Voltage drop calculation on alternators with several motors

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Abstract – This article presents a simplified method for calculating voltage drop in alternators during induction motor starting, considering parameters such as transient reactance (xd') and subtransient reactance (xd''), power factor, and initial loads. The analysis addresses the influence of excitation type and load conditions (constant impedance, constant kVA, and constant current). Equations for voltage drop estimation, reference tables, and correction graphs based on power factor and current variation are provided. Practical examples demonstrate the impact of motor starting using direct and compensatory starting method and the interaction between multiple motors connected to the same alternator. The proposed method enables optimized generator sizing, ensuring proper performance under transient voltage demands.

Keywords: voltage drop; alternators; motor starting; reactance; generator sizing.

1 Introduction

1.1 Voltage drop calculation

When applying a load to the alternator, there will be a sudden voltage drop which depends on the alternator reactance, current, cosø, load, and type of regulation. The main voltage drop and recovery occur on induction motor starting.
During induction motor starting, power factor is 0.3. To make the calculation easier, let's consider cosφ equal to zero, as well as to disregard power supply cable impedance and alternator inside resistance.
Considering the mentioned simplifying factors, the alternator type driving a load will comply with Figure 1.

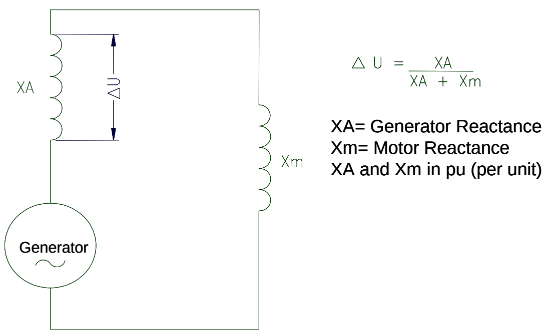

Figure 1: *Synchronous alternator impedance (simplified system)*

Figure 2 shows voltage variation referred to time (average values). The curves shown depend on the alternator parameters and on excitation response time and on the regulation system.

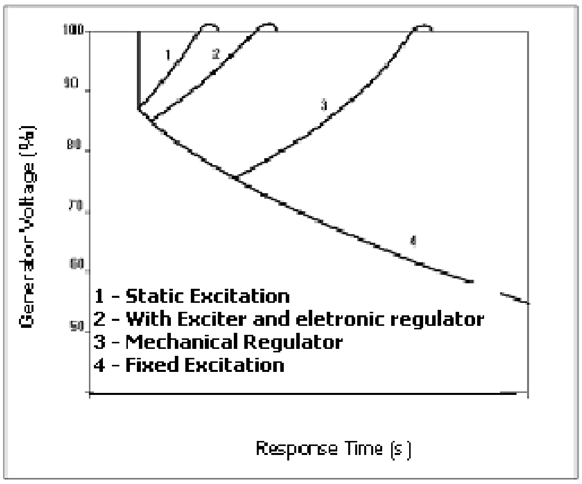

Figure 2: *Voltage variation referred to time*

Voltage drop calculation becomes complex if we take into consideration time reactance variation. We can get to certain figures close to reality, if we consider for voltage drop as the **transitory reactance (xd')**, for machine fitted with exciter and electronic regulator (brushless), and **subtransitory reactance (xd")** for machines fitted with static excitation (with brushes).
The voltage drop equation is then:

$$\Delta U = \frac{X_A}{X_A + X_m}$$

$$\Delta U_{\%} = \frac{X_d'}{1 + X_d'} \cdot 100$$

Or in general terms for any alternator Ip/In (motor starting current/ alternator rated current) value, the ratio applied is then:

$$\Delta U_{\%} = \frac{X'_d \cdot (I_P/I_N)}{1 + X'_d \cdot (I_P/I_N)} \cdot 100$$

Where:
X'd = xd' (in pu) on machines fitted with exciter and electronic regulator, (brushless alternators).
X'd = xd" (in pu) on machines fitted with static exciter, (alternators with brushes).
Ip = motor starting current (in amperes).
In = alternator rated current (in amperes).
Table 1 shows voltage drop value (ΔU) referred to X* d and Ip/In for cosφ equal to zero.

