

Analyzing the Effect of Ambient Temperature and Loads Power Factor on Electric Generator Power Rating

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Abstract—This study presents a technique clarifying the effect of ambient air temperature and loads power factor changing from standard values on electric generator power rating. The study introduces an optimized technique for selecting the correct electric generator power rating for certain application and operating site ambient temperature. The de-rating factors due to the previous effects will be calculated to be applied on a generator to select its power rating accurately to avoid unsafe operation and save its lifetime. The information in this paper provides a simple, accurate, and general method for synchronous generator selection and eliminates common errors.

Keywords—Ambient temperature, de-rating factor, electric generator, power factor.

I. INTRODUCTION

AN essential factor governing the correct sizing of an electric generator is the power rating. It is very important to initially select the correct electric generator power rating to supply certain loads due to the high initial cost of generators, their installation, and other equipment involved [1], [2].

There are many factors which affect the size of the generator set. These parameters include ambient temperature, altitude, the maximum allowed voltage and frequency dips, load power factor, motor loads, and the presence of non-linear loads [3], [4].

A study of the effect of ambient temperature and loads power factor will be discussed in this paper due to their general and important impact.

Generators must be capable of supplying the loads within the temperature limits for that application. Generators are rated for a maximum ambient temperature of 40 °C at full load which is related to machine insulation system, lamination steel, and copper windings. Insulation system must retain its properties over operating temperature range to protect the lifetime of the machine.

The flow of load current through copper windings which have electrical resistance causes power losses which create heat. This results in increasing winding and insulation temperature, which means that the winding resistance will also increase. Insulation materials can keep their ability to retain

their insulating properties up to a maximum specified temperature for a specified lifetime. The accepted insulation lifetime is 100,000 hours of continuous operating at the maximum permitted temperature specified [1], [5], [6].

The current carrying capacity of a generator conductors should be decreased (de-rating the generator power) as a result of the increase in ambient temperature above the maximum value (40 °C) to keep insulation temperature within range.

The standard insulation classes available and associated maximum permitted temperature rises based on reference ambient temperature 40 °C (the difference between reference insulation temperature and ambient temperature) are presented in Table I [6].

TABLE I
REFERENCE INSULATION TEMPERATURE BASED ON 40 °C [6]

Class insulation system	Reference temperature (°C)	Temperature rise (°C)
A	105	60
B	130	80
F	155	105
H	180	125

Power factor is the ratio of the active power to the apparent power (VA). Synchronous generators are rated at 0.8 lagging power factor, which is the minimum limit which can be served without affecting the generator performance and lifetime. As power factor drops under 0.8, the generator power must be de-rated to prevent overheating of the generator due to the increase in load reactive power which will lead into increasing electric current and VA.

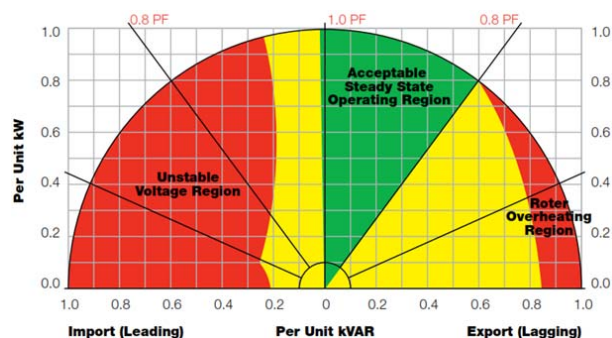


Fig. 1 Typical generator reactive capability curve [4]

The safe power factor operational limits are described by reactive capability curve. Fig. 1 shows a typical reactive

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capability curve given by one of generator manufacturers [4], [7]. The normal operating range of a generator is between 0.8 and 1.0 power factor (green area on the curve), the yellow region represents low efficiency operating condition (without damage effect), the red area represents the load operating condition which has a damaging effect on generator [4], [7]

