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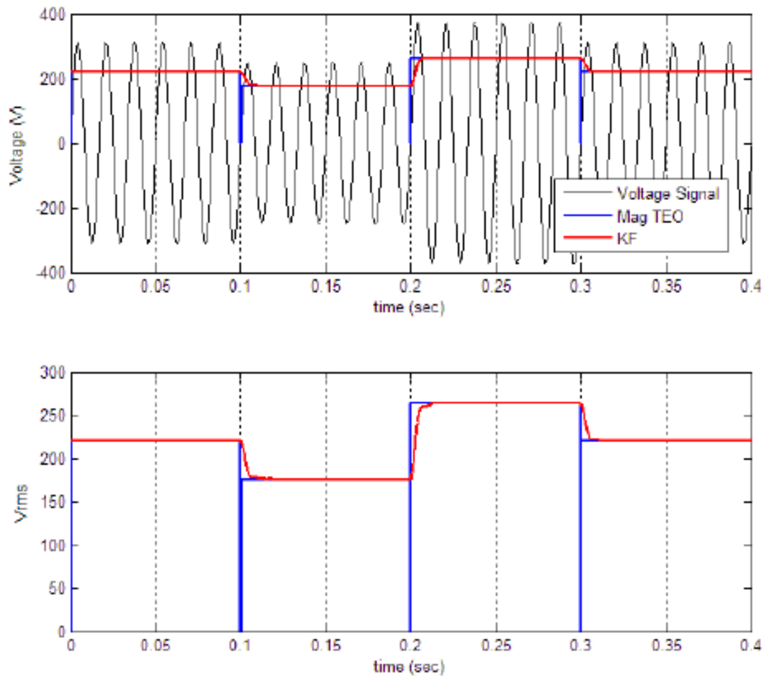
Power Distribution Systems

Lecture 6

Voltage Drop

Introduction

For satisfactory operation of motors, lamps and other electrical loads, it is desirable that consumers are supplied with substantially constant voltage. Too wide variations of voltage may cause unstable operation or even malfunctioning of consumers' appliances.



Voltage Definitions

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Nominal Voltage: This is the voltage *by which the system* is designated, e.g. 120/208 V, 220/380 V, 240/415 V, etc.

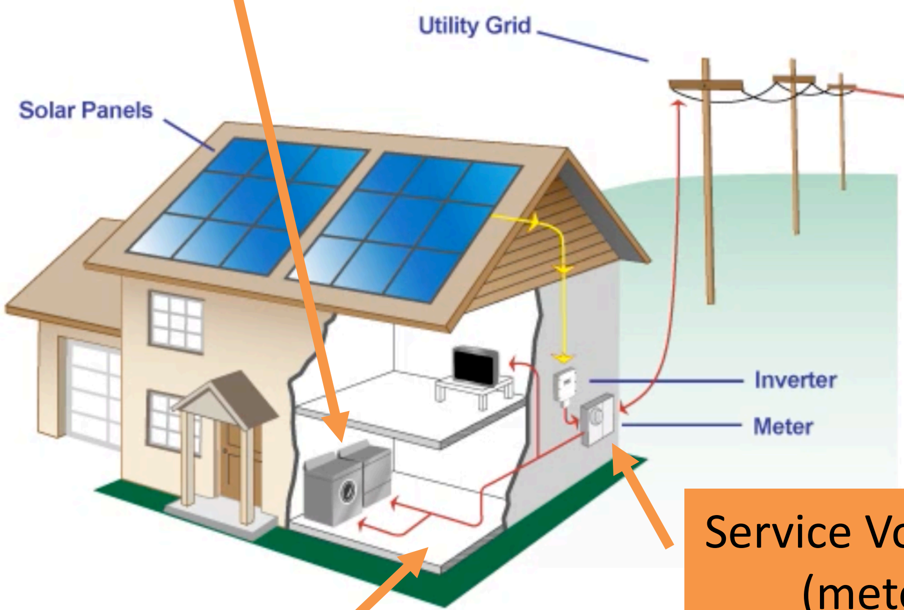
Rated Voltage: This is the nameplate voltage and it is the voltage at which the *equipment* is designed to operate for optimal performance. The rated voltage of the equipment is under the responsibility if manufacturers.

