# High-Altitude Considerations for Electrical Power Systems and Components

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*Abstract*—**The design and application of electrical systems at elevations in excess of 1000 m (3000 ft) requires knowledge of the effects of atmospheric conditions on each particular component. Failure to understand adequately and include the effects of high altitude in the design and application of the equipment may result in its poor performance, premature aging, and/or failure. The relationship of relative air density and altitude is discussed, followed by the effects of altitude on electric power system components. Along with the discussion of the effects of high altitude on each component are suggestions or solutions to the high-altitude problem. Although the subject deals with high-altitude applications of equipment, the performance of equipment from sea level to 1000 m may be affected by the relative air density. Since the relative air density decreases at a rate of approximately one percent per 100 m above sea level, the operation of any piece of equipment which is dependent on the air density will be different at 3300 ft compared to sea level. This subject is discussed so that independent conclusions may be drawn.**

## INTRODUCTION

THE DEVELOPMENT of synthetic fuels has introduced and will continue to introduce many new challenges to the engineering profession. In particular, the oil shale development in western Colorado imposes an electrical system constraint which is described by the ANSI Standards as an "unusual service condition." This unusual service condition, which is not a bit unusual in Colorado and Wyoming, is listed as "altitudes above 1000 m (3300 ft)."

The oil shale industry, unfortunately, does not have a monopoly on this unusual service condition. Most of the gas and oil development in the Overthrust Belt, many mining projects in Wyoming, $CO_2$ projects in Colorado, along with the many synthetic fuel projects are being developed in areas where the altitude far exceeds the 1000-m (3300-ft) level defined as unusual. With the increasing number of projects being built at high altitudes, more engineers will be faced with the altitude constraint in the design of the electrical system.

However, before proceeding with the discussion of high-altitude considerations for electrical power systems, the fact should be stressed that altitude is *not* a true constraint in the design of the electrical system. The actual constraint is based on a combination of temperature and barometric pressure. Temperature and barometric pressure together determine the relative air density, and the fact exists that, on the average, the relative air density decreases with an increase in altitude. In other words, the air is thinner at high altitudes, and it is the lack of air which adds the constraint to the electrical system design. As will be shown later, it is the combination of temperature and barometric pressure parameters, and to a certain extent humidity, which needs to be included in the actual design calculations. However, general rules or approximations are given in the standards based on altitudes. The proper use of these approximations will greatly reduce the effort required in designing the system, but the engineer should be aware of the generalities and assumptions made by the standards in order to be more cognizant of the limitation of design.

## RELATIVE AIR DENSITY

Air is probably the most commonly and widely used of all insulating mediums. The majority of electrical distribution lines and practically all transmission lines are built above ground using air as the dielectric for both phase to phase and phase to ground insulation.

Another dielectric which is commonly used is that of a vacuum. Therefore, a seemingly good analogy is that if air is a good insulator and a vacuum is even better, then the thinner the air the better the insulator. The fallacy to this is easily shown in Fig. 1 by the relative dielectric strength of air as a function of pressure. The dielectric strength of air varies directly with the pressure until the pressure is low enough that a "good" vacuum is created. The better the vacuum, the higher the dielectric strength. For common atmospheric conditions, the relative air density (RAD) is approximated by the following equation:

$$\mathrm{RAD} = \frac{(0.392B)}{(273 + T)} \tag{1}$$

where

RAD relative air density,
$B$ barometric pressure (mm of Hg),
$T$ temperature (°C).

The standard temperature and barometric pressure are 25°C and 760 mm, respectively.