II. AMBIENT TEMPERATURE DE-RATING

Temperature rise resulting from current passing through a conductor is given by:

$$T_r = 3I^2R\theta \quad (1)$$

where: T_r : Temperature rise in °C. I : Load line current in Ampere. R : Resistance of copper conductors in ohms per meter. θ : Thermal resistivity of copper in (m°C /w). Temperature rise also can be expressed as:

$$T_r = T_{ins} - T_{amb} \quad (2)$$

where: T_{ins} : Insulation class reference temperature (given in Table I). T_{amb} : Ambient temperature. The value of conductor resistance also is affected by the increase in the ambient temperature, this is expressed by:

$$R = R_{ref} [1 + K(T_{amb} - T_{ref})] \quad (3)$$

where: K : temperature coefficient of resistance of conductor material (for copper, $K=0.0039/^\circ\text{C}$). T_{ref} : Reference temperature at which K is specified for conductor material (copper). R_{ref} : Conductor Resistance at T_{ref} . From (2) and (3) in (1) by substitution, we get:

$$T_{ins} - T_{amb} = 3I^2\theta R_{ref} [1 + K(T_{amb} - T_{ref})] \quad (4)$$

$$\theta R_{ref} = \frac{T_{ins} - T_{amb}}{3I^2 [1 + K(T_{amb} - T_{ref})]} \quad (5)$$

From (5), we can get a formula for the square of current:

$$I^2 = \frac{T_{ins} - T_{amb}}{3\theta R_{ref} [1 + K(T_{amb} - T_{ref})]} \quad (6)$$

The value of θR_{ref} is constant for any operating point (I with T_{amb}), as it is a characteristic of conductor material, so we can calculate it from generator rated operating point where:

$$I = I_{rated}, T_{amb} = T_{amb, rated}$$

$$\theta R_{ref} = \frac{T_{ins} - T_{amb, rated}}{3I_{rated}^2 [1 + K(T_{amb, rated} - T_{ref})]} \quad (7)$$

where: I_{rated} : Rated generator current. $T_{amb, rated}$: Generator maximum ambient temperature (40 °C). From (7) in (6) by substitution, we get:

$$I^2 = \frac{I_{rated}^2 (T_{ins} - T_{amb}) [1 + K(T_{amb, rated} - T_{ref})]}{(T_{ins} - T_{amb, rated}) [1 + K(T_{amb} - T_{ref})]} \quad (8)$$

$$I = I_{rated} \sqrt{\frac{(T_{ins} - T_{amb}) [1 + K(T_{amb, rated} - T_{ref})]}{(T_{ins} - T_{amb, rated}) [1 + K(T_{amb} - T_{ref})]}} \quad (9)$$

Such that: $T_{amb, rated} < T_{amb} < \infty$

Multiplying both sides of (3) by $\sqrt{3}V$, where V is the line to line rated voltage, we get:

$$S = S_{rated} \sqrt{\frac{(T_{ins} - T_{amb}) [1 + K(T_{amb, rated} - T_{ref})]}{(T_{ins} - T_{amb, rated}) [1 + K(T_{amb} - T_{ref})]}} \quad (10)$$

The term $\sqrt{\frac{(T_{ins} - T_{amb}) [1 + K(T_{amb, rated} - T_{ref})]}{(T_{ins} - T_{amb, rated}) [1 + K(T_{amb} - T_{ref})]}}$ is the de-rating factor.

Equation (10) explains the de-rating effect of the increase in ambient temperature from rated ambient temperature on generator output rated power. The required generator power (S_{new}):

$$S_{new} = \frac{S_{rated}}{\text{derating factor}} \quad (11)$$

III. POWER FACTOR DE-RATING

Load power factor operational limits are described by reactive capability curve of a generator which indicates the maximum value of the active and the reactive power that the generator can supply at a certain operating power factor.

The continuous generator output power is limited by [8]:

A. Armature Current Limit

Armature current results in power loss (I^2R_a) which results in an increase in temperature, so one of generator rating limits is the maximum current such that its heating effect does not exceed the limits.

The per unit complex output power is given by:

$$S = P + jQ = |V_t| |I_t| (\cos\phi + j\sin\phi) \quad (12)$$

where: P : Output active power in per unit. Q : Output reactive power in per unit. V_t : Generator terminal voltage in per unit. I_t : Armature current in per unit. ϕ : Power factor angle.

