ECET 4520

Industrial Distribution Systems, Illumination, and the NEC

Voltage Drop Calculations

Voltage Drop in Distribution Systems

Due to the resistance (DC) or impedance (AC) of a distribution system's conductors, there may be a substantial difference between voltage present at a system's point-of-service and voltage at the outlets that supply the utilization equipment.

An under-voltage at the load-terminals can result in inefficient operation of heating, lighting, motor, and other type loads.

An excessive voltage drop may even impair the starting and/or proper operation of the loads.

Voltage Drop Effects

A terminal voltage that is 10% below rated voltage can result in a decrease in efficiency of substantially more than 10%.

For example: The light output of fluorescent lights would be reduced by 15% and that of incandescent lights would be reduced by 30%.

Voltage Drop Effects

Additionally, when motors are supplied with less-than-rated voltage, they typically run hotter and produce less torque.

If an induction motor is supplied with a voltage that is 10% below its rating, the running current will increase 11%, the operating temperature will increase by 12%, and the developed torque will be reduced by 19%.

The reduction in developed torque may cause the motor's speed to decrease, further increasing the potentially harmful current and temperature effects in the motor.

Branch Circuits

<u>210.19(A)(1) – Conductors – Min Ampacity & Size</u>

Branch-circuit conductors shall have an ampacity not less than the maximum load to be served. Conductors shall be sized to carry <u>not less than the larger of</u> 210.19(A)(1)(a) or (b).

(a) … the minimum conductor size shall have an allowable ampacity not less than (100% of) the non-continuous load plus 125% of the continuous load.

(b) The minimum conductor size shall have an allowable ampacity not less than the maximum load to be served after the application of any adjustment or correction factors.

Voltage Drop Guidelines

<u>210.19(A) – Conductors – Min Ampacity & Size</u>

INFORMATIONAL NOTE 4: Conductors for branch circuits sized to prevent a voltage drop exceeding 3% at the farthest outlet… and where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5%, provide reasonable efficiency of operation.

See Informational Note #2 of 215.2(A)(1)* for voltage drop on feeder conductors.

(* – The other note basically says the same about feeders.)

Voltage Drop Guidelines

90.5(C) – Explanatory Material

Explanatory material… is included in this Code in the form of informational notes. Such notes are informational only and are not enforceable as requirements of this Code.

Based upon the above statement, the guidelines provided by Info. Note #4 of 210.19(A) are not an NEC requirement.

Despite this fact, in terms of professional design standards, failure to consider any voltage drop concerns may result in a poorly designed system.

Calculating Voltage Drop

In general, the voltage drop that occurs in the conductors of a specific circuit in an AC system is a function of:

- **The load (current) that flows through the conductors**
  - Although proper circuit conductor sizing requires knowledge of the current magnitude, the impact of a circuit's voltage drop on the overall operational voltage of a system is a function of both the magnitude and phase angle of the circuit current.
- **The impedance (resistance and reactance) of the conductors.**
  - The NEC provides limited resistance and reactance information based on conductor type, size, temperature, and other operational parameters.

Conductor Characteristics

Conductor <u>resistance</u> (DC) or <u>impedance</u> (AC) information can be found within the NEC in:

Chapter 9 – "Tables"

specifically within Tables 8 and 9:

Table 8 – "Conductor Properties" (DC Resistance)
w/ Note for Temp. effects on Resistance

Table 9 – "AC Resistance & Reactance…"

Table 8 – Conductor Properties

Table 8 provides <u>DC resistance</u> information for both copper and aluminum conductors based on conductor type and size.