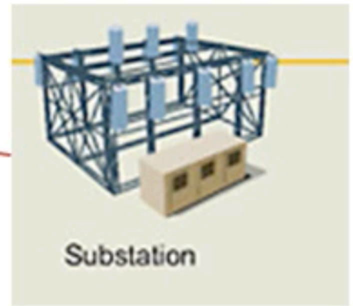
Service Voltage: This is the voltage at the point where the electrical of the supplier and the user are interconnected. *This is normally at the meter*. Maintaining an acceptable voltage at the service entrance is the utility's responsibility.

Utilization Voltage: This is the voltage *at the line terminals of utilization equipment.* It is less than the service voltage by the amount of voltage drop in the facility from service point to the utilization point. This voltage is the facility's responsibility.

Voltage Definitions

Rated Voltage (equipment)	Manufacturer Responsibility





Service Voltage (meter)

Nominal Voltage (system)

Utilization Voltage (plugs)	Facility Responsibility

Utility Responsibility

Voltage Limits

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The voltage limits are specified in prevailing standards in use, e.g. IEC, ANSI, etc.

In the European Union, the nominal low voltages are now 230/400V with a tolerance range of ±10% (±5% for rotating electrical equipment). The ±10% limits set the voltage at 253/440V maximum and 207/360V minimum.

In Turkiye, the nominal low voltages are 220/380V with a tolerance range of ±10%. In that case the maximum voltages are 242/418V and the minimum voltages are 198/342V.

IEC

ANSI
American National Standards Institute

Voltage Drop Calculations

Voltage drop has effect on performance and efficiency of some load operations. An excessive voltage drop in an electrical circuit can result in electrical equipment on the circuit running unsatisfactorily.

Some examples;

- 1% voltage drop can lead to reduction in tungsten lamp illumination by 3%
- Some home appliances which are operated by motors can be affected by reduction in voltage
- Some loads demand same power under any voltage level. Thus, reduction in voltage level will be accompanied by rise in current level.

  It means that if the voltage drops 10%, the current increases 10%. This may causes the equipment failure due to gradual temperature rise on the long run.

Voltage drop is also used to determine the conductor sizing.

Voltage Drop Calculation in Radial Feeder

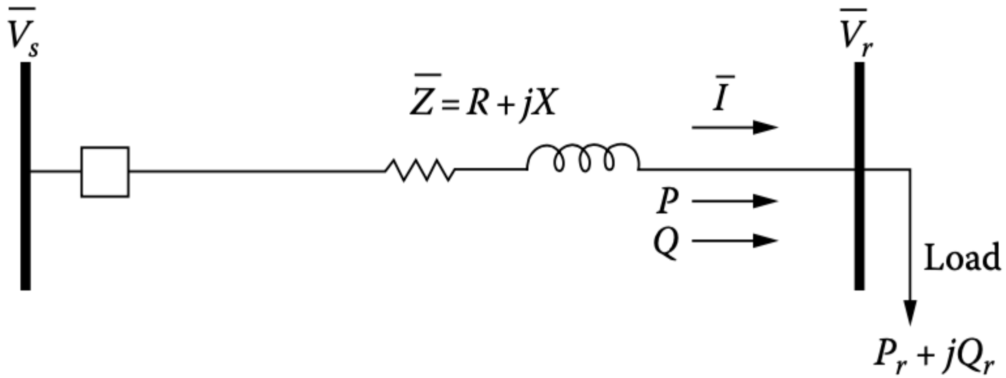
A line-to-neutral equivalent circuit of a three-phase line segment serving a balanced three-phase load is shown below.

Taking the receiving-end voltage as the reference phasor,

$$\overline{V}_r = V_r \angle 0°$$

From P_r+jQ_r , phase angle θ_l between V_r and I can be calculated.

