", "sub transmission", "transmission", and "generation" are intended to be descriptive of the function of parts of a complete electric system.

THE SECONDARY DISTRIBUTION SYSTEM AND UTILIZATION VOLTAGES

The secondary distribution system is that portion of the electric system which supplies electric energy to utilization equipment and devices at utilization voltage. Common rated secondary voltages of distribution transformers are 120, 240, and 480 volts. It is common practice to designate a three-phase voltage by its line-to-line voltage, that is, the voltage between phases. Thus, when one speaks of a 480 volt, three-phase circuit, he means the rated voltage between phases is 480 volts. Previously mentioned was the use of 831 volts for secondary distribution in which the voltage from phase-to-phase is 831 volts, the voltage from phase-to-neutral is 480 volts. Thus, this new secondary voltage is normally provided by connecting the 480 volt secondaries of three single-phase distribution transformers in wye-connection.

Similarly, the three-phase motors used on such a system are 440 volt motors with their phase windings connected in wye to give a rated motor voltage from phase-to-phase of 762 volts.

Obviously, all motors on a secondary circuit do not receive the same applied voltage. Seldom would we find the measured voltage at the terminals of a 440 volt motor to be exactly 440 volts. Therefore, motors must be designed to operate satisfactorily over a range of voltage. The usual statement relative to motors is that they will operate successfully over a range of plus or minus 10 percent of rated voltage, but not necessarily at guaranteed temperature rise. Plus or minus 10 per cent of 440 volts would give a range of 484 volts maximum, down to 396 volts minimum. The motor closest to the secondary terminals of the distribution transformer will be subjected to a higher voltage than any other motor on that circuit, while the motor farthest away from the secondary terminals will be subjected to the lowest voltage.

However, one would be extremely short-sighted if he were to design a system that would deliver only 396 volts to the most remote motor. In the first place, it would be impossible to design a system this close. And if one were successful in doing so, he would have closed the door to any future expansion of that system. In order to allow for future load growth and to assure a long life as well as successful operation of the motor, a more realistic voltage range, such as plus or minus 5 percent of rated motor voltage, is an acceptable criteria. This criteria, then, gives a preferred operating voltage range of 462 volts maximum down to 418 volts minimum. But it is the minimum voltage which is of more concern, since it is under low voltage conditions that a motor is more subject to overheating. Furthermore, low voltage means reduced torque at the motor shaft, and lower speed, which usually results in lower production.

Too high a voltage can also be troublesome, particularly if it gets in the range of 15 to 20 per cent above motor nameplate rating. Voltages in this range, when applied to a motor, will cause it to draw excessive current when running under full load. This excessive current may cause protective devices to trip out when the motor actually is not mechanically overloaded — the excessive current is due to the excessive voltage applied.

High slip motors are becoming the most popular type for powering beam pumping units. Too high a voltage reduces the slip at which the motor operates and defeats this valuable characteristic. On the cyclic loading of a beam pumping unit, a high slip motor operates more efficiently than does a low slip design. But as the motor voltage increases above rating, it reduces the amount of slip that any type induction motor will exhibit under a given load. Thus, if high voltage does not cause overheating or nuisance tripping, it still reduces slip, and thereby reduces efficiency on a cyclic load. Since pumping motors are designed with optimum slip for such duty, it is best to prevent high voltage and the resulting reduction in efficiency.

In terms of rated secondary voltage of the distribution transformer, the minimum voltage at the motor should be no less than (418/480)100, or 87 per cent. What restrictions does this minimum place on the voltage drops in the secondary circuit, and the distribution transformer?

The transformation ratio of a distribution transformer is based on "no load" conditions. That is, with no load on the transformer and with rated primary voltage applied, the secondary voltage output will be nameplate rated voltage. For example, if a transformer is rated 7200 volts primary and 480 volts secondary, then 480 volts will be obtained with 7200 volts applied under no load conditions. Under full load conditions at 0.80 power factor, the voltage drop (or regulation), through the transformer would be about 2.3 per cent. Thus, the secondary voltage would be 97.7 per cent or about 469 volts. This voltage exceeds the criteria of 105 per cent allowable at the motor (462 volts), but does not exceed the 110 per cent maximum allowable (484 volts). The primary voltage could be as high as 103 percent without exceeding 484 volts on the secondary.