1.2 Power factor influence

If voltage drop needs to be calculated for cosø different than zero, graphic of Figure 3 must be then used.
On this graphic, we may find the "x" correction value and it must be multiplied by ΔU to cosφ = 0.

$$\Delta U(\cos\phi\ any) = X \cdot \Delta U\ (\cos\phi = 0)$$

The voltage drop, as we can see on the curve, will reduce as the power factor increases.

1.3 Initial load influence

The alternator initial loads may be grouped in three types:

- Constant impedance;
- Constant kVA;
- Constant current.

Alternator current will reduce proportionally to alternator voltage, when this is under constant impedance load. As a consequence, this effect will reduce the voltage drop. This may be disregarded for calculation purposes.
Example of constant impedance load: lights, heaters and resistors.
When there is a constant kVA load, on voltage drop, we will have an increase of current, causing consequently increase in voltage drop.
An example of this type of load are the induction motors. Current variation (ΔI) on induction motors, in reference to voltage drop, can be obtained in Figure 4.

When an alternator is powering as induction motor that is starting and there is another motor already connected to alternator terminals, under duty, such current variation must be added to an induction motor starting current. Although power factors are different, they are considered, within a pessimism view, the same.
When combining constant KVA and constant impedance loads, we will have constant current loads, as the effect is opposite with possibility to become void. Depending on the individual values of these loads, the voltage drop would not cause current variations and, as a consequence, there would not be voltage drop.
These are considered the most common types of loads (combined). For voltage drop calculation with cosφ, we may use Table 1.

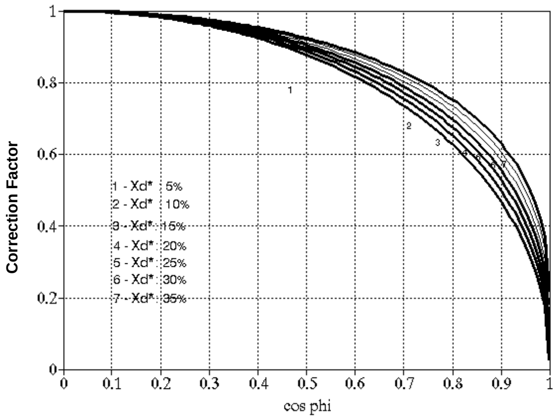

***Figure 3**: Correcting curves for ΔU referred to Cosφ and alternator reactance*

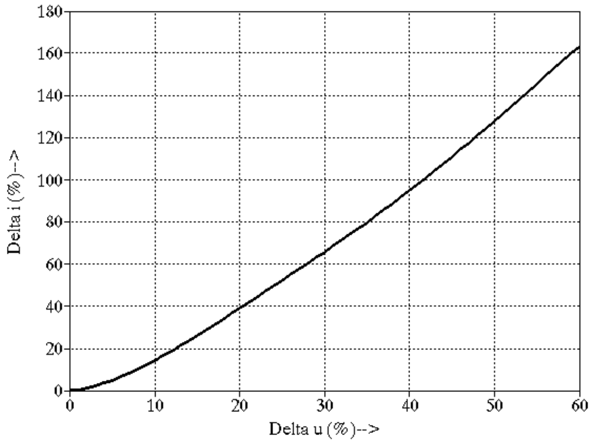

***Figure 4:** Current variation Δi on Induction Motors, in operation referred to voltage variation on its terminals*

Table 1: Voltage Drop on Synchronous alternators

VOLTAGE DROP (ΔU) for Cos. φ = 0 [pu]