Careful review of (1) will show that the RAD varies directly with the barometric pressure and inversely with the absolute temperature. One result is that RAD will vary from summer

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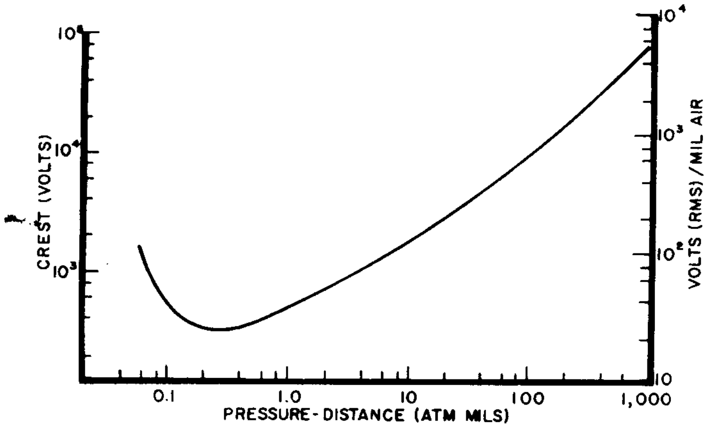

Fig. 1. Pressure-spacing dependence of dielectric strength of air.

to winter with the summer RAD normally being the lower value and, probably the system design constraint (see Table I).

As an example, the mean relative air density in Denver, CO, under fair weather conditions is 0.854 with a standard deviation of 0.034 [8]. However, the maximum is 1.062 which was recorded on a cold winter day while the minimum is 0.775 which was recorded on a hot summer day.

## HUMIDITY

The humidity also affects the dielectric strength of air. The amount of correction, 1/kh, is dependent on the type of voltage (direct, alternating, lightning impulse, or switching surge) and may be corrected by an exponent $W$, again depending on the type of voltage [9, tables 1.3, 1.4, and 1.5].

When determining the exact insulating qualities of air, the appropriate humidity correction factors must be included in the calculation. The humidity factor of a dry climate will have a tendency to lower the insulating quality of air while that of a moist climate will have a tendency to increase it. For a reference point, [4] states that 11 g/m$^3$ is the standard humidity.

## POWER TRANSFORMERS

The power transformer is one of the most important items in the industrial electrical system. Therefore, its operation is of paramount importance, and the effects of altitude on that device are of interest to the system designer.

Both the correction of temperature rises and derating factors for transformers operated at an altitude in excess of 1000 m (3300 ft) are discussed in [5]. In both cases, the standard does not discuss the operation of the equipment between sea level and 1000 m (3300 ft). The standard does state that when temperature rise tests are run at altitudes below 1000 m, no correction for the temperature rise correction factor is required. However, if a transformer is tested at a level below 1000 m and is to be operated above 1000 m, a temperature rise correction factor is to be applied. Similarly, the derating factors for dielectric strength are unity from sea level to 1000 m, at which point the dielectric strength is derated at a rate of approximately one percent per 100 m (three percent per 1000 ft).

TABLE I
RAD COMPARISON AT DIFFERENT TEMPERATURES (CONSTANT STANDARD PRESSURE FOR A GIVEN ELEVATION)

| ELEVATION | | PRESSURE(1) | | RAD | RAD | RAD |
|---|---|---|---|---|---|---|
| METERS | (FEET) | mm Hg | (INCHES Hg) | 5°C | 25°C | 29°F |
| 0 | 0 | 760 | 29.92 | 1.07 | 1.00 | .99 |
| 300 | 1,000 | 733 | 28.86 | 1.03 | .96 | .95 |
| 600 | 2,000 | 707 | 27.82 | 1.00 | .93 | .92 |
| 900 | 3,000 | 681 | 26.81 | .96 | .90 | .88 |
| 1,200 | 4,000 | 656 | 25.84 | .93 | .86 | .85 |
| 1,500 | 5,000 | 632 | 24.89 | .89 | .83 | .82 |
| 1,800 | 6,000 | 609 | 23.98 | .85 | .80 | .79 |
| 2,400 | 8,000 | 564 | 22.22 | .80 | .74 | .73 |
| 3,000 | 10,000 | 523 | 20.58 | .74 | .69 | .68 |

The rating of the transformer is based on a temperature rise of the unit over a given ambient temperature. When evaluating the rating of a particular transformer at a given altitude, both of these factors should be reviewed. First of all, the average ambient temperature at higher altitudes has a tendency to be lower. Secondly, because the air density is lower, the temperature rise on a transformer will be greater than at a lower altitude. The following formula is provided in [6] to calculate an increase in temperature rise due to altitude:

$$T_A = T_E(A - 1000)F \tag{2}$$

where

$T_A$ increase in temperature rise at altitude $A$ meters (°C),
$T_E$ observed temperature rise (°C),
$A$ altitude (m),
$F$ $4 \times 10^{-5}$, self-cooled mode,
$F$ $6 \times 10^{-5}$, forced-air cooled mode.