Table 8 Conductor Properties

Size (AWG or kcmil)	Conductors: Area mm²	Conductors: Area Circular mils	Stranding: Quantity	Stranding: Diameter mm	Stranding: Diameter in.	Overall: Diameter mm	Overall: Diameter in.	Overall: Area mm²	Overall: Area in.²	DC Resistance at 75°C (167°F) Copper Uncoated ohm/km	Copper Uncoated ohm/kFT	Copper Coated ohm/km	Copper Coated ohm/kFT	Aluminum ohm/km	Aluminum ohm/kFT
14	2.08	4110	1	—	—	1.63	0.064	2.08	0.003	10.1	3.07	10.4	3.19	16.6	5.06
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004	10.3	3.14	10.7	3.26	16.9	5.17
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005	6.34	1.93	6.57	2.01	10.45	3.18
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006	6.50	1.98	6.73	2.05	10.69	3.25
10	5.261	10380	1	—	—	2.588	0.102	5.26	0.008	3.984	1.21	4.148	1.26	6.561	2.00
10	5.261	10380	7	0.98	0.038	2.95	0.116	6.76	0.011	4.070	1.24	4.226	1.29	6.679	2.04
8	8.367	16510	1	—	—	3.264	0.128	8.37	0.013	2.506	0.764	2.579	0.786	4.125	1.26
8	8.367	16510	7	1.23	0.049	3.71	0.146	10.76	0.017	2.551	0.778	2.653	0.809	4.204	1.28
6	13.30	26240	7	1.56	0.061	4.67	0.184	17.09	0.027	1.608	0.491	1.671	0.510	2.652	0.808
4	21.15	41740	7	1.96	0.077	5.89	0.232	27.19	0.042	1.010	0.308	1.053	0.321	1.666	0.508
3	26.67	52620	7	2.20	0.087	6.60	0.260	34.28	0.053	0.802	0.245	0.833	0.254	1.320	0.403
2	33.62	66360	7	2.47	0.097	7.42	0.292	43.23	0.067	0.634	0.194	0.661	0.201	1.045	0.319
1	42.41	83690	19	1.69	0.066	8.43	0.332	55.80	0.087	0.505	0.154	0.524	0.160	0.829	0.253
1/0	53.49	105600	19	1.89	0.074	9.45	0.372	70.41	0.109	0.399	0.122	0.415	0.127	0.660	0.201
2/0	67.43	133100	19	2.13	0.084	10.62	0.418	88.74	0.137	0.3170	0.0967	0.329	0.101	0.523	0.159
3/0	85.01	167800	19	2.39	0.094	11.94	0.470	111.9	0.173	0.2512	0.0766	0.2610	0.0797	0.413	0.126
4/0	107.2	211600	19	2.68	0.106	13.41	0.528	141.1	0.219	0.1996	0.0608	0.2050	0.0626	0.328	0.100
250	127	—	37	2.09	0.082	14.61	0.575	168	0.260	0.1687	0.0515	0.1753	0.0535	0.2778	0.0847
300	152	—	37	2.29	0.090	16.00	0.630	201	0.312	0.1409	0.0429	0.1463	0.0446	0.2318	0.0707
350	177	—	37	2.47	0.097	17.30	0.681	235	0.364	0.1205	0.0367	0.1252	0.0382	0.1984	0.0605

- NEC 2014, Chapter 9 – "Tables", Table 8 – "Conductor Properties"

Table 8 – Conductor Properties

Table 8 provides DC resistance information for both copper and aluminum conductors based on conductor size.

Table 8 Conductor Properties

Size (AWG or kcmil)	Conductors: Area mm²	Conductors: Area Circular mils	Stranding: Quantity	Stranding: Diameter mm	Stranding: Diameter in.	Overall: Diameter mm	Overall: Diameter in.	Overall: Area mm²	Overall: Area in.²	DC Resistance at 75°C (167°F): Copper Uncoated ohm/km	Copper Uncoated ohm/kFT	Copper Coated ohm/km	Copper Coated ohm/kFT	Aluminum ohm/km	Aluminum ohm/kFT
14	2.08	4110	1	—	—	1.63	0.064	2.08	0.003	10.1	3.07	10.4	3.19	16.6	5.06
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004	10.3	3.14	10.7	3.26	16.9	5.17

Resistance is defined in terms of Ω/km or Ω/kFt and is based on a 75°C conductor temperature.

The table's notes provide a method for determining resistance at temperatures other than 75°C.