x*d [pu]	IP/IN														
	0.200	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.400	2.600	2.800	3.000
0.050	0.010	0.020	0.029	0.038	0.048	0.057	0.065	0.074	0.083	0.091	0.099	0.107	0.115	0.123	0.130
0.060	0.012	0.023	0.035	0.046	0.057	0.067	0.077	0.088	0.097	0.107	0.117	0.126	0.135	0.144	0.153
0.070	0.014	0.027	0.040	0.053	0.065	0.077	0.089	0.101	0.112	0.123	0.133	0.144	0.154	0.164	0.174
0.080	0.016	0.031	0.046	0.060	0.074	0.088	0.101	0.113	0.126	0.138	0.150	0.161	0.172	0.183	0.194
0.090	0.018	0.035	0.051	0.067	0.083	0.097	0.112	0.126	0.139	0.153	0.165	0.178	0.190	0.201	0.213
0.100	0.020	0.038	0.057	0.074	0.091	0.107	0.123	0.138	0.153	0.167	0.180	0.194	0.206	0.219	0.231
0.110	0.022	0.042	0.062	0.081	0.099	0.117	0.133	0.150	0.165	0.180	0.195	0.209	0.222	0.235	0.248
0.120	0.023	0.046	0.067	0.088	0.107	0.126	0.144	0.161	0.178	0.194	0.209	0.224	0.238	0.251	0.265
0.130	0.025	0.049	0.072	0.094	0.115	0.135	0.154	0.172	0.190	0.206	0.222	0.238	0.253	0.267	0.281
0.140	0.027	0.053	0.077	0.101	0.123	0.144	0.164	0.183	0.201	0.219	0.235	0.251	0.267	0.282	0.296
0.150	0.029	0.057	0.083	0.107	0.130	0.153	0.174	0.194	0.213	0.231	0.248	0.265	0.281	0.296	0.310
0.160	0.031	0.060	0.088	0.113	0.138	0.161	0.183	0.204	0.224	0.242	0.260	0.277	0.294	0.309	0.324
0.170	0.033	0.064	0.093	0.120	0.145	0.169	0.192	0.214	0.234	0.254	0.272	0.290	0.307	0.322	0.338
0.180	0.035	0.067	0.097	0.126	0.153	0.178	0.201	0.224	0.245	0.265	0.284	0.302	0.319	0.335	0.351
0.190	0.037	0.071	0.102	0.132	0.160	0.186	0.210	0.233	0.255	0.275	0.295	0.313	0.331	0.347	0.363
0.200	0.038	0.074	0.107	0.138	0.167	0.194	0.219	0.242	0.265	0.286	0.306	0.324	0.342	0.359	0.375
0.210	0.040	0.077	0.112	0.144	0.174	0.201	0.227	0.251	0.274	0.296	0.316	0.335	0.353	0.370	0.387
0.220	0.042	0.081	0.117	0.150	0.180	0.209	0.235	0.260	0.284	0.306	0.326	0.346	0.364	0.381	0.398
0.230	0.044	0.084	0.121	0.155	0.187	0.216	0.244	0.269	0.293	0.315	0.336	0.356	0.374	0.392	0.408
0.240	0.046	0.088	0.126	0.161	0.194	0.224	0.251	0.277	0.302	0.324	0.346	0.365	0.384	0.402	0.419
0.250	0.048	0.091	0.130	0.167	0.200	0.231	0.259	0.286	0.310	0.333	0.355	0.375	0.394	0.412	0.429
0.260	0.049	0.094	0.135	0.172	0.206	0.238	0.267	0.294	0.319	0.342	0.364	0.384	0.403	0.421	0.438
0.270	0.051	0.097	0.139	0.178	0.213	0.245	0.274	0.302	0.327	0.351	0.373	0.393	0.412	0.431	0.448
0.280	0.053	0.101	0.144	0.183	0.219	0.251	0.282	0.309	0.335	0.359	0.381	0.402	0.421	0.439	0.457
0.290	0.055	0.104	0.148	0.188	0.225	0.258	0.289	0.317	0.343	0.367	0.389	0.410	0.430	0.448	0.465
0.300	0.057	0.107	0.153	0.194	0.231	0.265	0.296	0.324	0.351	0.375	0.398	0.419	0.438	0.457	0.474
0.310	0.058	0.110	0.157	0.199	0.237	0.271	0.303	0.332	0.358	0.383	0.405	0.427	0.446	0.465	0.482
0.320	0.060	0.113	0.161	0.204	0.242	0.277	0.309	0.339	0.365	0.390	0.413	0.434	0.454	0.473	0.490
0.330	0.062	0.117	0.165	0.209	0.248	0.284	0.316	0.346	0.373	0.398	0.421	0.442	0.462	0.480	0.497
0.340	0.064	0.120	0.169	0.214	0.254	0.290	0.322	0.352	0.380	0.405	0.428	0.449	0.469	0.488	0.505
0.350	0.065	0.123	0.174	0.219	0.259	0.296	0.329	0.359	0.387	0.412	0.435	0.457	0.476	0.495	0.512
0.360	0.067	0.126	0.178	0.224	0.265	0.302	0.335	0.365	0.393	0.419	0.442	0.464	0.483	0.502	0.519
0.370	0.069	0.129	0.182	0.228	0.270	0.307	0.341	0.372	0.400	0.425	0.449	0.470	0.490	0.509	0.526
0.380	0.071	0.132	0.186	0.233	0.275	0.313	0.347	0.378	0.406	0.432	0.455	0.477	0.497	0.516	0.533
0.390	0.072	0.135	0.190	0.238	0.281	0.319	0.353	0.384	0.412	0.438	0.462	0.483	0.503	0.522	0.539
0.400	0.074	0.138	0.194	0.242	0.286	0.324	0.359	0.390	0.419	0.444	0.468	0.490	0.510	0.528	0.545