$\theta_l = \tan^{-1}(Q_r/P_r)$



p.s. If Q_r is +, load is inductive meaning lagging power factor
If Q_r is -, +, load is capacitive meaning leading power factor

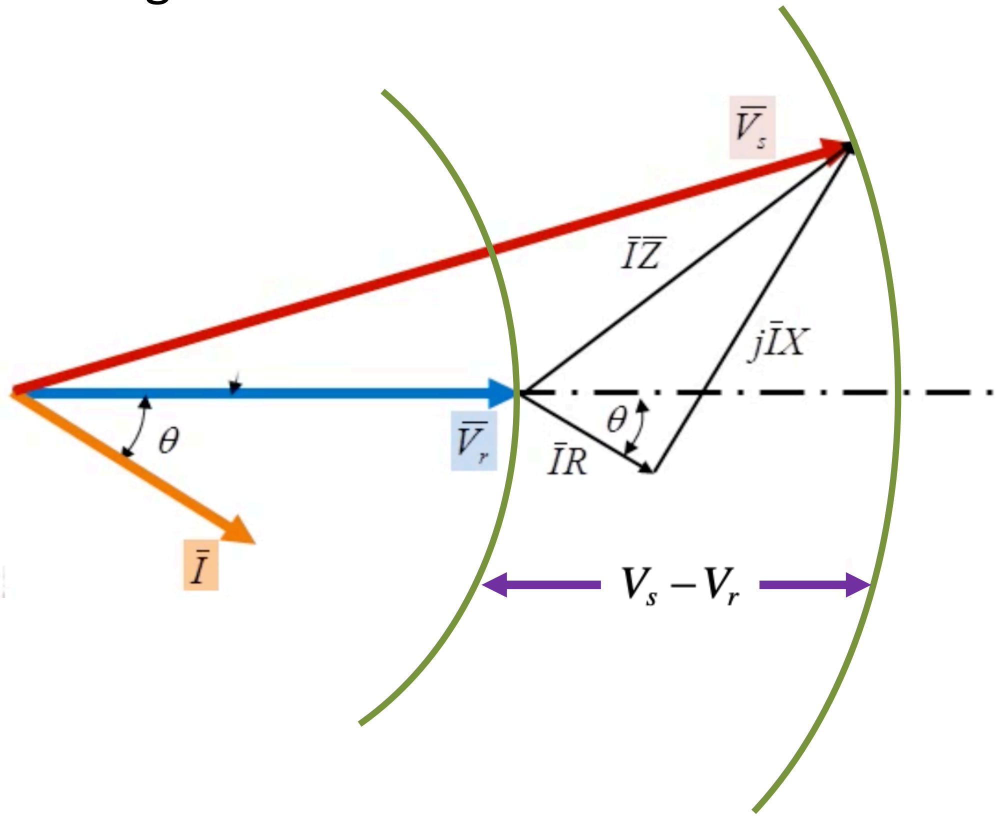
Voltage Drop Calculation in Radial Feeder

From phasor diagram, the sending-end voltage

$$\bar{V}_s = V_s \angle\delta$$

The per unit voltage regulation is defi

$$\mathrm{VR}_{\mathrm{pu}} \triangleq \frac{V_s - V_r}{V_r} \qquad V_s - V_r$$



The percent voltage regulation is

$$\mathrm{VR}_{\mathrm{pu}} = \frac{V_s - V_r}{V_r} \times 100$$

or

$$\%\mathrm{VR} = \mathrm{VR}_{\mathrm{pu}} \times 100$$

Voltage Drop Calculation in Radial Feeder

The per unit voltage drop is defined as

$$\mathrm{VD}_{\mathrm{pu}} \triangleq \frac{V_s - V_r}{V_B}$$

where V_B is normally selected to be V_r

The percent voltage drop is

$$\%\mathrm{VD} = \frac{V_s - V_r}{V_B} \times 100$$

or

$$\%\mathrm{VD} = \mathrm{VD}_{\mathrm{pu}} \times 100$$

where V_B is the arbitrary base voltage.

Voltage Drop Calculation in Radial Feeder

The sending-end voltage is

$$\bar{V}_s = V_r + \overline{IZ} \qquad \text{or} \qquad V_s = (\cos\delta + j\sin\delta) = V_r\angle 0° + I(\cos\theta - j\sin\theta)(R + jX)$$

