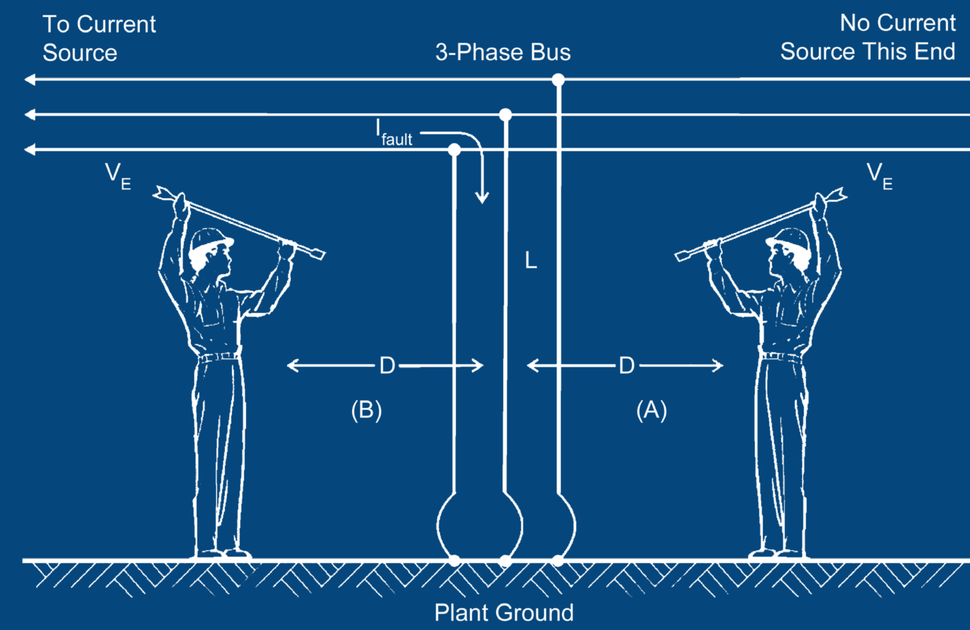
Temporary Protective Ground Cable Impedance
K-Factors for Predicting Worker Touch Voltage

RECLAMATION

Managing Water in the West

Temporary Protective Ground Cable Impedance K-Factors for Predicting Worker Touch Voltage



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Preface

The Institute of Electrical and Electronics Engineers Standard No. 1246-2011™, *IEEE Guide for Temporary Protective Grounding Systems Used in Substations* (IEEE 1246) provides a method to predict worker touch voltage at grounded worksites in high voltage, alternating current substations using impedance correction K-factors for temporary protective grounds (TPG). This book provides supportive information for the grounding models and derivations of TPG impedance equations presented in IEEE 1246. Chapter 1 introduces the reactive voltage drop principle that occurs on TPG. Chapter 2 develops the ground loop induction formulas for a basic single-phase TPG grounding scenario. Chapter 3 expands the use of the K-factor to practical single- and three-phase substation bus examples. Chapter 4 develops the K-factor for bracket TPG grounding scenarios and Chapter 5 expands the use of K-factors referenced in the standard to power line TPG grounding scenarios.

This book's development is based on years of research performed by the Hydropower Diagnostics and SCADA Group and onsite testing performed at various Bureau of Reclamation and Western Area Power Administration facilities. Support and funding was provided through the Bureau of Reclamation Science and Technology Program.

The authors gratefully acknowledge the assistance of all who contributed to this research work.

Philip Atwater and James DeHaan

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Chapter 1

Introduction

The electric power industry has, for a long time, recognized the need for grounding deenergized, high voltage power lines and equipment for bare-hand contact during maintenance or construction activities. Grounding of the line or equipment conductors is typically accomplished by applying temporary protective grounds (TPG) according to the utility's procedure to create an equipotential safe work zone. However, in practice, the various conductive parts of the work zone are rarely at the same potential when an accidental reenergization occurs. This is due to voltage drops in the fault current carrying conductors, both TPG and the grounded equipment, which cannot be avoided.

As stated in the Institute of Electric and Electronic Engineers Standard No. 1246-2011 [1] (IEEE 1246), historically, the TPG cable resistance was placed in parallel with the worker's body to calculate current through the body during an accidental energization of a grounded worksite. The TPG cable resistive *(IR)* voltage drop resulting from the alternating current (ac) power system available short-circuit current was the key factor in determining worker touch voltage and body current. Recent modeling of grounded worksites, and laboratory and field testing (see IEEE 1246, Section 7, "Model Comparison With Field Test Data"), demonstrated that the TPG cable reactive *(IX)* voltage drop often is a significant component of the worker touch voltage and body current.

Grounded worksites inherently produce a reactive voltage drop (touch potential) when TPGs conduct ac short circuit current. Induction ground loops are typically formed by the TPGs, grounded line or equipment conductors, and a current return path between TPG and worker. The worker completes the ground loop circuit by touching a grounded conductor (intentionally grounded by TPG) and another grounded object at the worksite. The induction ground loop creates the reactive *IX* voltage drop exposure to the worker. The combined resistive and reactive voltage drops of a TPG cable can be several times higher than the resistive voltage drop alone.

Therefore, the TPG effective ac impedance (not only resistance) should be considered for realistic worker exposure evaluation. This situation led to the development of TPG composite impedance, which accounts for the physical layout of the TPGs at the grounded worksite. To simplify the calculation of the TPG impedance, the TPG impedance K-factors were introduced. The use of the K-factor to predict worker touch voltage modifies the historic method of calculating TPG resistive (IR) voltage drop by including the additional effects of reactive voltage drop of the TPG cable. Worker touch voltage may be approximated using the following equation:

$$Vt = If \times Rc \times K \qquad (0)$$

where

Vt	is the touch voltage, Vrms
If	is the available short-circuit current, kA rms sym.
Rc	is the TPG cable resistance (excluding clamps and ferrules), milliohm
K	is the TPG impedance multiplier

Application of K-factors for the worker touch voltage calculation procedure is covered in IEEE 1246. However, explanation of magnetic induction concepts and derivation of equations is limited, and additional explanation is provided in this book.

Chapter 2

Single-Phase TPG Grounding

Basic Single-Phase TPG Grounding Model

In the simplest grounding form, a single TPG conductor is shunted across a worker's body, as shown schematically in figure 1. The worker's body is represented by resistance R_w. The TPG conductor has resistance R_c. Induction ground loop *a,b,c,d* is formed with the TPG and worker and is assumed rectangular in shape in this example with TPG conductor length *L* and depth of ground loop *D* (distance from TPG to worker).