Where:

- IP = Motor starting current (in amperes).
- IN = Alternator rated current (in amperes).
- X*d = Xd' for motors with exciter and electronic voltage regulator (Brushless alternator) or Xd'' for motors with static exciter (alternators with brushes).

1.4 Motor Starting Limitation

We consider as starting current limit of an induction motor the value up to 2.5x alternator rated current. Above this value, the residual voltage drop becomes significant and the time period it remains there (thermal limit) is short, as shown in graphic Figure 5, which can be shorter than the motor starting time period.

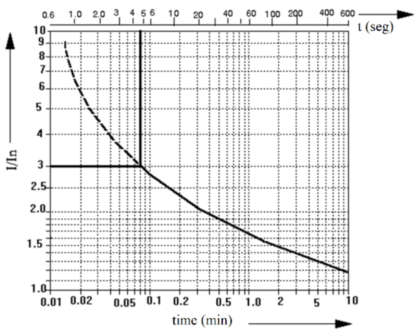

Figure 5: *Momentary Overload x rated Current Curve*

On the specific case of 2x IN the overload time, as shown on the graphic, is 20s to 30s.

To reduce induction motor starting current, star-delta starting or compensating switch are usually applied.

The starting current variation referred to voltage (K1) is shown in the graphic of Figure 6 (Constant K1). This current reduction must be considered on the voltage drop calculation.

Another topic to be considered is the drive machine output power, which is usually designed with cos ø = 0.8 (useful power (kW) = 0.8 x apparent power (kVA). The voltage drop caused by motor starting can make the motor not suitable to drive the load. Graphic of Figure 6 shows torque reduction (K2) with voltage drop. Driven load must be analysed so as to get minimum torque value and consequent voltage drop limitation.

For parallel-operation alternators, the total reactance must be calculated applying the following equation:

$$\frac{I_T}{X'_d} = I_G \frac{1}{X'_d} + I_G \frac{1}{X'_d} + \cdots + \frac{I_{Gn}}{X'_d}$$

$$\frac{I_T}{xd^*} = I_G \frac{1}{xd^*} + I_G \frac{2}{xd^*} + \ldots + \frac{I_{Gn}}{xd^*}$$

Where:

- xd* = total reactance (xd' or xd'', case by case).
- xd*...n = reactance of each alternator connected in parallel.
- IT = Total rated current of all parallel-connected alternators.
- IG1...n = Rated current of each parallel-connected alternator.

NOTE: If two identical parallel–connected alternators are used, the total reactance is equal to individual alternator reactance.