The standard also states that a derating factor of 0.4 percent per 100 m above 1000 m for a liquid-immersed air-cooled transformer and 0.5 percent per 100 m for liquid-immersed forced air-cooled transformers shall be applied.

When considering the rating for a transformer for high-altitude applications, several alternatives exist. In deciding which alternative to use, consideration should be given to the fact that the standard requires no derating from sea level to 1000 m. For the standard deratings of 0.4- and 0.5-percent per 100 m in elevation previously discussed, this amounts to a four- and five-percent derating for liquid-immersed self-cooled and forced air cooled transformers, respectively, from a sea level condition to 3300 ft. The following alternatives exist.

1) Choose a transformer rating sufficiently high to handle the load and necessary altitude derating.

2) Choose a 55/65°C rated transformer using the 55°C rating for a particular load, knowing that the transformer can be operated at 65°C. This automatically allows up to a 12 percent altitude derating if the user allows the equipment to be operated at 65°C.

3) If it can be determined that the average ambient tem-

perature is sufficiently below the standard or if the transformer loads are low in the summer and high in the winter, the standard rating of the transformer may be used.

4) The manufacturer can be contacted and asked to design and build a transformer for the particular altitude application. The design, in all probability, will include a standard transformer core and coil design with more cooling surface to dissipate the heat.

The standards provide a dielectric strength derating factor of approximately one percent per each 100 m over 1000 m above sea level. When derating the dielectric strength of a transformer for altitude, this should be done only for insulation that depends on air. The internal dielectric strength of the transformer which is oil immersed and not exposed to the atmosphere has a constant dielectric strength which is not derated for altitude. The phase to ground, phase to phase, and high voltage phase to low voltage phase insulation of external bushings are examples of insulation which are derated for altitude. Perhaps one of the most commonly ignored clearances for high-altitude applications involves the high voltage to low voltage bus duct. The reason for this problem is that the bus duct is usually supplied by a different manufacturer than the transformer (Fig. 2).

While it is difficult to ascertain whether the manufacturer has designed a transformer for a rating at sea level, 1000 m, or somewhere in between (all within standard), the external dielectric strength can be easily determined by measurement. In addition, the electrical insulation tests are corrected to standard conditions resulting in the dielectric strength closely matching sea level conditions. Unless otherwise determined by test or measurement, the external dielectric strength of a transformer at 1000 m is approximately 90 percent of the sea level condition. Likewise and due to the derating of dielectric strength of one percent per 100 m, the dielectric strengths at 2000 and 3000 m compared to standard conditions are 80 percent and 70 percent, respectively.

Similar to the problem of choosing the proper rating of the transformer, several solutions exist to choosing the proper insulation levels.

1) Apply surge protection (which allows an adequate protective margin) to the transformer. However, be sure to apply the protective characteristics of the surge arrester to the actual basic impulse insulation level (BIL) of the device at a given altitude derated for altitude from standard conditions. This usually requires a one-percent per 100 m derating from sea level.

2) Specify additional clearances to meet the insulation requirements at the higher altitude. This usually requires the listing of minimum clearance dimensions.

3) Use a higher voltage bushing or high-altitude bushing. Caution should be taken not to miscoordinate phase to phase clearances by increasing the phase to ground clearance. One simple rule to assure insulation coordination is to assure that the phase to phase dimensions are ten percent greater that phase to ground.

Although the application of a particular transformer may appear to be satisfactory at a higher than the standard elevation of 1000 m, the manufacturer should still be contacted to assure that the unit can be safely and adequately applied at the higher elevation. Such problems as insufficient oil for low-temperature operation may result in insufficient internal dielectric strength, and marginally applied ancillary equipment may be inadequate at higher altitudes.