Equation (12) represents a circle of center (0, 0) and radius $|V_t| |I_t|$ which is complex power rating of the generator (VA) as shown in Fig. 2.

B. Field Current Limit

Field current flowing in field windings causes power loss (I^2R_f) which results in an increase in temperature, therefore the field current value is a second limit on generator operation.

From the steady-state equivalent circuit and phasor diagram

of synchronous generator shown in Fig. 3:

$$E_f \sin \delta = X_s I_t \cos \phi \tag{13}$$

$$E_f \cos \delta = V_t + X_s I_t \sin \phi \tag{14}$$

Rearranging:

$$I_t \cos \phi = \frac{E_f \sin \delta}{X_s} \tag{15}$$

$$I_t \sin \phi = \frac{E_f \cos \delta - V_t}{X_s} \tag{16}$$

The Active power:

$$P = V_t I_t \cos \phi = E_f V_t \sin \delta / X_s \tag{17}$$

The Reactive power:

$$Q = V_t I_t \sin \phi = \frac{V_t \cos \delta}{X_s} - \frac{V_t^2}{X_s} \tag{18}$$

where E_f is the induced voltage in stator windings in per unit. Equations (17) and (18) indicate that, for a given field current, the relationship between active and reactive powers is a circle of center $(0, -\frac{V_t^2}{X_s})$ and radius $(\frac{V_t E_f}{X_s})$ in per unit, as shown in Fig. 4.

C. End Region Heating Limit

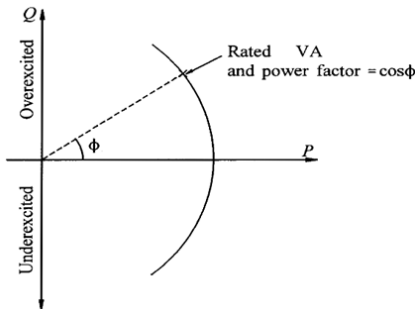


Fig. 2 Generator armature current limit [8]

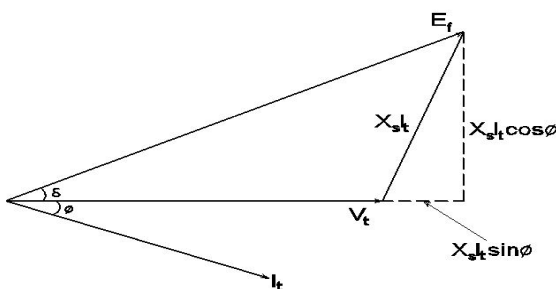


Fig. 3 Synchronous generator phasor diagram [8]

When the synchronous generator is under-excited (leading power factor), the armature end leakage flux is increased, this flux enters and leaves in a path perpendicular to stator

laminations causing eddy currents and heating in the laminations.

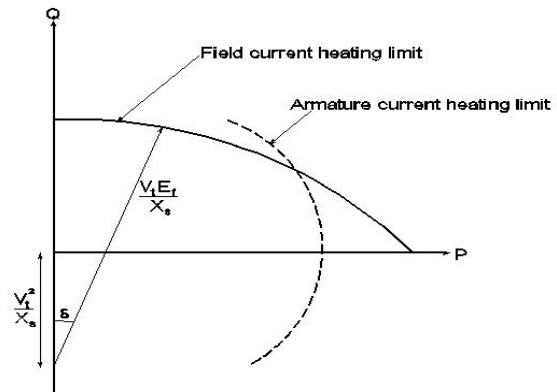


Fig. 4 Generator field current limit [8]

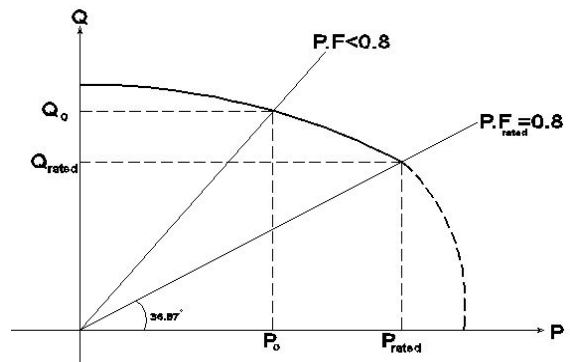


Fig. 5 Maximum output active and reactive power of generator at certain load power factor

The reactive capability curve of a generator gives the maximum output active power (P_0) and reactive power (Q_0) that the generator can supply at certain load power factor, as shown in Fig. 5.