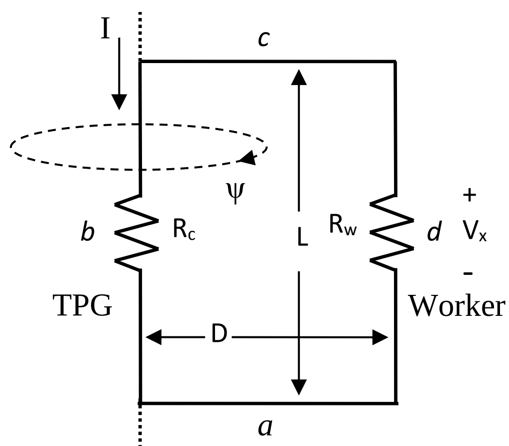


Figure 1. Electrical schematic of basic grounding model for single TPG shunting worker's body. The portion of magnetic flux ψ internal to closed loop *a,b,c,d* (defined $\psi_{s(d)}$) induces voltage V_X in contact with the worker.

Current *I* through the TPG (side *b*) creates magnetic flux ψ. Sides *a* and *c* connect the worker to either end of the TPG. Voltage V_x is induced in the loop from flux linkages $\psi_{s(d)}$, which penetrate (link with) the enclosed loop area. No current is assumed through the body (side *d*) because $R_w \gg Rc$. This assumption is justified because the body core resistance is approximately six orders of magnitude greater than the resistance of a typical TPG cable (1 kΩ versus 1 mΩ). Therefore, current through the worker side of the ground loop has a negligible effect in determining voltage induced in the loop.

Induced voltage V_X in figure 1 is equivalent to the *IX* reactive voltage drop of the TPG where *X* is the self-reactance of the TPG conductor out to distance *D*; defined $X_{s(d)}$. Self-reactance $X_{s(d)}$ can be found by treating the TPG and worker's body current paths as two parallel conductors of equal length *L* separated by distance *D*.

Figure 2 shows the same circuit of figure 1 looking parallel with the plane of the ground loop (side *c* above *a*).

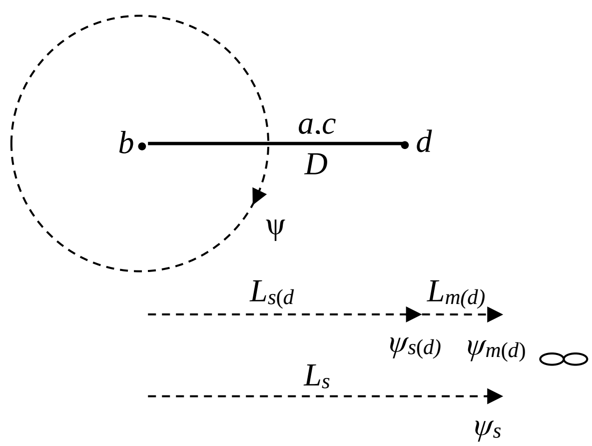


Figure 2. View of circuit in figure 1 from top, showing self- and mutual inductances of TPG conductor (point *b*) with worker position (point *d*).

Magnetic flux components ψ_s, $\psi_{s(d)}$, and $\psi_{m(d)}$ (all produced by current *I*) create the self- and mutual inductances depicted by the horizontal dashed vectors.

Inductance $L_{s(d)}$ is the TPG self-inductance out to distance *D* due to flux linkages $\psi_{s(d)}$. Mutual inductance $L_{m(d)}$ is created from flux linkages $\psi_{m(d)}$ beyond point *d*, which do not penetrate the area enclosed by the ground loop and, therefore, do not contribute to the voltage induced in the loop. The TPG self-inductance L_s results from the total flux linkages ψ_S with current *I*. Figure 2 shows that flux linkage $\psi_{s(d)}$ is equivalent to ψ_s minus $\psi_{m(d)}$; therefore:

$$L_{s(d)} = L_s - L_{m(d)} \tag{1}$$

Formulas for calculating self- and mutual inductances of equal length parallel conductors are straightforward from Grover [2] and are shown in equations (6) and (7) below.

Induced voltage V_X in figure 1 is the product of current and reactance ($I\,X_{s(d)}$) and leads the TPG current by 90 degrees. The total touch voltage V_t across the worker is, therefore, the phasor sum of the TPG conductor resistance and reactance voltage drops:

$$\widehat{V_t} = \hat{I}\left(R_C + 0.0003 + jX_{s(d)}\right) \tag{2}$$

where $X_{s(d)}$ is the self-reactance from $L_{s(d)}$, and *j* is the 90-degree phase shift operator. Note that an additional 0.3 milliohm is added with conductor resistance R_c in equation (2) to account for the resistance of the TPG cable clamps and ferrules at each end.

In scalar form:

$$V_t = I\sqrt{(R_C + 0.0003)^2 + X_{s(d)}^2} \tag{3}$$

where all values of resistance and reactance are in ohms, and current I is in amps.

Dividing both sides of equation (3) by current magnitude I gives an expression for the TPG composite impedance magnitude:

$$Z_g = {}^{V_t}/_{I} = \sqrt{(R_C + 0.0003)^2 + X_{s(d)}^2} \tag{4}$$

Finally, TPG composite impedance Z_g is normalized to the TPG conductor resistance by dividing by R_c. This is the defined TPG impedance correction K-factor, a dimensionless quantity. Therefore, for the TPG grounding configuration in figure 1, the expression for the TPG impedance correction K-factor is:

$$K = \frac{Z_g}{R_C} = \frac{\sqrt{(R_C+0.0003)^2+X_{s(d)}^2}}{R_C} \tag{5}$$

Formulas for the self-inductance of a single straight conductor and mutual inductance of two equal length parallel straight conductors are reprinted from Grover [2] in inductance unit of Henry.

$$L_s = 2L\left[ln\left(\frac{2L}{r}\right) - 0.75\right]x10^{-9} \quad \mathrm{H} \tag{6}$$

$$L_{m(d)} = 2L\left[ln\left(\frac{L}{d} + \sqrt{1+\left(\frac{L}{d}\right)^2}\right) - \sqrt{1+\left(\frac{d}{L}\right)^2} \quad + \frac{d}{L}\right]x10^{-9} \quad \mathrm{H} \tag{7}$$

where

L_s	=	self-inductance of single conductor out to infinite distance
$L_{m(d)}$	=	mutual inductance of parallel conductors separated by d
L	=	conductor length, centimeters (cm)

r = conductor radius, cm
d = distance between center of conductors, cm

Grover's formula in equation (7) quantifies mutual inductance due to *flux linkages common to both parallel conductors* (e.g., TPG and worker position) out to infinity, as shown in figure 2 for $\psi_{m(d)}$; *not the flux in the space between conductors*. However, flux linkages $\psi_{s(d)}$ bounded by the closed ground loop circuit of dimension D induce voltage V_x. By inspection of figure 2, flux linkages $\psi_{s(d)}$ are equivalent to ψ_s minus $\psi_{m(d)}$, making $L_{s(d)} = L_s - L_{m(d)}$. The above inductance formulae are based, in part, on a characteristic *1/d* relationship of magnetic flux density with radial distance from the current carrying conductor.

Therefore, for equations (3) through (5):

$$X_{s(d)} = X_s - X_{m(d)} = 2\pi f\left(L_s - L_{m(d)}\right)\ \Omega \qquad (8)$$

where
$X_{s(d)}$ = TPG self-reactance to touch point (distance D).