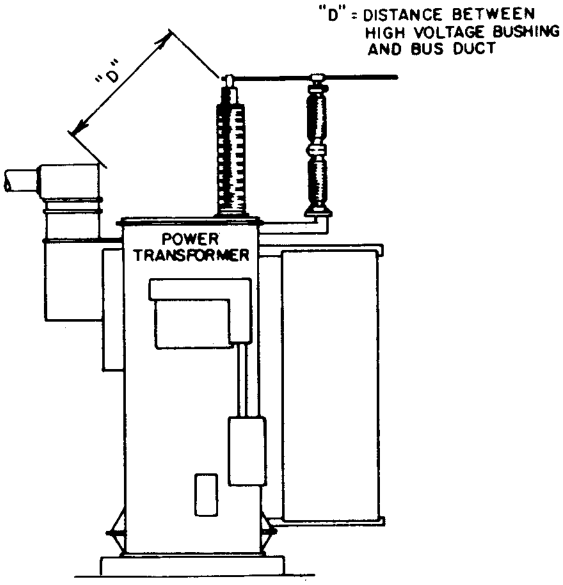

Fig. 2.

## MOTORS AND GENERATORS

A large portion of the load in a typical industrial complex consists of motors. Although not as widely used as motors, the generator is another device used in an industrial plant for emergency, supplemental or total power requirements. Due to the similar construction of the motor and generator, they are both covered in this section.

NEMA Standard MG1-14.04 discusses the application and operation of motors above 1000 m. Although NEMA MG-1 states that the usual service condition of a motor or generator is at an altitude which does not exceed 1000 m, motors can be operated above 1000 m under the following three conditions:

1) Motors and generators having Class A or B insulation and air temperature rises as stated in MG-1 provided that the ambient temperature compensates for the increased temperature due to the reduced cooling at the higher altitude (see Table II).

2) Motors having a service factor of at least 1.15 will operate satisfactorily at a unity service factor at an ambient temperature of 40°C up to an altitude of 2740 m (9000 ft).

3) Motors and generators which have been designed with a reduced temperature rise at an ambient temperature of 40°C at sea level and in accordance with MG-1.

As was a concern with the transformer design is the fact that the motor and generator are designed for a given ambient temperature with a given temperature rise at sea level and no derating to an altitude of 1000 m. However, under a given ambient temperature of 40°C, motors are allowed to be derated at approximately 0.86 percent per 100 m above 1000 m to an altitude of 2740 m. Therefore, when applying motors

TABLE II

| AMBIENT TEMPERATURE DEGREES C | MAXIMUM ALTITUDE METERS (FEET) |
|---|---|
| 40 | 1,000 (3,300) |
| 30 | 2,000 (6,600) |
| 20 | 3,000 (9,900) |

and generator to a system above 1000-m altitude, the manufacturer should be contacted and asked to confirm whether or not the motor was designed under sea level or 1000-m conditions.

## OIL AND VACUUM CIRCUIT BREAKERS

The oil or vacuum circuit breaker's design should be reviewed to assure adequate clearances phase to phase, phase to ground, and pole to pole across bushings of the same phase. If not, the application of surge arresters, larger bushings or both, should be investigated.

A slight current derating of approximately two percent per 1000 m occurs which is generally not critical for circuit breakers. The interrupting capability remains constant at all elevations due to the current interrupting means being handled under oil or in a vacuum and not exposed to the atmosphere. Therefore, both the oil and vacuum circuit breakers have relatively good applications at higher elevations.

## AIR MAGNETIC CIRCUIT BREAKERS

The air magnetic circuit breaker has a similar current derating of approximately two percent per 1000 m. The clearances of the air magnetic circuit breaker should be checked to assure the adequacy of the dielectric strength. However, confusion exists as to whether or not the interrupting rating decreases for high-altitude application.