Notes: 1. These resistance values are valid **only** for the parameters as given. Using conductors having coated strands, different stranding type, and, especially, other temperatures changes the resistance.
2. Formula for temperature change: $R_2 = R_1 [1 + \alpha (T_2 - 75)]$ where $\alpha_{cu} = 0.00323$, $\alpha_{AL} = 0.00330$ at 75°C.

Temperature Effect on Resistance

As per Table 8 – Note 2:

Conductor resistance at operating temperatures other than 75°C may be determined by:

$$R_2 = R_1 \cdot \left[1 + \alpha \cdot \left(T_2 - 75\right)\right]$$

where: R_1 **is the resistance at 75°C (provided by Table 8),**

R_2 **is the resistance at operating temp T_2,**

T_2 **is the operating conductor temp, and**

α **is the conductor material's temperature coefficient (α_{cu} = 0.00323 and α_{al} = 0.00330)**

DC Conductor Resistance Example

<u>Example</u> – determine the DC resistance (Ω/kFt) of a 500kcmil, copper conductor at a 90°C operating temperature.

As per Table 8, the DC resistance at 75°C is:

$$R_1 = 0.0258\ \Omega/kft.$$

Remember that "normal" copper wire is "Uncoated"

Table 8 Conductor Properties

			Conductors							Direct-Current Resistance at 75°C (167°F)					
			Stranding			Overall				Copper					
Size (AWG or kcmil)	Area			Diameter		Diameter		Area		Uncoated		Coated		Aluminum	
	mm^2	Circular mils	Quantity	mm	in.	mm	in.	mm^2	$in.^2$	ohm/ km	ohm/ kFT	ohm/ km	ohm/ kFT	ohm/ km	ohm/ kFT
400	203	—	37	2.64	0.104	18.49	0.728	268	0.416	0.1053	0.0321	0.1084	0.0331	0.1737	0.0529
500	253	—	37	2.95	0.116	20.65	0.813	336	0.519	0.0845	0.0258	0.0869	0.0265	0.1391	0.0424
600	304	—	61	2.52	0.099	22.68	0.893	404	0.626	0.0704	0.0214	0.0732	0.0223	0.1159	0.0353

DC Conductor Resistance Example

<u>Example</u> – determine the DC resistance (Ω/kFt) of a 500kcmil, copper conductor at a 90°C operating temperature.

As per Table 8, the DC resistance at 75°C is:

$$R_1 = 0.0258\ \Omega/kft.$$

Using α_{cu} = 0.00323, the resistance adjusted for 90°C is:

$$R_2 = R_1 \cdot [1 + \alpha \cdot (T_2 - T_1)] = 0.0258 \cdot [1 + 0.00323 \cdot (90 - 75)]$$

$$= 0.0258 \cdot [1 + 0.04845] = \boxed{0.02705\ \Omega/kFt}$$

roughly a 5% increase from 75°C to 90°C

Table 9 - AC Resistance/Reactance

Table 9 provides <u>AC resistance and reactance</u> information for both copper and aluminum conductors based on conductor type and size, and the type of conduit used for the raceway.

Table 9 AC Resistance and Reactance for 600-Volt Cables, 3-Phase, 60 Hz, 75°C (167°F) – Three Single Conductors in Conduit