Basic Single-Phase TPG Example

Example curves for K versus D are shown below. The K-factors are for 60-hertz (Hz) values of reactance $X_{s(d)}$ in equation (5). Example data spreadsheets show all of the calculated variables required to determine K.

The TPG conductor radius r and resistance per meter of copper conductor are given in table 1 for class K and M stranded conductors.

Table 1. Conductor Radius and Resistance

Conductor size (AWG or kcmil)	Conductor radius (cm)	Resistance (mΩ/m)
2	0.428	0.551
1/0	0.537	0.344
2/0	0.645	0.278
4/0	0.819	0.175
250	0.906	0.148

Source: From National Electrical Manufacturer's Association (NEMA) WC 58-1997, table 5-1 (average value for Class K and M conductors).
Note: AWG = American wire gauge, kcmil = circular mils

The conductor resistance per meter values in table 1 is used to determine TPG cable resistance R_c from length L.

Families of K-factor curves shown below (figures 3-5) are plotted from equation (5) for the basic grounding model in figure 1. Tables 2 and 3 are example data spreadsheets for No. 4/0 AWG copper TPGs (L = 4.57 meters [m] and 10 m).

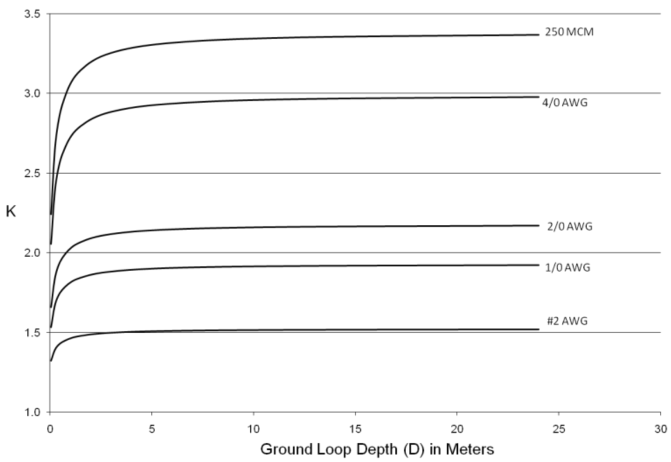


Figure 3. 60-Hz TPG impedance K-factors for single TPG shunt across body; TPG length = 2 m.

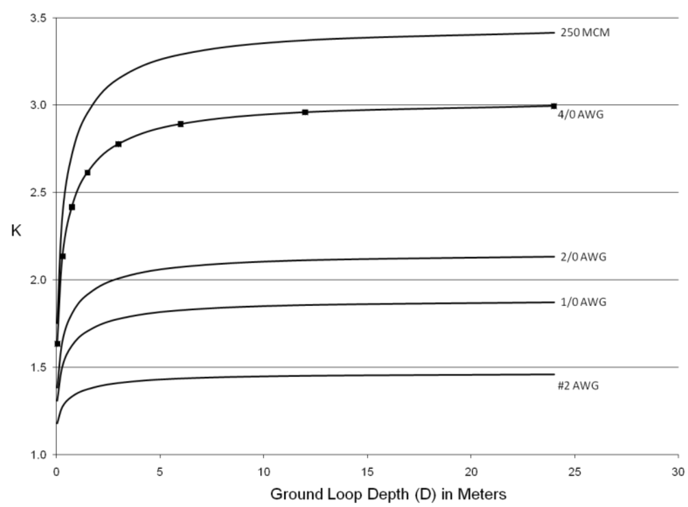


Figure 4. 60-Hz TPG impedance K-factors for single TPG shunt across body; TPG length = 4.57 m.

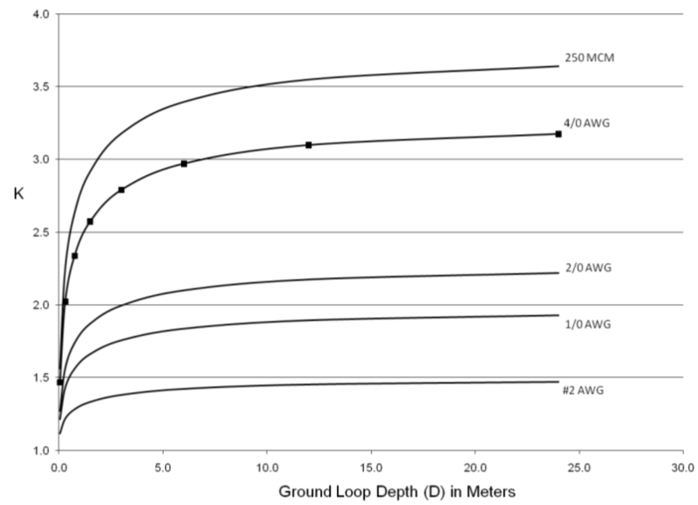


Figure 5. 60-Hz TPG Impedance K-factors for single TPG shunt across body; TPG length = 10 m.

Worker touch voltage V_t is determined in figure 1 (V_x becomes V_t) for the worksite available short-circuit current I, resistance of the TPG, and the above-derived K-factor as follows:

$$V_t = I \bullet R_C \bullet K \tag{9}$$

In summary, the TPG impedance correction K-factor in equation (5) adjusts conductor resistance R_C to the effective impedance of the TPG in shunt with the worker from a distance. The K-factor is a function of the specific TPG grounding layout with the worker (simple rectangular geometry of figure 1 in this example).

Table 2. Data Spreadsheet for No. 4/0 AWG Copper TPG, *L* = 4.57 m (15 ft)

TPG size	rad. (cm)	*L* (m)	R_c	f (Hz)
No. 4/0	0.819	4.57	7.9975E-04	60
Simple Configuration Single TPG Shunt Across Body				
D (m)	$X_{m(d)}$	$X_{s(d)}$	Z_g	K
0.05	1.454E-03	7.057E-04	1.307E-03	1.634E+00
0.3	8.549E-04	1.305E-03	1.706E-03	2.134E+00
0.75	5.712E-04	1.588E-03	1.932E-03	2.416E+00
1.5	3.821E-04	1.778E-03	2.090E-03	2.614E+00
3	2.301E-04	1.929E-03	2.221E-03	2.777E+00
6	1.258E-04	2.034E-03	2.312E-03	2.891E+00
12	6.485E-05	2.095E-03	2.366E-03	2.958E+00
24	3.271E-05	2.127E-03	2.394E-03	2.994E+00
X_s	K_s			
2.160E-03	3.030E+00			

Z_g = equivalent TPG impedance (includes R of cable, clamps, ferrules) for single TPG shunt across body
$X_{s(d)}$ = TPG self-reactance to touch point (distance D), ohm
$X_{m(d)}$ = TPG mutual reactance with touch point (distance D), ohm
X_s = TPG self-reactance out to infinite distance, ohm
R_c = resistance of TPG copper conductor, ohm
L = TPG length, m
D = distance from TPG to worker, m
K = TPG impedance correction factor
K_s = TPG impedance correction factor for self-reactance X_s (not $X_{s(d)}$)
Note: ft = feet, m = meters