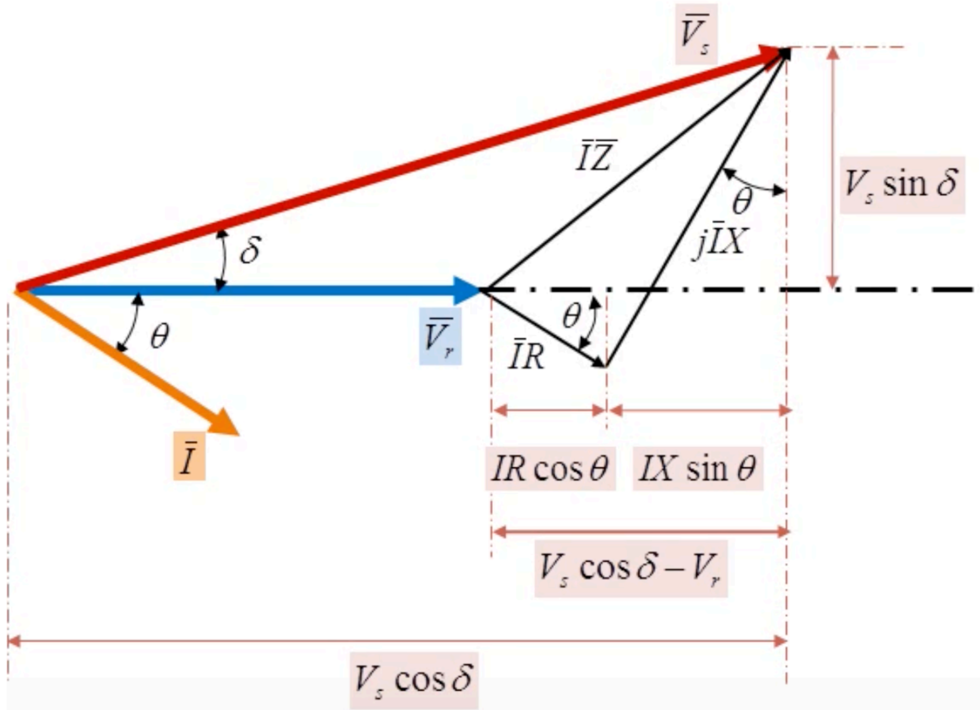
In typical *distribution* circuits,

$$R \cong X$$

and the voltage angle δ is typically

$$0° \le \delta \le 4°$$

Therefore, for a typical *distribution* circuit, the sin δ can be neglected



Thus,

$$V_s \cong V_s \cos\delta$$

$$V_s \cong V_r + IR\cos\theta + IX\sin\theta$$

The voltage drop between the source and load is approximately equal to the real part of the impedance drop.

$$V_{drop} \cong \mathrm{Re}(Z \cdot I) \qquad \mathrm{VD_{pu}} = \frac{IR\cos\theta + IX\sin\theta}{V_B}$$

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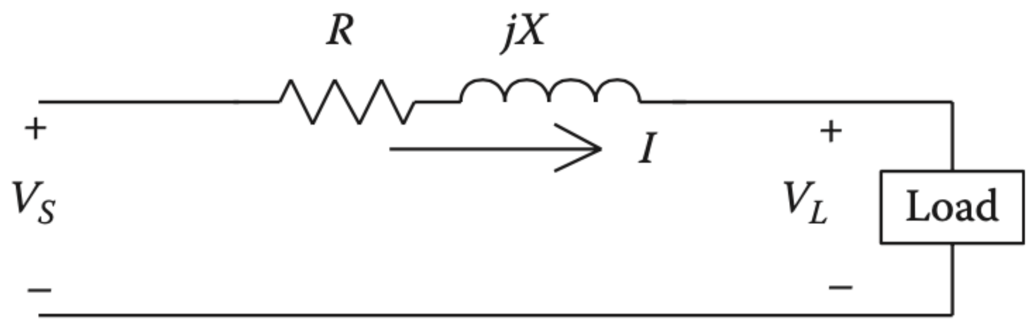
Example 6.1

In the following system, the impedance of the line is Z=0.2841+j0.5682Ω, The current flowing through the line is I_{12}=43.0093$\angle -25.8419$ A, the sending-end voltage is V_s =2400$\angle 0$ V. Calculate the difference between exact voltage drop and approximate voltage drop.