Size (AWG or kcmil)	Ohms to Neutral per Kilometer / Ohms to Neutral per 1000 Feet: X_L (Reactance) for All Wires		AC Resistance for Copper Wires			AC Resistance for Aluminum Wires			Effective Z at 0.85 *PF* for Copper Wires			Effective Z at 0.85 *PF* for Aluminum Wires			(AWG or kcmil)
	PVC, Aluminum Conduits	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	
12	0.177 0.054	0.223 0.068	6.6 2.0	6.6 2.0	6.6 2.0	10.5 3.2	10.5 3.2	10.5 3.2	5.6 1.7	5.6 1.7	5.6 1.7	9.2 2.8	9.2 2.8	9.2 2.8	12
10	0.164 0.050	0.207 0.063	3.9 1.2	3.9 1.2	3.9 1.2	6.6 2.0	6.6 2.0	6.6 2.0	3.6 1.1	3.6 1.1	3.6 1.1	5.9 1.8	5.9 1.8	5.9 1.8	10
8	0.171 0.052	0.213 0.065	2.56 0.78	2.56 0.78	2.56 0.78	4.3 1.3	4.3 1.3	4.3 1.3	2.26 0.69	2.26 0.69	2.30 0.70	3.6 1.1	3.6 1.1	3.6 1.1	8
6	0.167 0.051	0.210 0.064	1.61 0.49	1.61 0.49	1.61 0.49	2.66 0.81	2.66 0.81	2.66 0.81	1.44 0.44	1.48 0.45	1.48 0.45	2.33 0.71	2.36 0.72	2.36 0.72	6
4	0.157 0.048	0.197 0.060	1.02 0.31	1.02 0.31	1.02 0.31	1.67 0.51	1.67 0.51	1.67 0.51	0.95 0.29	0.95 0.29	0.98 0.30	1.51 0.46	1.51 0.46	1.51 0.46	4
3	0.154 0.047	0.194 0.059	0.82 0.25	0.82 0.25	0.82 0.25	1.31 0.40	1.35 0.41	1.31 0.40	0.75 0.23	0.79 0.24	0.79 0.24	1.21 0.37	1.21 0.37	1.21 0.37	3
2	0.148 0.045	0.187 0.057	0.62 0.19	0.66 0.20	0.66 0.20	1.05 0.32	1.05 0.32	1.05 0.32	0.62 0.19	0.62 0.19	0.66 0.20	0.98 0.30	0.98 0.30	0.98 0.30	2
1	0.151 0.046	0.187 0.057	0.49 0.15	0.52 0.16	0.52 0.16	0.82 0.25	0.85 0.26	0.82 0.25	0.52 0.16	0.52 0.16	0.52 0.16	0.79 0.24	0.79 0.24	0.82 0.25	1

Note that the actual table states "Uncoated Copper" wires instead of "Copper Wires"

- NEC 2014, Chapter 9 – "Tables", Table 9 – "AC Resistance & Reactance"

Table 9 - AC Resistance/Reactance

Table 9 provides <u>AC resistance and reactance</u> information for both copper and aluminum conductors based on conductor type and size, and the type of conduit used for the raceway.

The resistance and reactance values provided by Table 9 are based on 600V, UL-Type RHH wires with Class B stranding, in cradled configuration, utilized in 3Φ, 60Hz circuits that are composed of three single conductors in conduit at 75°C.

Despite this limitation, the values provided are representative of other 600V conductors operating at 60Hz and 75°C.

Table 9 - AC Resistance/Reactance

Although the AC <u>resistance values</u> provided within Table 9 are based on a 75°C temperature, the values can be adjusted for temperatures other than 75°C in the same manner as the DC resistances provided by Table 8.

$$R_2 = R_1 \cdot [1 + \alpha \cdot (T_2 - 75)]$$

Note that the <u>reactance values</u> provided within Table 9 are <u>independent of temperature</u>, and thus do NOT need to be adjusted for temperatures other than 75°C.

AC Conductor Impedance Example

Determine the AC <u>resistance</u> and <u>reactance</u> in Ω/kFt of a set of 3Φ, 600V, 500kcmil, <u>copper conductors</u> with a 75°C rating if they are enclosed in <u>aluminum conduit</u>.

As per Table 9, the resistance/reactance at 75°C is:

$$R = 0.032\ \Omega/kft \qquad X = 0.039\ \Omega/kft$$

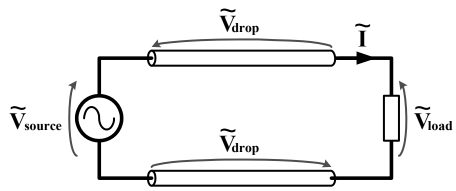
Table 9 AC Resistance and Reactance for 600-Volt Cables, 3-Phase, 60 Hz, 75°C (167°F) – Three Single Conductors in Conduit