Table 3. Data Spreadsheet for No. 4/0 AWG Copper TPG, *L* = 10 m

TPG size	rad. (cm)	L (m)	R_c	f (Hz)
No. 4/0	0.819	10	1.7500E-03	60
Simple Configuration Single TPG Shunt Across Body				
D (m)	$X_{m(d)}$	$X_{s(d)}$	Z_g	K
0.05	3.767E-03	1.549E-03	2.569E-03	1.468E+00
0.3	2.435E-03	2.881E-03	3.536E-03	2.021E+00
0.75	1.777E-03	3.539E-03	4.090E-03	2.337E+00
1.5	1.308E-03	4.008E-03	4.502E-03	2.573E+00
3	8.858E-04	4.430E-03	4.882E-03	2.789E+00
6	5.411E-04	4.775E-03	5.196E-03	2.969E+00
12	2.989E-04	5.017E-03	5.420E-03	3.097E+00
24	1.549E-04	5.161E-03	5.553E-03	3.173+00
X_s	K_s			
5.316E-03	3.256E+00			

Z_g = equivalent TPG impedance (includes R of cable, clamps, ferrules) for single TPG shunt across body
$X_{s(d)}$ = TPG self-reactance to touch point (distance D), ohm
$X_{m(d)}$ = TPG mutual reactance with touch point (distance D), ohm
X_s = TPG self-reactance out to infinite distance, ohm
R_c = resistance of TPG copper conductor, ohm
L = TPG length, m
D = distance from TPG to worker, m
K = TPG impedance correction factor
K_s = TPG impedance correction factor for self-reactance X_s (not $X_{s(d)}$)

TPG Self Impedance

The K-curves tend to flatten for values of *D* greater than about 5 m. This occurs because as *D* increases, the value of $X_{s(d)}$ quickly approaches the TPG self-reactance X_s, due to the rapid decrease in mutual reactance $X_{m(d)}$. This suggests that for practical applications, a representative worst-case, single-value K-factor could be chosen, letting $X_{s(d)} = X_s$ in equation (5) for a given TPG conductor size and length (identified as K_s in tables 2 and 3). The value of K_s for the 10-m TPG (rounded to two decimal places) is included in table C.1 of IEEE 1246.

Chapter 3

Three-Phase Grounding

Practical Single- and Three-Phase TPG Grounding Model for Substation Bus

In this chapter, the basic TPG model is expanded to represent more practical single- and three-phase grounding methods implemented in ac substations. The three-phase grounding method is depicted on the book cover.

Figure 6 depicts an electrical circuit model of three-phase, single-point worksite grounding in an ac substation. Temporary protective grounds connect the station bus to the ground grid between the worker touch point (represented by R_W) and energy source. A worker could also be located between the TPGs and energy source (not shown). The objective is to express V_t (V_{exp} in figure) in terms of the substation available three-phase, short-circuit current magnitude I_f, taking into account the effects of magnetic coupling from the three TPG currents I_a , I_b , and I_c.

TPGs Between Energy Source and Worker

During an accidental energization of the grounded worksite, balanced three-phase currents are assumed in the overhead bus and TPGs from the energy source. Therefore:

$$\widehat{I_a} = I_f\,(1 + j0)$$
$$\widehat{I_b} = I_f\,(-0.5 - j0.866)$$
$$\widehat{I_c} = I_f\,(-0.5 + j0.866)$$
I_f = worksite available short-circuit current magnitude, A and $\widehat{I_a} + \widehat{I_b} + \widehat{I_c} = 0$

No current is conducted in the bus beyond the TPGs toward the worker (no energy source at the right side in figure 6), and no current enters the earth from the ground grid. Note that any potential that might exist across ground grid resistance R_g would not appear in the induction ground loop described next.

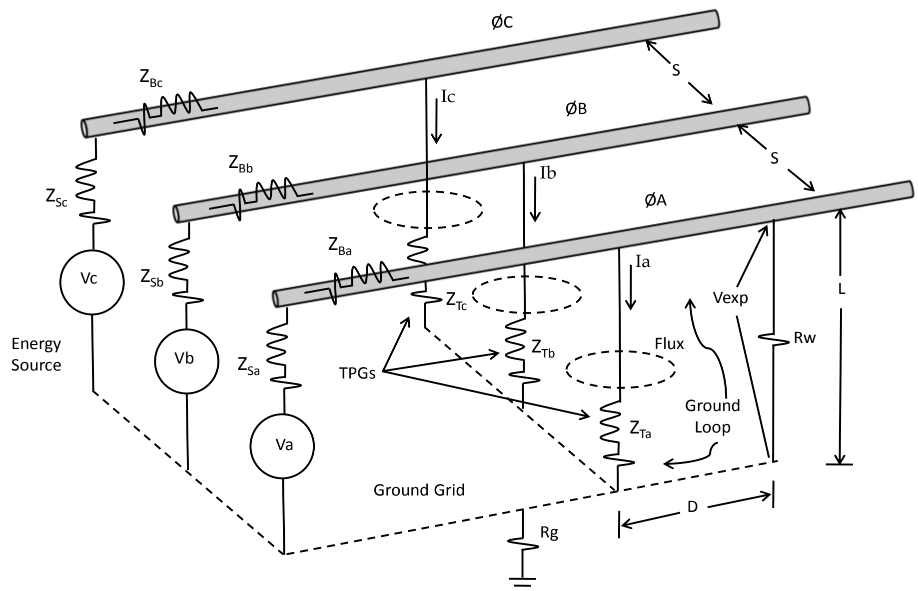


Figure 6. Electrical schematic representation for three-phase, single-point TPG grounding of an ac substation bus. One TPG is connected from each bus conductor to the substation ground grid. Lumped impedances for the TPGs (Z), bus (Z_B), and energy source (Z_S) are shown. Resistance R_g represents the substation ground grid earth resistance. (Source: figure C.3 from IEEE 1246 [1])

An induction ground loop circuit is formed with the worker comprised of the A-phase TPG and portion of overhead bus between TPG and worker, and station ground grid conductor between worker and TPG. The worker actually connects with the ground grid conductor by contacting a grounded object in the station (transformer or circuit breaker tank, support pedestal, etc.). The ground loop is assumed rectangular with dimensions *L* and *D*. No current is assumed in the portion of station ground grid conductor with the loop (balanced three-phase, short-circuit current is confined to grid conductors directly between TPGs).