Assume loads of rated active power (P_1), rated reactive power (Q_1), operating at a power factor of 0.8 lag supplied from a generator of rated power S_1 . For the operation at power factor less than 0.8 (PF_2) without thermal stresses, this technique will be applied:

Step1. The reactive capability curve of generator rated at S_1 will be drawn to obtain the maximum output active power (P_0) and reactive power (Q_0) that the generator can supply at the operating power factor, as shown in Fig. 5.

Step2. The active power is needed to be constant to match all operating power factor ranges, therefore:

$$P_2 = P_1 \tag{19}$$

$$Q_2 = Q_0 \tag{20}$$

where P_2 and Q_2 are the required new active and reactive power respectively. The required new generator complex

power is:

$$S_2 = \sqrt{P_2^2 + Q_2^2} \quad (21)$$

Step3. The new generator power rating (S_{new}) will be the closest complex power to S_2 from generator manufacturer's standard ratings.

Step4. The de-rating factor (DF) for generator output power, when load's power factor is less than 0.8 lagging, can be calculated as:

$$DF = S_{new}/S_1 \quad (22)$$

The reactive capability curve of the newly selected generator should be checked to be sure that the generator can supply the required load active and reactive power at the operating power factor.

IV. RESULTS

Applying this study on a generator of parameters obtained from manufacturer's data and shown in the Appendix [9].

A. Ambient Temperature De-Rating

By substituting generator data in (10):

$$S = 595 \sqrt{\frac{(180-T_{amb})[1+0.0039(40-20)]}{(180-40)[1+0.0039(T_{amb}-20)]}} \quad (23)$$

$$\text{Derating factor} = \sqrt{\frac{(180-T_{amb})[1+0.0039(40-20)]}{(180-40)[1+0.0039(T_{amb}-20)]}} \quad (24)$$

Plotting (23) and (24) using MATLAB program as shown in Figs. 6 and 7:

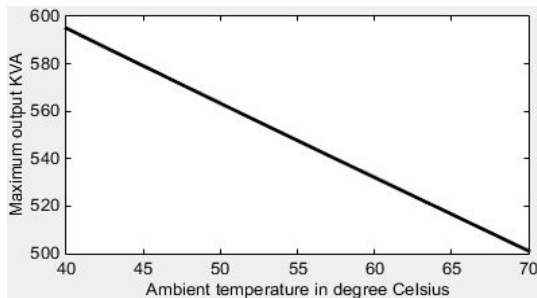


Fig. 6 Ambient temperature de-rating effect on generator output kVA

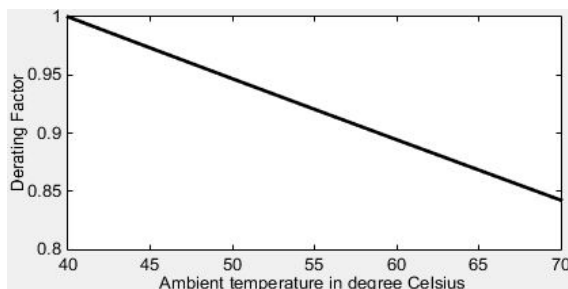


Fig. 7 De-rating factor versus ambient temperature

From these curves, the maximum output power of generator (S_{max}) can be calculated to be suitable for operating site ambient temperature, where:

$$S_{max} = S_{rated} * \text{Derating factor}$$

The required new generator power (S_{new}) is calculated as:

$$S_{new} = S_{rated}/\text{Derating factor} = S_{rated} * \text{Correction factor}$$

where Correction factor = 1/Derating factor.