Size (AWG or kcmil)	Ohms to Neutral per Kilometer / Ohms to Neutral per 1000 Feet															(AWG or kcmil)
	X_L (Reactance) for All Wires		AC Resistance for Copper Wires			AC Resistance for Aluminum Wires			Effective Z at 0.85 PF for Copper Wires			Effective Z at 0.85 PF for Aluminum Wires				
	PVC, Aluminum Conduits	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit		
300	0.135 0.041	0.167 0.051	0.144 0.044	0.161 0.049	0.148 0.045	0.233 0.071	0.249 0.076	0.236 0.072	0.194 0.059	0.207 0.063	0.213 0.065	0.269 0.082	0.282 0.086	0.289 0.088		300
400	0.131 0.040	0.161 0.049	0.108 0.033	0.125 0.038	0.115 0.035	0.177 0.054	0.194 0.059	0.180 0.055	0.161 0.049	0.174 0.053	0.184 0.056	0.217 0.066	0.233 0.071	0.240 0.073		400
500	0.128 0.039	0.157 0.048	0.089 0.027	0.105 0.032	0.095 0.029	0.141 0.043	0.157 0.048	0.148 0.045	0.141 0.043	0.157 0.048	0.164 0.050	0.187 0.057	0.200 0.061	0.210 0.064		500

Calculating Voltage Drop

Although the magnitude of the AC voltage drop that occurs across a conductor is a function of the conductor impedance and the magnitude of the conductor current, the <u>impact</u> of voltage drop on a system's overall operational voltages is a function of both the <u>magnitude and phase angle</u> of the conductor currents.

$$\tilde{V}_{load} = \tilde{V}_{source} - 2 \cdot \tilde{V}_{drop} = \tilde{V}_{source} - 2 \cdot \tilde{I} \cdot Z_{conductor}$$



A steady-state phasor analysis of the circuit requires the use of complex numbers during the calculations.

Calculating Voltage Drop

Given a 277V, 1Φ source supplying a load through a pair of 130ft, #2 AWG, copper conductors in PVC conduit, determine the load voltage if:

a) I_{load} = 110A @ pf = 1.0

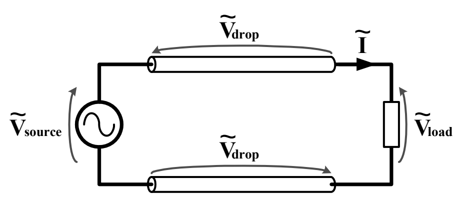
$$\tilde{I} = 110\angle 0° \text{ amps}$$

$$\begin{aligned}\tilde{V}_{load} &= \tilde{V}_{source} - 2 \cdot \tilde{I} \cdot Z_{cond} \\ &= 277\angle 0° - 2 \cdot (110\angle 0°) \cdot (0.0247 + j0.00585) \\ &= 277\angle 0° - 5.58\angle 13.3° \\ &= \boxed{271.6\angle 0.27° \text{ volts}}\end{aligned}$$

b) I_{load} = 110A @ pf = 0.7 lagging

$$\tilde{I} = 110\angle -45.6° \text{ amps}$$

$$\begin{aligned}\tilde{V}_{load} &= \tilde{V}_{source} - 2 \cdot \tilde{I} \cdot Z_{cond} \\ &= 277\angle 0° - 2 \cdot (110\angle -45.6°) \cdot (0.0247 + j0.00585) \\ &= 277\angle 0° - 5.58\angle -32.3° \\ &= \boxed{272.3\angle 0.63° \text{ volts}}\end{aligned}$$



130ft, #2 AWG, copper in PVC:
R = 0.19 Ω/kFt X = 0.045 Ω/kFt
Z = (R + jX)·(0.130kFt)
= (0.0247 + j0.00585) Ω

Effective Impedance

Table 9 also provides an <u>Effective Impedance</u> (*Ze*) for the conductors, both in Ω/km and Ω/kFt, based on a *0.85 lagging* operational power-factor.

The Effective Impedance value provides a simple method for calculating the voltage-drop that will occur in a circuit without the use of "complex number" mathematics.