Touch voltage V_t (V_{exp} in figure) is the phasor sum of the A-phase TPG conductor resistance and self-reactance voltage drops due to I_a (equation (2) in chapter 2), plus mutual reactance voltage drops from TPG currents I_b and I_c as follows:

$$\widehat{V_t} = \widehat{I_a}(R_C + 0.0003 + jX_a) + j\widehat{I_b}X_{ab} + j\widehat{I_c}X_{ac} \qquad (10)$$

where

- X_a = $X_{s(d)}$ = A-phase TPG self-reactance to touch point D, ohm
- X_{ab} = A-phase TPG mutual reactance to touch point *D* due to current in B-phase TPG, ohm
- X_{ac} = A-phase TPG mutual reactance to touch point *D* due to current in C-phase TPG, ohm

The resistance of the A-phase TPG clamps and ferrules is again represented by 0.3 milliohm. Equation (10) is equation (C.1) in IEEE 1246.

The circuit model for obtaining expressions for the mutual reactances (X_{ab}, X_{ac}) of magnetically coupled circuits is shown in figure 7. Ground loop circuit *a,b,c,d* with the A-phase TPG acquires an induced voltage V_x due to magnetic flux linkages produced by current I_a , and currents I_b and I_c in the external B- and C-phase TPG conductors. Note that a resistive IR voltage drop component of V_t occurs only from the A-phase TPG (phase touched by worker). The B- and C-phase TPG currents couple only reactive voltage drops into the induction ground loop circuit through mutual reactances X_{ab} and X_{ac} . All conductors lie in the same plane and are either parallel or perpendicular as they appear in the figure, making the ground loop circuit rectangular with dimensions *L* and *D*. Magnetic fluxes ψ_b and ψ_c produced by the external currents link with (penetrate) the ground loop circuit in the same direction as flux ψ_a (right hand rule); therefore, the reactance terms in equation (10) are all additive.

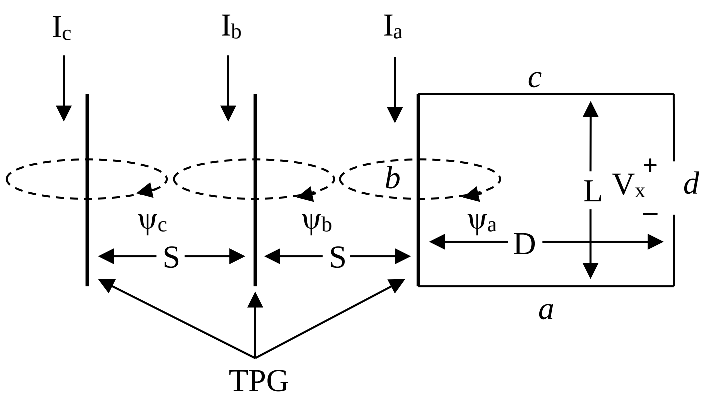


Figure 7. Circuit model representation for the TPGs shown in figure 6 for obtaining mutual reactances (X_{ab}, X_{ac}). V_x represents the location of the worker. All conductors lie in the same plane and are either parallel or perpendicular.

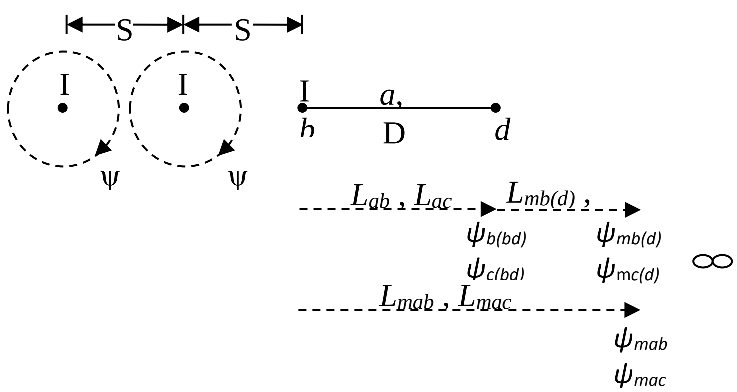


Figure 8. Circuit model representation for the TPGs shown in figure 7, redrawn looking parallel to the plane of the ground loop.

The circuit of figure 7 is redrawn in figure 8, looking parallel to the plane of the ground loop. Fluxes ψ_b and ψ_c, produced by currents I_b and I_c, link ground loop *a,b,c,d,* creating mutual inductances L_{ab} and L_{ac}, depicted by the horizontal dashed vectors. Other magnetic flux components of the I_b and I_c currents and associated inductances are shown, which are necessary to determine mutual inductances L_{ab} and L_{ac}:

where

- $\psi_{b(bd)}$ = flux produced by I_b linking area bounded by ground loop *a,b,c,d*
- $\psi_{c(bd)}$ = flux produced by I_c linking area bounded by ground loop *a,b,c,d*
- $\psi_{mb(d)}$ = mutual flux produced by I_b linking touch point *d* (distance S+D) out to infinite distance
- $\psi_{mc(d)}$ = mutual flux produced by I_c linking touch point *d* (distance 2S+D) out to infinite distance
- ψ_{mab} = mutual flux produced by I_a or I_b linking both A- and B-phase TPGs out to infinite distance
- ψ_{mac} = mutual flux produced by I_a or I_c linking both A- and C-phase TPGs out to infinite distance
- L_{ab} = A-phase TPG mutual (coupled) inductance with touch point *d* (distance D), due to current in B-phase TPG (due to $\psi_{b(bd)}$), H
- L_{ac} = A-phase TPG mutual (coupled) inductance with touch point *d* (distance D), due to current in C-phase TPG (due to $\psi_{c(bd)}$), H
- L_{mab} = A- and B-phase TPGs mutual inductance (due to ψ_{mab}), H
- L_{mac} = A- and C-phase TPGs mutual inductance (due to ψ_{mac}), H
- $L_{mb(d)}$ = B-phase TPG mutual inductance with touch point *d* (distance S+D) (due *to* $\psi_{mb(d)}$) , H
- $L_{mc(d)}$ = C-phase TPG mutual inductance with touch point *d* (distance 2S+D) (due to $\psi_{mc(d)}$) , H

The word "coupled" distinguishes mutual inductances L_{ab} and L_{ac} from the other defined mutual inductances. These coupled inductances occur from magnetic fluxes that are bounded by the ground loop area, whereas all other mutual inductances arise from magnetic fluxes that are unbounded to infinite distance from two parallel conductors.