Verification of the obtained correction factors resulted from (24) with the Egyptian code for the bases of designing electrical installations in buildings (vol.10: Emergency generators) are shown in Table II.

TABLE II
VERIFICATION OF THE OBTAINED RESULTS WITH THE EGYPTIAN CODE FOR THE BASES OF DESIGN

Ambient temperature (°C)	Resulted correction factor from the study	Egyptian code correction factor	Error (%)
30	0.9487	0.952	0.346
35	0.9738	0.976	0.22
40	1	1	0
45	1.0274	1.026	0.136
50	1.0562	1.053	0.3
55	1.0864	1.082	0.41

B. Load Power Factor De-Rating

1. At Rated Operation with Power Factor Equals 0.8 Lag:

$$S_1 = 595 \text{ kVA}$$

$$P_1 = 595 * 0.8 = 476 \text{ kW}$$

$$Q_1 = \sqrt{S_1^2 - P_1^2} = 357 \text{ kVAR}$$

The capability curve for the generator in this case will be drawn using equations illustrated in Section II.

a) *Armature Current Limit:* As discussed in Section II, the armature current limit is represented by a circle of center (0,0) and radius (r_a) where, $r_a = S_{rated} = 1$ pu

The circle equation is:

$$(Q - 0)^2 + (P - 0)^2 = r_a^2 \quad (25)$$

Rearranging:

$$Q = \sqrt{1 - P^2} \text{ pu}, \quad 0.8 \leq P < 1 \quad (26)$$

b) *Field Current Limit:* Field current limit is represented by a circle of center $(0, -\frac{V_t^2}{X_s})$ and radius (r_f) where, $r_f = (V_t E_f / X_s)$.

E_f is calculated from phasor diagram Fig. 3 at rated conditions.

$$E_f = \sqrt{(V_t + I X_s \sin \phi)^2 + (I X_s \cos \phi)^2} \text{ pu} \quad (27)$$

$$E_f = \sqrt{(1 + 1 * 4.255 * \sin 36.87)^2 + (1 * 4.255 * \cos 36.87)^2} = 4.92 \text{ pu}$$

$$\text{Center} = (a, b) = (0, -\frac{1}{4.255}) = (0, -0.235) \text{ pu.}$$

$$r_f = (1 * 4.92/4.255) = 1.1563 \text{ pu.}$$

The circle equation is:

$$(Q - b)^2 + (P - a)^2 = r_f^2$$

$$Q = b + \sqrt{r_f^2 - P^2} \text{ pu, } 0 < P < 0.8 \quad (28)$$

By substitution with values of r_f and b , we get:

$$Q = (-1/4.255) + \sqrt{(1.1563)^2 - P^2} \text{ pu} \quad (29)$$

2. At Operation with Power Factor Less than 0.8 Lag ($PF_2 = 0.7$).

Step1. By plotting (26) and (30), we will get the reactive capability curve for the specified generator rated at S_1 as shown in Fig. 8. The black curve represents the field current limit, the green curve represents the armature current limit, and the red straight line represents the power factor line in case of 0.7 lag. The power factor line equation is:

$$Q = P \tan \phi \quad (30)$$

where ϕ is the angle between the power factor line, and x-axis (Power factor angle).

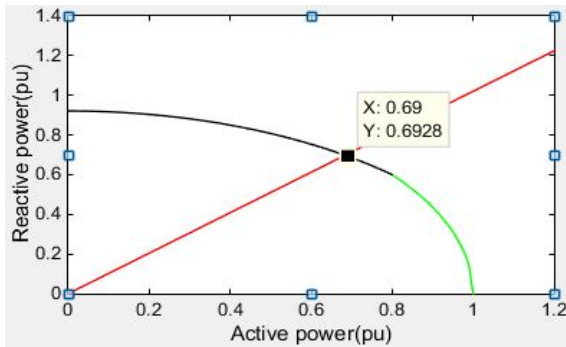


Fig. 8 Reactive capability curve of 595 kVA generator and 0.7 lagging power factor line