At least one manufacturer has the opinion that the interrupting capability of an air magnetic circuit breaker should be derated for altitudes above 1000 m. There is a strong reason to believe that the interrupting capability of an air magnetic circuit breaker should be derated for altitude due to the fact that the interrupting medium is air, and the dielectric strength of air at higher altitudes is less than at sea level.

With reason to believe that an air magnetic circuit breaker should have its interrupting capability derated, the manufacturer should be contacted and requested to furnish derating factors for his breaker at the altitude in question. If the particular breaker that is being contemplated for use has its interrupting capability derated below the expected fault capability of the system, the next larger size breaker should be applied. Another alternative would be to use a vacuum or oil circuit breaker. One of the most logical choices would be the vacuum breaker since both the vacuum and air magnetic circuit breakers are used in metalclad switchgear.

## STORAGE BATTERY SYSTEM

The storage battery system consists of two basic elements, the battery and the battery charger. While altitude appears to affect only the required ventilation for the battery room, it appears that the battery charger is directly affected by altitude.

The hydrogen production from a battery (primarily the lead acid type) poses a safety hazard if the concentration becomes too high. The usual criteria is to keep the hydrogen concentration well below three percent by volume. Therefore, calculations are usually made on hydrogen production from a battery.

According to Boyle's law, the volume of a gas is inversely proportional to the pressure. Therefore, when calculating the volume of hydrogen gas produced from a battery at a given altitude, the volume of hydrogen must be increased according to the following equation:

$$V_{\text{alt}} = \frac{V_{\text{std}} \cdot 760 \text{ mm}}{P_{\text{alt}}} \tag{3}$$

where

$V_{\text{alt}}$ volume of hydrogen produced at given altitude (L),
$V_{\text{std}}$ volume of hydrogen produced under standard conditions (L),
$P_{\text{alt}}$ atmospheric pressure at a given altitude (mm of Hg).

As an example, the amount of hydrogen by volume produced at 3000-m altitude is approximately 43 percent more than at sea level. (The amount of hydrogen remains the same; the percent concentration increases due to the thinness of the atmosphere.)

The battery charger, which requires air for cooling, appears to be affected by altitude. One manufacturer provided the derating of a battery charger with respect to altitude as shown in Table III.

The most logical solution for the high-altitude application of a battery charger is to increase the rating of the battery charger and have the manufacturer limit the charging rate to some lesser value than rated.

## SURGE ARRESTERS

Most manufacturers of surge arresters have provided extended altitude ranges to include 6000- and 10 000-ft applications. The primary problem in applying surge arresters at higher than rated altitudes is that the arrester is commonly a sealed system. The sealed system is composed of either dry air or nitrogen under a given pressure.

If a low-altitude designed surge arrester is applied at a high altitude, the possibility exists that the internal pressure will be sufficiently high to cause a leak in the seal. A leak of this type could allow moisture to enter the arrester and cause a surge arrester failure.

A second potential problem exists with the new metal oxide arresters in which the overall length of the housing is decreased substantially. Attention must be given to assure that an adequate margin exists between the arrester protective characteristics and the external flashover of the housing at a high altitude.

TABLE III

| ALTITUDE (NOT TO EXCEED) | DERATING FACTOR |
|---|---|
| 1,000 m | 1.00 |
| 1,500 m | .94 |
| 3,000 m | .82 |

TABLE IV

| NOMINAL VOLTAGE | MINIMUM CLEARANCE GUARD TO LIVE PARTS | |
|---|---|---|
| | INCHES | CM |
| 301 - 600 | 2 | 5 |
| 2,400 | 3 | 8 |
| 7,200 | 4 | 10 |
| 13,800 | 6 | 15 |
| 23,000 | 9 | 23 |
| 34,500 | 12 | 31 |
| 46,000 | 16 | 41 |
| 69,000 | 23 | 58 |
| 115,000 | 37 | 94 |
| 138,000 | 44 | 112 |
| 161,000 | 58 | 147 |
| 230,000 | 66 | 168 |

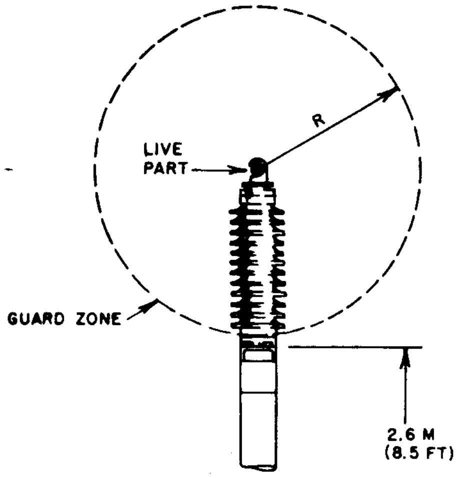

Fig. 3.