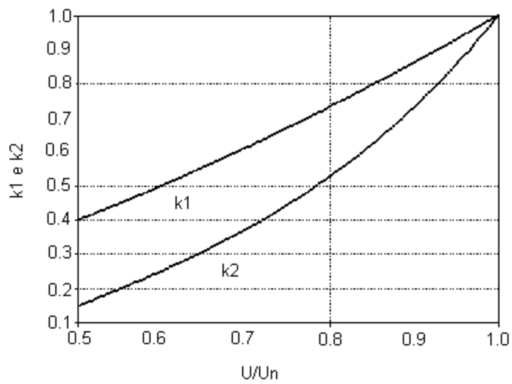

Figure 6: *Current (K1) and Torque (K2) Reduction Factors on induction motor starting referred to voltage on its terminals*

1.5 Example of Voltage drop calculation

Required information:

- Alternator AG10250SI20AI, 292 kVA, 440V Xd'=18.39% (Xd'=0.1839pu);

- Induction motors.
  a. 100 HP - 4 poles - 440 V - IN = 120 A IP = 1056 A.
  b. 75 HP - 4 poles - 440 V - IN = 87.5 A IP = 647.5 A.
  c. 25 HP - 4 poles - 440 V - IN = 31.5 A IP = 271 A.

- Alternator load receiving conditions.
  a. First it starts a 100HP, using soft starter with TAP of 65%.
  b. Other condition would be to start (with TAP of 65%) of a 75HP motor, considering that the 100 and 25HP motors are in operation.

SOLUTION:
Rated current alternator calculation:

$$I_g = \frac{29200}{\sqrt{3} \cdot 440} = 383\ A$$

1. **Voltage drop calculation caused by the starting of a 100HP motor (with soft starter on Tap 65%), considering 25 and 75HP motors switched-off:**

IN (Motor rated current) = 120A
IP (Motor starting current) = 1056 A

NOTE: Pretend a voltage drop of 15% on the alternator (initial supposition).

Using a soft starter with TAP65% and considering the initial voltage drop on the alternator of 15% the total voltage drop on the motor terminals is:

(1-0.15) x 0.65 = 0.85 x 0.65 = 0.55

From graphic of Figure 6 with 0.55 of voltage drop, we get the constant of current reduction (K1):

K1 = 0.45

Then the motor starting current on its terminals is:

$$IP_{motor\ 65\%} = IP_{100\%} \cdot K_1$$
$$IP_{motor\ 65\%} = 1056 \cdot 0.45 = 475\ A$$

However, when referring to soft starter, we have to refer the motor starting current (secondary of the soft starter) to the alternator (primary of the soft starter), then we have IPmotor ref:

$$\frac{IP_{prim}}{I_{sec}} = \frac{IP_{motorref}}{IP_{motor65\%}} = 0.65$$
$$IP_{motor} = IP_{motor65\%} \cdot 0.65$$
$$IP_{motor} = 475 \cdot\ 0. = 309\ A$$

So, on the alternator terminals, comparing the motor starting current with alternator rated current (IP/IN):

$$\frac{IP_{motor}}{I_g} = \frac{309}{383} = 0.8068$$

We will have a voltage drop of:

$$\Delta V = \frac{(0.1839 \cdot 0.8068)}{1 + (0.1839 \cdot 0.8068)} \cdot 100 = 12.92\%$$

Recalculating (1º itemization) for alternator voltage drop of 14.29%, we have:

Total voltage drop:

$$0{,}65 \cdot (1 - 0.1292) = 0{,}56$$

Constant of total voltage drop of current (k1) due to the voltage drop (0.56):

$$K_1 = 0{,}46$$
$$IP_{motor65\%} = IP_{100\%} \cdot K_1$$
$$IP_{motor65\%} = 1.056 \cdot 0{,}46 = 485.76\ A$$

Starting current referred to the primary of the soft starter (alternator terminals) and ratio IP/IN.

$$IP_{motor} = IP_{motor65\%} \cdot 0.65$$
$$IP_{motor} = 485.76 \cdot 0.65 = 315.74\ A$$
$$\frac{IP_{motor}}{I_g} = \frac{315.74}{383} = 0.8244$$

However, with the drop of 1º itemization value, we will have a voltage drop of:

$$\Delta V = \frac{(0.1839 \cdot 0.8244)}{1 + (0.1839 \cdot 0.8244)} \cdot 100 = 13.16\%$$