Step2. The active and reactive power

$$P_2 = P_1 = 476 \text{ kW}$$

$$Q_2 = 0.6928 \text{ pu} = 0.6928 * 595 = 412.216 \text{ kVAR}$$

The required new generator complex power is:

$$S_2 = \sqrt{P_2^2 + Q_2^2} = \sqrt{476^2 + 412.216^2} = 629.7 \text{ kVA}$$

Step3. The closest generator power rating to S_2 from generator manufacturer's standard ratings is:

$$S_{\text{new}} = 655 \text{ kVA}$$

Step4. The de-rating factor (DF) for generator output power when the load's power factor is 0.7 lagging:

$$DF = S_1/S_{\text{new}} = 595/655 \cong 0.91$$

3. At Operation with Power Factor Less than 0.8 Lag ($PF_3 = 0.6$)

Step1. The reactive capability curve for the specified generator rated at S_1 and the power factor line in case of 0.6 lag are shown in Fig. 9.

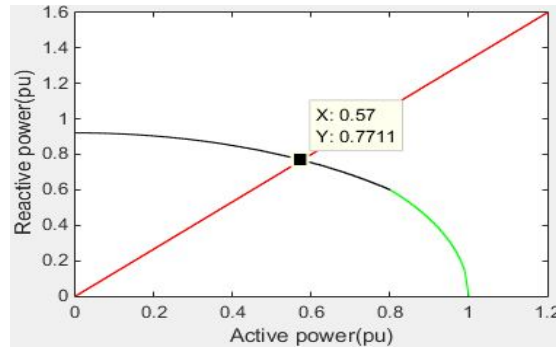


Fig. 9 Reactive capability curve of 595 kVA generator and 0.6 lagging power factor line

Step2. The active and reactive power

$$P_3 = P_1 = 476 \text{ kW}$$

$$Q_3 = 0.77 \text{ pu} = 0.77 * 595 = 458.15 \text{ kVAR}$$

The required new generator complex power is:

$$S_3 = \sqrt{P_3^2 + Q_3^2} = \sqrt{476^2 + 458.15^2} \cong 661 \text{ kVA}$$

Step3. The closest generator power rating to S_3 from generator manufacturer's standard ratings is:

$$S_{\text{new}} = 700 \text{ kVA}$$

Step4. The de-rating factor (DF) for generator output power when the loads power factor is 0.6 lagging:

$$DF = S_1/S_{\text{new}} = 595/700 = 0.85$$

TABLE III
VERIFICATION OF THE OBTAINED RESULTS WITH DATA OF ONE OF ELECTRIC GENERATORS MANUFACTURER'S

Power factor (lag)	Resulted correction factor from the study	Manufacturer's data	Error (%)
0.8	1	1	0
0.7	0.91	0.92	1
0.6	0.85	0.85	0

Verification of the resulted de-rating factors with one of electric generators manufacturer's data [10] is shown in Table

III.

V. CONCLUSION

This paper proposed a superior and accurate method to select the correct electric generator power rating to supply certain loads. The de-rating effect of operating site ambient temperature and loads power factor on generator rating was discussed.

The proposed analysis clarifies the effective impact of the increase in operating site ambient temperature above the standard value on generator output power rating. The importance of reducing this impact is illustrated to guarantee safe operation of the electric generator and saving its lifetime.

Selection of the most suitable generator output power rating to operate safely with low power factor loads was studied clearly. Also, a generator ability to supply the active and reactive power required by the load at any power factor was discussed clearly.

Based on the described techniques and results, the de-rating factors for both of operating site ambient temperature and power factor can be calculated accurately for any generator and as a result the required power rating suitable for the operating conditions.

APPENDIX

TABLE IV
ELECTRIC GENERATOR PARAMETERS [9]

Parameter	Value
Rated continuous power	595 kVA
Rated Voltage	380 V
Rated Power Factor	0.8
Rated Current	904 A
Inertia (J)	11 kg.m ²
Insulation class	H
Rated Ambient Temperature	40 °C
Stator winding resistance	0.00446 Ω per phase at 20 °C
X_d	4.255 pu
X'_d	0.29 pu
X''_d	0.193 pu
X_q	1.98 pu
X''_q	0.212 pu

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