K factor

The complex power at the receiving end is

$\bar{S}_r = P_r + jQ_r = \bar{V}_r \bar{I}^*$ (vectoral) $S_r = V_r I$ (absolute value)

$I = S_r / V_r$

Substituting current I into voltage drop $\mathrm{VD_{pu}} = \dfrac{IR\cos\theta + IX\sin\theta}{V_B}$

$$\mathrm{VD_{pu}} \cong \frac{(S_r/V_r)R\cos\theta + (S_r/V_r)X\sin\theta}{V_B}$$

$$\mathrm{VD_{pu}} \cong \frac{S_r \times R\cos\theta + S_r \times X\sin\theta}{V_r V_B}$$

$$\mathrm{VD_{pu}} \cong \frac{RP_r + XQ_r}{V_r V_B}$$

K factor

The voltage drop can be written in the following form

$$\mathrm{VD_{pu}} \cong \frac{S_r \times R\cos\theta + S_r \times X\sin\theta}{V_r V_B} \approx \frac{S_{3\phi} \times l_{eff}\left(r\cos\theta + x\sin\theta\right)\times\left(\frac{1}{3}\times 1000\right)}{V_B^2} \qquad (V_r \approx V_B)$$

$$VD_{pu} \approx K S_{3\phi} l_{eff} \qquad K = \frac{\left(r\cos\theta + x\sin\theta\right)\times\left(\frac{1}{3}\times 1000\right)}{V_B^2}$$

where

K is the parameter in pu voltage drop per kVA-km

l_{eff} is effective length in km (for concentrated load, l_{eff} is *length of line; for distributed load,* l_{eff} is *half of the length of line)*

$S_{3\phi}$ is three-phase power in kVA

r & x are resistance and inductive reactance parameters in Ω/km

K factor

Cable manufacturers provide tables of voltage drop factors K for their cables.

The unit K provided in some of these tables is V/A/km or V/A/m

$$K = \frac{\Delta V}{I.L}$$

conductor size (mm^2)	K value					
	2 cores		3 cores		3 cores (trefoil format.)	
	cos ϕ =1	cos ϕ = 0.8	cos ϕ =1	cos ϕ = 0.8	cos ϕ =1	cos ϕ = 0.8
1	45.00	36.100	39.000	31.300	38.300	30.800
1.5	30.20	24.300	26.100	21.000	25.700	20.700
2.5	18.20	14.700	15.700	12.700	15.400	12.500
4	11.4	9.210	9.850	7.980	9.650	7.870
6	7.56	6.160	6.540	5.340	6.420	5.280
10	4.55	3.730	3.940	3.240	3.870	3.220
16	2.87	2.390	2.480	2.070	2.440	2.070
25	1.81	1.550	1.570	1.340	1.540	1.340
35	1.31	1.140	1.130	0.988	1.110	0.993
50	0.967	0.866	0.838	0.750	0.820	0.760
70	0.669	0.624	0.579	0.541	0.568	0.555
95	0.484	0.476	0.419	0.412	0.410	0.428

K factor

The voltage drop can be written in the following form

$$\mathrm{VD}_{\mathrm{pu}} \cong \frac{S_r \times R\cos\theta + S_r \times X\sin\theta}{V_r V_B} \approx \frac{S_{3\phi} \times l_{eff}\left(r\cos\theta + x\sin\theta\right) \times \left(\frac{1}{3} \times 1000\right)}{V_B^2} \qquad (V_r \approx V_B)$$

$$VD_{pu} \approx K S_{3\phi} l_{eff}$$

$$K = \frac{\left(r\cos\theta + x\sin\theta\right) \times \left(\frac{1}{3} \times 1000\right)}{V_B^2}$$

where

K is the parameter in pu voltage drop per kVA-km

l_{eff} is effective length in km (for concentrated load, l_{eff} is *length of line; for distributed load,* l_{eff} is *half of the length of line)*