## LOW-VOLTAGE CIRCUIT BREAKERS

Low-voltage circuit breakers, 600 V and below, have a standard rating through 2000 m. Above that elevation the circuit breakers are derated at approximately one percent per 100 m and two percent per 1000 m above 2000 m for voltage and current, respectively.

## SHUNT POWER CAPACITORS

The normal service condition for capacitors includes elevations of 1800 m (6000 ft) and below. However, when consideration is given to the design of a capacitor, it appears that the primary concern for applying capacitors at higher altitudes would be the dielectric strength of the bushings.

To resolve the problem of inadequate dielectric strength of the bushings, one of two options is suggested.

1) Request a high-altitude bushing which is sufficient for the particular application.
2) Coordinate the bushing insulation level with a proper and adequate surge arrester.

## LIVE PARTS

Transmission and distribution lines, substation buses, and other electrical equipment depend on air for a means of insulation. Therefore, minimum clearances have been designated by the National Electrical Safety Code (NESC) for electrical supply stations and overhead lines.

Altitude considerations were first introduced in the 1977 edition of the NESC. In both the 1977 and the 1981 NESC, Section 23 sets provisions for calculating additional clearances for overhead lines if the line to neutral voltage exceeds 50 kV.

The NESC is considered the standard of the industry for minimum clearances and has been adopted by many regulatory bodies. However, this standard does not preclude the use of good engineering judgment and sometimes different clearances are required for a particular application.

Since most industrial plants are operated at 230 kV and below, reference will be made to Section 12 of the NESC and in particular Table 2, Part A of that section. Columns 1 and 4 are reproduced on Table IV for reference.

The column representing "minimum clearance guard to live parts" approximates the amount of air clearance to safely insulate a live part under standard conditions for a given voltage provided that nothing is allowed to enter the confines of that air space. In an electrical supply station where only authorized persons are allowed, a vertical dimension of 2.6 m (8.5 ft) is added to this minimum clearance guard to live parts to obtain the minimum vertical clearances on unguarded parts (Fig. 3).

Since the minimum clearance guard to live parts is a clearance under standard conditions, additional space should be added to compensate for higher altitudes. Since the relative air density decreases at a rate of approximately one percent per 100 m of altitude above sea level, the clearances should be increased at a rate of one percent per 100 m above sea level. However, if the standards are strictly followed where no derating occurs for 1000 m and below, an additional clearance of one percent per 100 m above 1000 m can be used.

No derating should be used for the other components of clearances in the NESC since they provide only isolation and not insulation. For example, increased clearances due to conductor sag and temperature are not altitude dependent.

An alternative to increasing the clearances would be the proper use of surge arresters to minimize the impulse voltage applied to the particular voltage. If the impulse level to which the equipment is subjected is minimized, standard clearances may be used.

## CONCLUSION

The design of an electrical power system is affected by the altitude of the system. Many of the standards indicate that an electrical device will operate satisfactorily at elevations between sea level and 1000 m. Usually, a derating is applied on equipment operated above 1000 m and in a few cases, 2000 m.

The application of a piece of equipment at any elevation should be reviewed since the relative air density at 1000 m is approximately ten percent less than at sea level. Therefore, a device designed under standard conditions will probably operate differently at 1000 m than at sea level. Discussion with the manufacturer upon design considerations may prove to be quite enlightening. The application of surge arresters and a close review of equipment ratings with regard to a particular application at a high altitude during the design of the electrical power system will minimize operational problems.

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