By inspection of figure 8, mutual inductances L_{ab} and L_{ac} can be determined, noting that the flux linkages creating them ($\psi_{b(bd)}$ and $\psi_{c(bd)}$) are equivalent to the difference in the mutual flux linkages of TPG-to-TPG and TPG-to-worker, or:

$$\psi_{b(bd)} = \psi_{mab} - \psi_{mb(d)} \tag{11}$$

$$\psi_{c(bd)} = \psi_{mac} - \psi_{mc(d)} \tag{12}$$

Stated in terms of the associated inductances:

$$L_{ab} = L_{mab} - L_{mb(d)} \tag{13}$$

$$L_{ac} = L_{mac} - L_{mc(d)} \tag{14}$$

Ground loop induced voltage V_x related to the self- and mutual inductances associated with current I_a is similar to figure 2 in chapter 2. Using variable subscripts suitable for this three-phase circuit model, the A-phase TPG inductances become:

$$L_{s(d)} \rightarrow L_a \tag{15}$$

$$L_{m(d)} \rightarrow L_{ma(d)} \tag{16}$$

where:

L_a = A-phase TPG self-inductance out to touch point d (distance D), H

$L_{ma(d)}$ = A-phase TPG mutual inductance with touch point *d* (distance *D*), H

and self-inductance L_s is unchanged (A-phase self -inductance out to infinite distance). The desired reactances for equation (10) are then:

$$X_a = 2\pi f\left(L_s - L_{ma(d)}\right) \quad \Omega \tag{17}$$

$$X_{ab} = 2\pi f\left(L_{mab} - L_{mb(d)}\right) \quad \Omega \tag{18}$$

$$X_{ac} = 2\pi f\left(L_{mac} - L_{mc(d)}\right) \quad \Omega \tag{19}$$

Equations (17), (18), and (19) are IEEE 1246 equations (C.5), (C.6), and (C.7), respectively.

The self- and mutual inductances in equations (17) through (19) are determined from equations (6) and (7) in chapter 2. However, the circuit depicted in figures 7 and 8 is planar, while the circuit geometry of figure 6 is L-shaped with the worker position normal to the plane of the three TPGs. In this case, distances from the B- and C-phase TPGs to worker position point d are found using the right-triangle rule:

$$d = \sqrt{(nS)^2 + D^2} \tag{20}$$

with n = 1 or 2 for mutual inductance $L_{mb(d)}$ or $L_{mc(d)}$, respectively.

The A-phase TPG composite impedance magnitude Z_{g3}, due to balanced three-phase currents in the TPGs, is found by substituting the rectangular form of short-circuit currents into equation (10), collecting real and imaginary terms and converting to magnitude, then dividing by I_f:

$$Z_{g3} = \sqrt{[R_C + 0.0003 + 0.866(X_{ab} - X_{ac})]^2 + [X_a - 0.5(X_{ab} + X_{ac})]^2} \tag{21}$$

Equation (21) is IEEE 1246 equation (C.2)

TPGs Between the Energy Source and Worker Example

Equation (21) represents an equivalent TPG impedance magnitude. When multiplied by the worksite available, three-phase, short-circuit current, it gives the worker touch voltage V_t, shown as V_{exp} in figure 6. The TPG self- and mutual reactances are readily calculated by computer software for a range of values of *L*, *D*, and *S* in figure 6. The TPG impedance correction K-factors are then determined by dividing Z_{g3} by R_C. Touch voltage V_t is calculated with equation (9) in chapter 2.

The family of 60-Hz, K-factor curves in figure 9 is for three-phase grounding with No. 4/0 AWG copper TPGs, L = 4.57 m (15 ft), for balanced three-phase TPG currents. Table 4 is a sample data spreadsheet for substation bus spacing S = 3 m.

The K-curves are plotted from equation (21):

$$K = {Z_{g3}}/{R_c}$$
$$= {1}/{R_c}\sqrt{[R_C + 0.0003 + 0.866(X_{ab} - X_{ac})]^2 + [X_a - 0.5(X_{ab} + X_{ac})]^2} \qquad (22)$$

The TPG conductor resistance R_c is determined from table 1 in chapter 2 for length *L*.

Note that the three-phase, grounding K-curve for bus spacing S = 24 m is identical to the single-phase, grounding K-curve shown in figure 4 in chapter 2.

Table 4. Sample Data Spreadsheet for Three-Phase, Single Point Grounding No. 4/0 AWG Copper TPGs, L = 4.57 M, Bus Spacing S = 3 M

TPG size	rad. (cm)	L (m)	S (m)	R_c									
#4/0	0.819	4.57	3	7.998E-04									
L – configuration (Aθ or Cθ exposure voltage)													
D (m)	X_s	$X_{ma(d)}$	X_{mab}	Z_{g3}	X_{mac}	$X_{mb(d)}$	$X_{mc(d)}$	K	X_a	X_{ab}	X_{ac}	D1 (m)	D2 (m)
0.05	2.160E-03	1.454E-03	2.301E-04	1.307E-03	1.258E-04	2.301E-04	1.258E-04	1.634E+00	7.058E-04	2.583E-08	4.037E-09	3.000E+00	6.000E+00
0.3	2.160E-03	8.550E-04	2.301E-04	1.706E-03	1.258E-04	2.292E-04	1.256E-04	2.134E+00	1.305E-03	9.241E-07	1.451E-07	3.015E+00	6.007E+00
0.75	2.160E-03	5.712E-04	2.301E-04	1.932E-03	1.258E-04	2.245E-04	1.249E-04	2.415E+00	1.588E-03	5.591E-06	8.987E-07	3.092E+00	6.047E+00
1.5	2.160E-03	3.821E-04	2.301E-04	2.088E-03	1.258E-04	2.100E-04	1.223E-04	2.611E+00	1.778E-03	2.011E-05	3.482E-06	3.354E+00	6.185E+00
3	2.160E-03	2.301E-04	2.301E-04	2.210E-03	1.258E-04	1.719E-04	1.134E-04	2.764E+00	1.930E-03	5.827E-05	1.241E-05	4.243E+00	6.708E+00
6	2.160E-03	1.258E-04	2.301E-04	2.281E-03	1.258E-04	1.134E-04	9.072E-05	2.852E+00	2.034E-03	1.168E-04	3.505E-05	6.708E+00	8.485E+00
12	2.160E-03	6.485E-05	2.301E-04	2.306E-03	1.258E-04	6.296E-05	5.814E-05	2.883E+00	2.095E-03	1.672E-04	6.763E-05	1.237E+00	1.342E+00
24	2.160E-03	3.271E-05	2.301E-04	2.311E-03	1.258E-04	3.246E-05	3.174E-05	2.889E+00	2.127E-03	1.977E-04	9.403E-05	2.419E+00	2.474E+00

Z_{g3} = A-phase TPG equivalent impedance (includes R of cable, clamps, ferrules) producing touch potential at worker position during balanced three-phase short-circuit current

X_s = TPG self-reactance out to infinite distance
$X_{ma(d)}$ = Aθ TPG mutual reactance with touch point (distance D)
X_a = Aθ TPG self-reactance to touch point (distance D)
X_{mab} = Aθ and Bθ TPGs mutual reactance
X_{mac} = Aθ and Cθ TPGs mutual reactance
$X_{mb(d)}$ = Bθ TPG mutual reactance with touch point (distance D)
$X_{mc(d)}$ = Cθ TPG mutual reactance with touch point (distance D)
X_{ab} = Aθ TPG mutual reactance with touch point (distance D), due to current in B-phase TPG
X_{ac} = Aθ TPG mutual reactance with touch point (distance D), due to current in C-phase TPG
R_c = TPG conductor length L resistance, ohm
L = Length of TPGs (same for all phases), m
S = Substation bus spacing, m
D1 = $\sqrt{[S^2+D^2]}$ diagonal distance from B-phase TPG to worker touch point, d, m
D2= $\sqrt{[(2S)^2+D^2]}$ diagonal distance from C-phase TPG to touch point, d, m
rad. = Radius of TPG conductor, cm
K = TPG impedance correction factor
All reactances in ohms at 60 Hz