Effective Impedance

Note that for power factors other than 0.85 lagging, the effective impedance may be calculated using a formula provided in the FPNs for Table 9:

$$Z_e = R \cdot \cos\theta + X \cdot \sin\theta$$

where: R is the conductor resistance (Ω/length),
X is the conductor reactance (Ω/length), and
cosθ is power factor of the load supplied by the circuit.

Note that sinθ may be determined from:

$$\theta = \cos^{-1}(pf)$$

θ is positive for lagging pf
θ is negative for leading pf

Voltage Drop Across a Conductor

Voltage Drop from Effective Impedance – the voltage drop across a conductor may be calculated by:

$$V_{drop} = I \cdot Ze$$

where: I is the magnitude of the line current flowing in the conductor, and

Z_e is the effective impedance of the conductor in ohms.

Thus, the operating voltage at the load-end of a circuit will be:

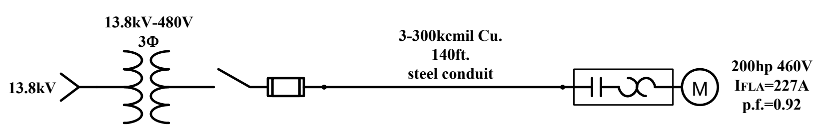
1Φ circuits

$$\tilde{V}_{load} = \tilde{V}_{source} - 2 \cdot \tilde{V}_{drop}$$

3Φ circuits

$$\tilde{V}_{load(line)} = \tilde{V}_{source(line)} - \sqrt{3} \cdot \tilde{V}_{drop}$$

Voltage Drop Example

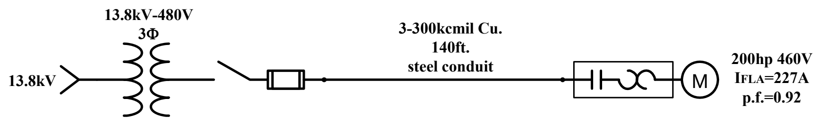


Determine the Operational Line-Voltage seen at the terminals of the motor when the motor is drawing rated current at a power factor of 0.92 lagging, assuming rated line-voltage at the secondary terminals of the transformer.

Notes – assume a 60°C conductor temperature.

– ignore the switch, the fuse, and the overload relay when calculating voltage drop.

Voltage Drop Example

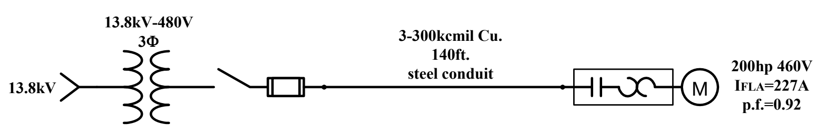


Step 1 – Determine the Impedance Characteristics of the circuit conductors.

Table 9 AC Resistance and Reactance for 600-Volt Cables, 3-Phase, 60 Hz, 75°C (167°F) – Three Single Conductors in Conduit

Size (AWG or kcmil)	Ohms to Neutral per Kilometer / Ohms to Neutral per 1000 Feet															(AWG or kcmil)
	X_L (Reactance) for All Wires		AC Resistance for Copper Wires			AC Resistance for Aluminum Wires			Effective Z at 0.85 *PF* for Copper Wires			Effective Z at 0.85 *PF* for Aluminum Wires				
	PVC, Aluminum Conduits	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit		
300	0.135 0.041	0.167 0.051	0.144 0.044	0.161 0.049	0.148 0.045	0.233 0.071	0.249 0.076	0.236 0.072	0.194 0.059	0.207 0.063	0.213 0.065	0.269 0.082	0.282 0.086	0.289 0.088		300
400	0.131 0.040	0.161 0.049	0.108 0.033	0.125 0.038	0.115 0.035	0.177 0.054	0.194 0.059	0.180 0.055	0.161 0.049	0.174 0.053	0.184 0.056	0.217 0.066	0.233 0.071	0.240 0.073		400
500	0.128 0.039	0.157 0.048	0.089 0.027	0.105 0.032	0.095 0.029	0.141 0.043	0.157 0.048	0.148 0.045	0.141 0.043	0.157 0.048	0.164 0.050	0.187 0.057	0.200 0.061	0.210 0.064		500