It might be assumed that there can be selected a tap with which to operate so that the primary voltage will never exceed 103 per cent of the rated tap voltage. But it must kept in mind that 2.3 per cent regulation was allowed in the transformer and full load conditions were assumed. However, it is probable that at times the closest motor may be energized when the transformer is not fully energized. Therefore, a primary voltage as high as 103 percent is not allowable. Assuming only one percent regulation under minimum load conditions would give a maximum allowable primary voltage of 101.7 percent.

It is practical to allow for some variation in applied primary voltage, for instance, a modest variation of plus or minus two percent, that is, maximum voltage of 101.7 per cent and minimum voltage of 97.7 per cent. Now, under full load conditions, the secondary voltage will be approximately 97.7 minus 2.3, or 95.4 per cent (458 volts). Since the voltage at the most remote motor cannot be less than 87 per cent (of 480 volts), the allowable drop in the secondary circuit is 95.4 minus 87, or 8.4 per cent. If more than a total variation of four per cent is encountered on the primary circuit, then a smaller allowable voltage drop is available for the secondary circuit.

There is, then, an obvious relationship between voltage drops in the secondary circuit and the primary circuit. How these voltage drops are apportioned is the crux of the economics of distribution systems.

One could spend many valuable man-hours of engineering time attempting to analyze each individual combination of primary and secondary circuit conditions. No two conditions would be alike, but surprisingly, many of them would be similar. After finishing such a tedious and time-consuming job, there would be two inevitable answers: (1) this engineering talent could have been used much more profitably in some other endeavor, and (2) the assumptions necessary to make such a study invalidate the results in each individual case. But, since the results are quite similar for all the cases, it would be much better in terms of time and money spent to use a single set of typical results to apply to all conditions, that is, establish a satisfactory design criteria, then design toward that criteria.

Much work of this nature — determination of the most economical apportionment of voltage drops — has been done. Advantage of this work should be taken. In the following example various operating conditions will be assumed in order to illustrate the procedure and thinking involved in allocating voltage drops.

1. An unregulated primary source is assumed. The limits of this source will be plus or minus five per-cent of rated voltage.
2. The nearest distribution transformer is assumed to be at the primary bus.
3. Maximum voltage (105 per cent) on the distribution transformer primary is assumed. Under these assumed conditions, the maximum voltage at the first motor, on the first distribution transformer, will be 105 minus 1, or 104 per cent of 480 volts. In terms of rated motor voltage (440 volts) this would be 113.4 per cent (499 volts), which would be above the tolerable limit of 110 per cent.
4. One per cent voltage drop to the first motor, including transformer and secondary circuit drop, is allowed at the time of minimum load on the first transformer.
5. A maximum voltage drop of two per cent in the primary circuit is allowed, and this drop is assumed to occur at the time of minimum voltage at the primary bus. The voltage at the most remote distribution transformer would be 95 minus 2, or 93 per cent.
6. The most remote distribution transformer is assumed to be loaded to 110 per cent of rated kva, 0.80 pf. If regulation at full load, 0.80 pf, is 2.3 per cent, it will be (1.10)(2.3), or 2.5 per cent at 110 per cent load. Thus, the secondary voltage would be 93 minus 2.5, or 90.5 per cent. This gives a voltage of 435 volts at the transformer secondary.
7. A minimum voltage of 95 per cent of 440 volts (rated motor voltage), or 418 volts is allowed. On a 480 volt base, this voltage would be 87 per cent.