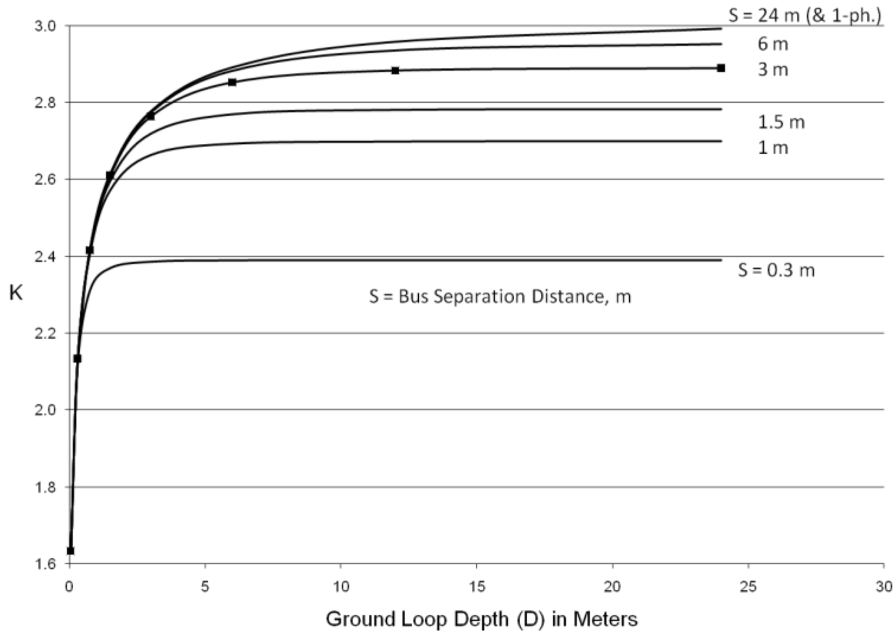


Figure 9. 60-Hz TPG impedance K-factor curves for three-phase, single-point TPG grounding; TPGs between worker and energy source; No. 4/0 AWG copper TPGs, L = 4.57 m

Assessment of Three-Phase Results

Comparison of K-factor curves in chapter 2, as well as the above example, reveals that the three-phase K-values approach an upper limit of the corresponding single-phase values as bus spacing S increases. This is to be expected because mutual reactances X_{ab} and X_{ac} become small relative to self-reactance X_a, and equation (21) reduces to equation (4) in chapter 2, making $Z_{g3} \approx Z_g$. It implies that, for conservative results, the single-phase grounding model (figure 1 in chapter 2) can be used for three-phase grounding (figure 6). The error is less than about 10 percent if bus spacing S > 1.5 m.

A second degree of conservancy may be applied if the single-phase K-factors are based only on TPG conductor self-inductance L_s ($L_{m(d)}$ = 0 in equation (1) and $X_{s(d)} = X_s$ in equations (3) through (5) in chapter 2); defined K_s. This is the basis for the K-factors given in table C.1 of IEEE 1246.

Working Between Energy Source and TPGs

For this scenario, the worker touch point (R_W) in figure 6 with the A-phase overhead bus is to the left of the TPG at distance D (not shown). The induction ground loop circuit comprises the A-phase TPG and portions of the overhead bus and station ground grid conductor between TPG and the worker. The ground loop is again assumed rectangular with dimensions L and D, and there is no current in the station ground grid conductor forming the loop with the worker.

In the previous three-phase grounding example, it was shown that the B- and C-phase TPG currents had minor influence on the touch voltage in the A-phase TPG ground loop circuit. Therefore, this three-phase grounding example can be modeled in the single-phase representation of figure 10 for simplicity of calculation.

Sides *b* and *c* of the induction ground loop in figure 10 represent the A-phase TPG and overhead bus, respectively. The A-phase, short-circuit current enters the upper left corner of the loop and exits the lower right corner into the plane of the page (toward B- and C-phase TPGs). There is no current in sides *a* and *d* of the ground loop and essentially no magnetic flux produced by the exit current links the loop.

Flux produced by the A-phase current links the ground loop in figure 10 from the bus (ψ_{bus}) in addition to the TPG ($\psi_{s(d)}$). Therefore, touch voltage V_t includes an additional reactive voltage component from the bus current compared to figure 1 in chapter 2.

The self-inductance L_{bus} of the bus segment forming the ground loop with the worker (side *c*) cannot be calculated directly from Grover's formula, equations (6) and (7) in chapter 2. Current in the bus exists beyond the boundary of the loop (toward energy source), which does not fit the condition of equal length parallel conductors for sides *a* and *c*. Noting that dimension *D* runs parallel with the bus, self-reactance X_{bus} can be approximated using an ohms per-meter factor based on the self-inductance of a fixed length of tubular conductor.

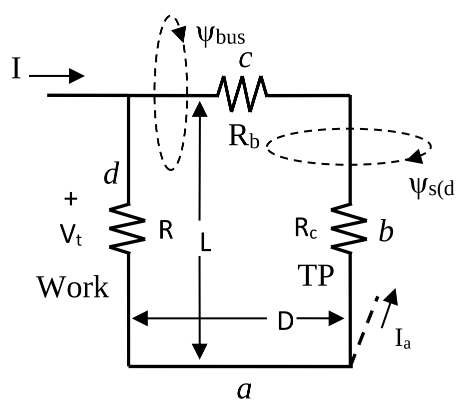


Fig. 10. Single-phase schematic representation of three-phase grounding model for worker positioned between TPGs and energy source. Side a represents the station ground grid conductor. Current I_a exits the ground loop at lower right corner into the plane of the page.

Modification of equation (5) in chapter 2 to include the bus segment self-reactance X_{bus} and resistance R_{bus} becomes:

$$K = \frac{\sqrt{(R_C+0.0003+R_{bus})^2+\left(X_{s(d)}+X_{bus}\right)^2}}{R_C} \qquad (23)$$

Formula for the self-inductance of straight tubular conductor is reprinted from Grover [2] in inductance unit of Henry. For modeling purposes, the station overhead bus is assumed schedule 40 pipe bus.[1] Larger bus sizes will result in slightly lower K-factors.

$$L_b = 2l\left[\ln\left(\frac{2l}{r}\right) + ln\xi - 1\right] \times 10^{-9} \quad \text{H} \tag{24}$$

where

L_b = self-inductance of straight tubular conductor, H
l = length of tubular conductor (note $l \neq D$; see below), cm
r = pipe bus outer radius (one-half outside diameter), cm
$Ln\xi$ = 0.0416 for schedule 40 pipe bus

Working Between Energy Source and TPGs Grounding Model Example

This example shows a family of K-factor curves with the worker positioned between the energy source and TPGs. The curves are valid for both single- and three-phase grounding if bus spacing $S > 1.5$ m. The family of K-factor curves shown in figure 11 is plotted from equation (23). A sample data spreadsheet is shown in table 5.