Voltage Drop Example



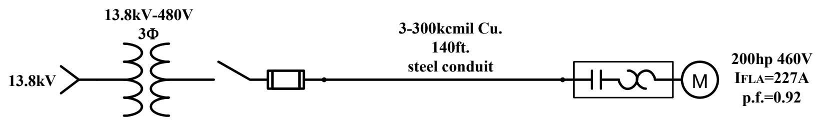
Step 1 – Determine the Impedance Characteristics of the circuit conductors.

From NEC Table 9:

R = 0.045 (Ω/kft) (at 75°C)

X = 0.051 (Ω/kft)

Voltage Drop Example



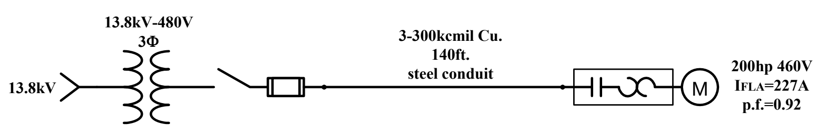
Step 1 – Determine the <u>Impedance Characteristics</u> of the circuit conductors.

Adjust the resistance for 60°C (R$_{75°C}$ = 0.045)

$$R_2 = R_1 \cdot [1 + \alpha \cdot (T_2 - T_1)] = 0.045 \cdot [1 + 0.00323 \cdot (60 - 75)]$$
$$= 0.045 \cdot [1 - 0.04845] = 0.045 \cdot [0.95155] = 0.04282 \, \Omega/kft.$$

Note – the reactance is unaffected by temperature.

Voltage Drop Example



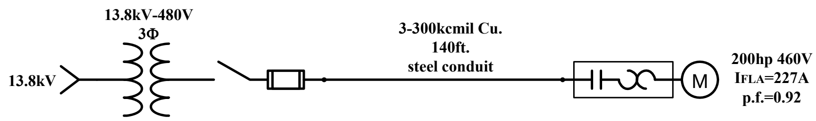
Step 1 – Determine the <u>Impedance Characteristics</u> of the circuit conductors.

Conductor Impedance Values at 60°C:

R = 0.04282 (Ω/kft)

X = 0.051 (Ω/kft)

Voltage Drop Example



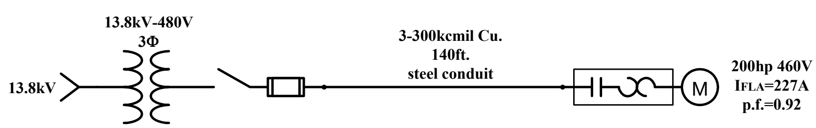
Step 2 – Determine the <u>Effective Impedance</u> of the circuit conductors.

Since the p.f. of the load ≠ 0.85, the effective impedance must be calculated using:

$$Ze = R \cdot \cos\theta + X \cdot \sin\theta$$

which is a function of the operating power factor of the circuit.

Voltage Drop Example



Step 2 – Determine the <u>Effective Impedance</u> of the circuit conductors.

$$Ze = R \cdot \cos\theta + X \cdot \sin\theta$$

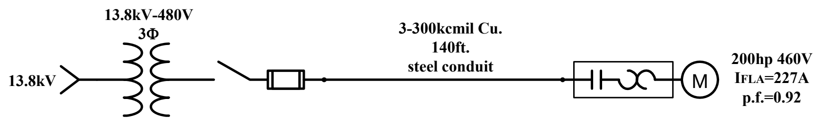
Solving for sinθ:

$$\theta = \cos^{-1}(pf) = \cos^{-1}(0.92) = +23.074°$$

$$\sin\theta = \sin(23.074°) = 0.392$$

Note that θ is "positive" since the power factor is "lagging".