With 90.5 per cent voltage available at the distribution transformer, and 87 per cent allowable at the most remote motor, the allowable secondary drop is 90.5 minus 87, or 3.5 per cent of 480 volts. On a 440 volt base, the allowable secondary drop would be about 3.8 per cent. Based on the above, the following voltage drop allocations are derived:

Primary circuit	2.0 per cent
Distribution transformer	2.5 per cent
Secondary circuit	3.5 per cent
	8.0 per cent

(All based on 480 volts)

Or, based on 440 volts:

Primary circuit	2.2 per cent
Distribution transformer	2.7 per cent
Secondary circuit	3.8 per cent
	8.7 per cent

There are so many variables involved, that each distribution circuit requires a certain amount of engineering judgment to be used in the initial stages. Once the installation is made, more engineering judgment is required as the system grows or conditions change. Examples of these variables might be:

1. Regulation at the primary bus, with or without line drop compensation.
2. Ratio of peak load to minimum load.
3. Availability of distribution transformer taps.
4. Power factor of load.

USE OF CAPACITORS ON LEASE DISTRIBUTION SYSTEMS

In order that an electric motor be capable of delivering mechanical energy at its shaft, it is necessary that the iron in the stator be magnetized. To do this requires an electric current which actually contributes no mechanical energy at the motor shaft. This current can be measured, and is essentially the no-load current of the motor. That is, the current is drawn by the motor when there is no mechanical load coupled to the shaft.

This no-load current (a major portion of which is magnetizing current) must be supplied to the motor in one of two ways.

First, it may be supplied from the distribution system. In this case, the magnetizing current flows through the entire electric system, from the source of voltage to the motor.

A second way of supplying this current is through the use of capacitors. Actually, the capacitor cannot supply all of the no-load current, since part of this current does supply the energy requirement for electrical and mechanical losses (windage and friction). That portion (the major part) of the no-load current which magnetizes the stator iron can be supplied by capacitors. Thus, if we were to install capacitors at the terminals of a motor, the magnetizing current would not be required from the generating source and would cease to flow through the electric system.

Suppose the load current consists of five parts magnetizing current, and five parts power current. This distribution would give a total current of 7.07 units. However if the magnetizing current were supplied entirely from capacitors, the current from the electric system would be five units — the power current only. Thus, the current flowing would have been reduced to (5/7.07)100, or 70.7 per cent of its original value. If, in this example, the original value of current were full load current on a distribution transformer, the transformer would now be loaded to only 70.7 per cent of its rated capacity. Thus, we say that through the use of capacitors, system capacity is released. When one considers that the cost of installing this sytem capacity is in the order of 100 to 200 dollars per KVA, it becomes apparent that "released capacity" is one of the greatest benefits of capacitors.

It was noted that the addition of capacitors has reduced the current flowing in all parts of the electric system. Since the current is smaller, the resulting voltage drops have also been reduced. But this reduction in voltage drops is not in proportion to the reduction in current. A simple example will illustrate the effect of using power factor correcting capacitors, both on "released" capacity, and reduction in voltage drop.

Again, assuming that the load current on a distribution transformer is five parts magnetizing current and five parts power current, one finds that the total current is 7.07 units. Since the power factor is the ratio of power current to total current, then P. F. = 5/7.07 - 0.707 per unit, or 70.7 per cent. Full load current at 70.7 percent power factor will cause a voltage drop in the distribution transformer of about 2.25 per cent. And if capacitors are added to correct the power factor to 0.95 or 95 per cent, the load current would be reduced to 5/.95, or 5.26 units. At 0.95 power factor, full load, the regulation of the distribution transformer is about 2.02 per cent. Thus, at 70.7 per cent load, the regulation would be (0.707)(2.02), or 1.46 per cent. Thus, through the use of capacitors, we have reduced the voltage drop by 0.8 per cent in the distribution transformer alone. Furthermore, there will be additional reductions in voltage drops in the primary and secondary circuits. Hence through the use of capacitors, not only is system capacity added, but also voltage drops are reduced so that it will be feasible to take advantage of this capacity.

Another benefit of capacitors is in reduced losses. In the example above, the current was reduced from 7.07 units to 5.26 units. Since heat losses are proportional to the square of the current, the losses in this case have been reduced by a factor of $(5.26/7.07)^2$, or 0.55. The capacitors, of course, have no effect on transformer core losses, or motor losses.

Because of the benefits to be derived from the use of capacitors, they are often the most economical solution for improving the performance of an existing distribution system. Many new systems are installed with capacitors as a part of the initial installation, in order to minimize initial costs.

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