2. Voltage drop calculation caused by the starting of a 75HP motor (with soft starter on Tap of 65%), considering 25 and 100HP motors are already in operation:

2.1. Individual contribution of the 75HP motor (IN = 87.5 A - IP = 647.5 A):

Supposing an initial voltage drop of 15% and using soft starter with TAP 65%:

$$(1-0{,}15)\cdot 0{,}65 = 0{,}85\cdot 0{,}65 = 0{,}55$$

Then, in Figure 6: K1 = 0.45

Starting current motor referred to the primary soft starter (alternator terminal):

$$IP_{motor65\%=647{,}5\cdot 0{,}45\cdot 0{,}65}$$
$$IP_{motor65\%=189\,A}$$

Ratio IP/IN on the alternator terminals:

$$\frac{IP_{motor65\%}}{I_g} = \frac{189}{383} = 0.493$$

The resulting voltage drop, only considering the starting of the 75HP motor, will be:

$$\Delta V = \frac{(0{,}1839\cdot 0{,}493)}{1+(0.1839\cdot 0.493)}\cdot 100$$

$$\Delta V \ = \ 8.31\%$$

2.2. Contribution of the 100HP and 25 HP motors when starting a 75HP motor:

NOTE: The calculation process is interactive and follows the procedures described below:

2.1.1. Supposed drop value = 15% from graphic of Figure 4, we get current variation of the motors under load. For the case in question, we have Δi = 26% (0,26).

Then, the motor current adders are:

100HP motor (IN = 120 A - 440 V)
Addition = Δi . 120 = 0.26 x 120
Addition = 31.2 A

Δi 100HP motor:

$$\Delta i\ (M100) = \frac{Addition}{Ig} = \frac{31{,}2}{383}$$
$$\Delta i(M100) = 0.0815$$

25HP motor (IN = 31.5 A - 440 V)
Addition = Δi. 31.5 = 0.26 x 31.5
Addition = 8.2 A

Δi 25HP motor:

$$\Delta i(M25) = \frac{8{,}2}{383} = 0{,}0214$$

Total IP/IN calculation:

$$\frac{IP}{IN} = \frac{IP}{Ig}(M75) + \Delta i(M100) + \Delta i(M25)$$
$$\frac{IP}{IN} = \ 0{,}493 + 0{,}0815 + 0{,}0214$$

Total IP/IN:

$$\frac{I_P}{I_N} = 0{,}5959$$

$$\Delta V = \frac{(0.1839\cdot 0.5959)}{1+(0.1839\cdot 0.5959)}\cdot 100 = 9.88\%$$

As we supposed ΔV = 15% and it resulted on a drop of 9.88%, the calculation will be remade:

2.1.2. Supposing now a drop of ΔV = 9.88%, of Figure 4, Δi = 15% (=0.15)

$$(1-0.988)\cdot 0.65 = 0.90\ \cdot 0.65 = 0.58$$

Then, in Figure 6 $K_1 = 0.49$

$$IP_{motor65\%} = 647.5\cdot 0.49\ \cdot 0.65 = 206.22\ A$$

Thus, K1=0.49

$$\frac{IP}{Ig}(M75) = \frac{206.22}{383} = 0.5384$$

$$\frac{IP}{IN} = \frac{IP}{Ig}(M75) + \Delta i(M100) + \Delta i(M25)$$
$$\frac{IP}{IN} = \ 0.5384\ \left(\frac{120\cdot 0.15}{383}\right) + \left(\frac{31.5\cdot 0.15}{383}\right) = 0.5977$$

$$\Delta V = \frac{(0.1839\cdot 0.5977)}{1+(0.1839\cdot 0.5977)}\cdot 100 = 9.90\%$$

Then, ΔV stipulated ≈ ΔV calculated.
Calculation can be concluded.

CONCLUSION: We can note that the contribution from the motors already in operation did not cause significant increase, on this case, on the general voltage drop.
With the present calculation method , it is possible to design and select optimized generators that meet the application´s voltage transient demands. WEG application team is always available to provide further support for the customer selection requirements.