Voltage Drop Example

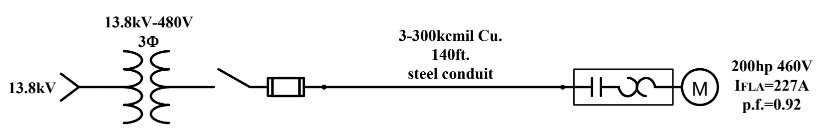


Step 2 – Determine the <u>Effective Impedance</u> of the circuit conductors.

Thus, given R = 0.04282 and X = 0.051, the effective impedance in Ω/kFt is:

$$Ze = R \cdot \cos\theta + X \cdot \sin\theta$$
$$= (0.04282)\cdot(0.92) + (0.051)\cdot(0.392)$$
$$= 0.0394 + 0.02 = 0.0594 \,\Omega/kft.$$

Voltage Drop Example

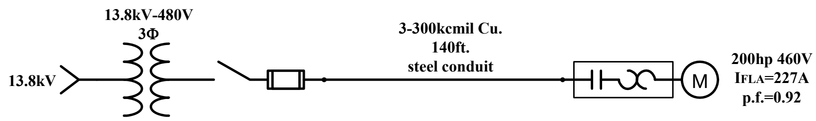


Step 2 – Determine the <u>Effective Impedance</u> of the circuit conductors.

Taking into account the length of the circuit, the effective impedance in Ω is:

$$Ze = 0.0394 + 0.02 = 0.0594 \,\Omega/kft \cdot \frac{140\, ft}{1000\, ft/kft} = 0.008316\Omega$$

Voltage Drop Example

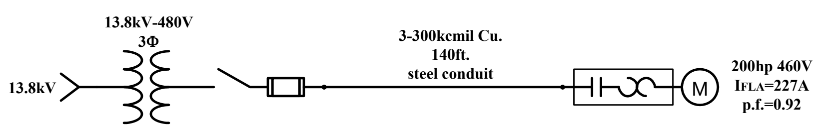


Step 3 – Determine the <u>Voltage Drop</u> across each conductor due to the line current.

$$V_{drop} = I \cdot Ze = (227A) \cdot (0.008316\Omega) = 1.888V$$

Note that this is the per-conductor voltage drop, which relates to a per-phase (line-neutral) voltage drop.

Voltage Drop Example



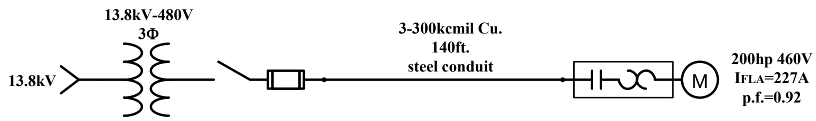
Step 4 – Determine the <u>Line-Voltage</u> at the motor's terminals.

Since the calculated voltage drop relates to a decrease in the phase voltage magnitude,

$$V_{drop(phase)} = 1.888V$$

the line voltage will experience a $\sqrt{3}x$ greater decrease in magnitude.

Voltage Drop Example



Step 4 – Determine the <u>Line-Voltage</u> at the motor's terminals.

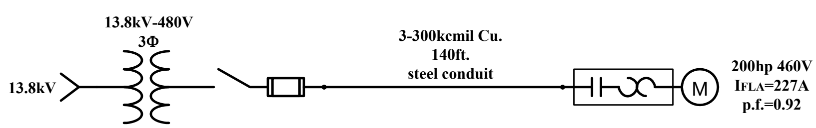
Thus:

$$V_{drop(Line)} = \sqrt{3} \cdot V_{drop(phase)} = \sqrt{3} \cdot (1.888\,V) = 3.27\,V$$

resulting in a motor-terminal line-voltage:

$$V_{line(load-end)} = V_{line(service-end)} - V_{drop(Line)} = 480 - 3.27 = 476.7\,V$$

Voltage Drop Example



Step 4 – Determine the <u>Line-Voltage</u> at the motor's terminals.

Note that a 3.27*V* drop in the line-voltage magnitude from 480*V* to 476.7*V* relates to a 0.68% decrease.

This value is well below the 3% limit suggested by Informational Note 4 of Article 210.19(A).