$S_{3\phi}$ is three-phase power in kVA

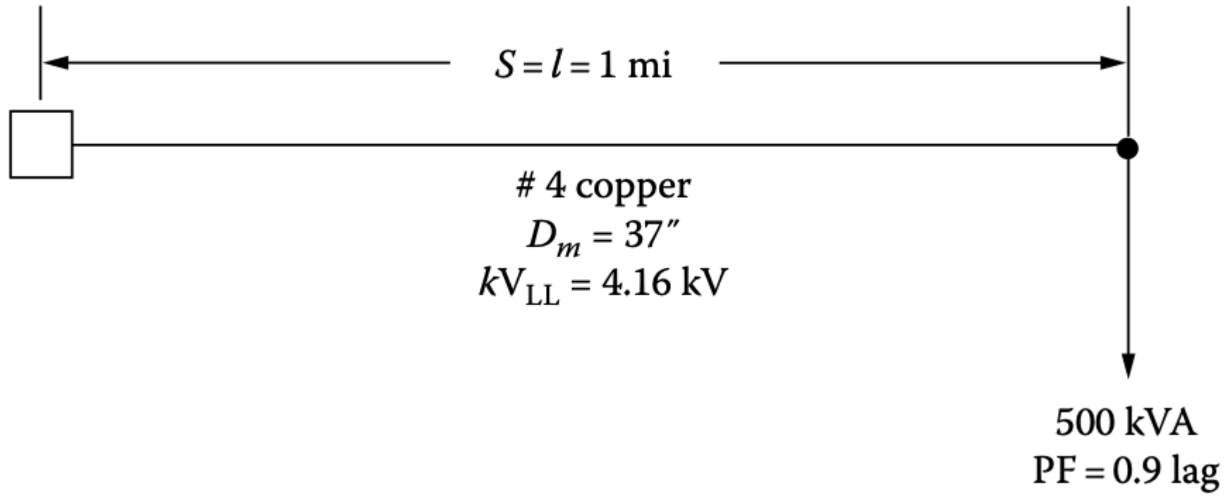
r & x are resistance and inductive reactance parameters in Ω/km

Example 6.2

Assume that a three-phase 4.16 kV wye-grounded feeder main has four copper conductors with z= 1.503=j 0.7456 Ω/mi and a lagging-load power factor of 0.9. Determine the *K* factor of the main.

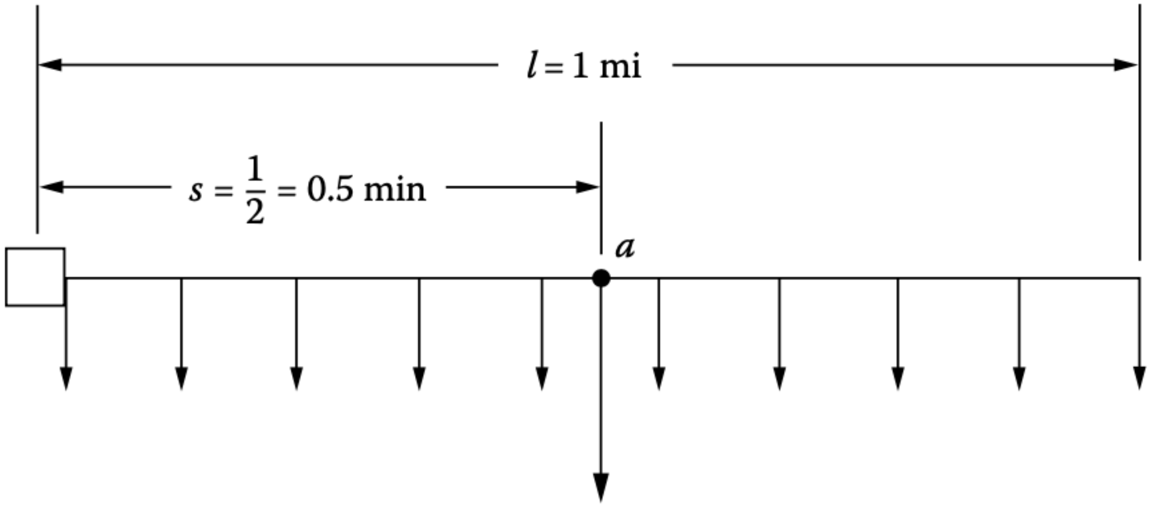
Example 6.3

Assume that the feeder shown in following figure has the same characteristics as the one in Example 6.2, and a concentrated load of 500 kVA with a lagging-load power factor of 0.9 is connected at the end of a 1 mi long feeder main. Calculate the percent voltage drop in the main.



Example 6.4

Assume that the feeder shown in the figure below has the same characteristics as the one in Example 6.3, but the 500 kVA load is uniformly distributed along the feeder main. Calculate the percent voltage drop in the main.



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Example 6.5

A three-segment feeder is shown in the following figure. The *K* factor for the line segments is *K* = 0.00035291. Determine the percent voltage drop from N0 to N3.