Self-reactance $X_{s(d)}$ is determined from equation (8) in chapter 2 using equations (6) and (7) in chapter 2 for L_s and $L_{m(d)}$. TPG conductor resistance R_c is calculated from table 1 in chapter 2 for 4.57-m length No. 4/0 AWG copper conductor. Station overhead bus resistance R_{bus} is calculated from the ac resistance per meter of seamless pipe specified in footnote 1 for distance D. Station overhead bus reactance

[1] Schedule 40 seamless pipe 3.5-inch outside diameter and 3.06-inch inside diameter, ac resistance at 70 ºC is 26.7 μΩ.

X_{bus} is approximated based on inductance L_b from equation (24) for a 24-m length of same seamless pipe bus specified in footnote 1.

Letting l = 2,400 cm and r = 4.45 cm in equation (24) gives L_{b24} = 28.9 µH.

Therefore:

$$X_{bus} \approx 2\pi f D \left({}^{L_{b24}}\!/_{24} \right) = 0.00046 \bullet D \quad \Omega \;\; (\mathrm{f} = 60 \text{ Hz}) \qquad (25)$$

where D is the distance from TPG to worker position, m.

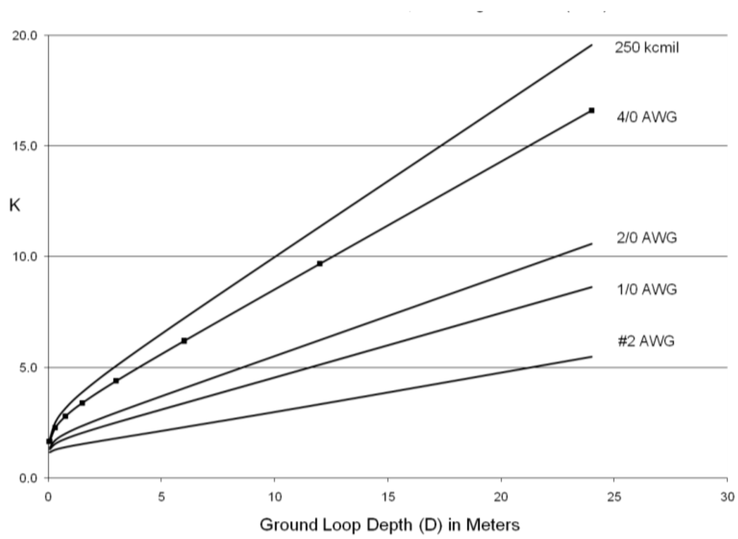


Figure 11. 60-Hz TPG impedance K-factor curves for single-phase, single-point grounding, worker between energy source and TPG, L = 4.57 m (15 ft)

Table 5. Data Spreadsheet for No. 4/0 AWG Copper TPG Length L = 4.57 m (15 ft)

TPG size	rad. (cm)	*L* (m)	R_c	R_{bus} (ohm/m)	X_{bus} (ohm/m)	
4/0	0.819	4.57	7.998E-04	2.670E-05	4.600E-04	
D (m)	$X_{s(d)}$	$X_{m(d)}$	X_{bus}	Z_g	*K*	R_{bus}
0.05	7.058E-04	1.45E-03	2.300E-05	1.320E-03	1.65	1.335E-06
0.3	1.305E-03	8.550E-04	1.380E-04	1.819E-03	2.27	8.010E-06
0.75	1.588E-03	5.712E-04	3.450E-04	2.234E-03	2.79	2.003E-05
1.5	1.778E-03	3.821E-04	6.900E-04	2.718E-03	3.40	4.005E-05
3	1.930E-03	2.301E-04	1.380E-03	3.514E-03	4.39	8.010E-05
6	2.034E-03	1.258E-04	2.760E-03	4.957E-03	6.20	1.602E-04
12	2.095E-03	6.485E-05	5.520E-03	7.746E-03	9.69	3.204E-04
24	2.127E-03	3.271E-05	1.104E-02	1.328E-02	16.61	6.408E-04
X_s 2.160E-03						

Z_g = equivalent single TPG impedance (includes R of cable, clamps, ferrules) during short circuit current producing touch potential at worker position, ohm
X_s = self-reactance of TPG out to infinite distance, ohm
$X_{m(d)}$ = mutual reactance of TPG with worker position (distance D), ohm
$X_{s(d)}$ = self-reactance of TPG out to distance D (worker position), ohm
R_c = resistance of TPG copper conductor, ohm
L = length of TPG, m
D = distance from TPG to worker, m
rad. = radius of TPG conductor, cm
R_{bus} = bus segment length D, ac resistance, ohm
X_{bus} = bus segment length D, self-reactance, ohm
K = TPG impedance correction factor
Note: All values of reactance at 60 Hz.

Placement of TPG Grounds

Comparing the K-factor curves for the two examples in this paper illustrates that working between an energy source and TPGs can create a substantially higher touch voltage (higher value K-factors). This suggests that for single-point worksite grounding applications, the TPGs should be placed between worker and energy source whenever possible.

The K-factor values in the previous section will increase if the substation ground grid conductor (side a in figure 10) conducts a portion or all of the A-phase, short-circuit return current. The latter case is represented by the K-factor curves given in IEEE 1246, figures C.18, C.19, and C.20. For those K-factor curves, equation (23) was modified to include the resistance and self-reactance of the station ground grid conductor segment in a method similar to that described above for the overhead bus.

Chapter 4

Bracket Grounding

Bracket TPG Grounding Model for Substation Bus Overview

In addition to single- and three-phase grounding, bracket grounding is another option implemented in grounding ac substations. It uses a set of grounds on each side of the work area. Figure 12 depicts a form of bracket grounding. Only one phase is shown because single-phase modeling has been proven sufficiently accurate for three-phase grounding (see chapter 3). The station overhead bus is grounded with two identical TPGs separated by distance B. The worker (R_w) contacts the station bus and ground grid anywhere between the TPGs. An energy source is located to the left of TPG1, and there is no energy source to the right of TPG2. The sum of TPG currents I_1 and I_2 equals the station available, short-circuit current I_f from the source. Touch voltage V_t is to be determined for worker-to-TPG1 distance $D < B$.

For conservative analysis (highest touch voltage), current I_2, carried by TPG2, is modeled returning to the source in a single station ground grid conductor directly below the overhead bus. As shown in figure 12, magnetic flux produced by currents in the TPGs, overhead bus, and ground grid conductor links (penetrates) the shaded area, forming an induction ground loop with the worker.

Determination of TGP Currents I_1 and I_2

The bus I_f current division in the TPGs is first solved for I_1 and I_2. Current division in the TPGs is dependent on the TPGs' self- and mutual inductances associated with fluxes ψ_1 and ψ_2, and the bus and ground grid conductor impedances between the TPGs.

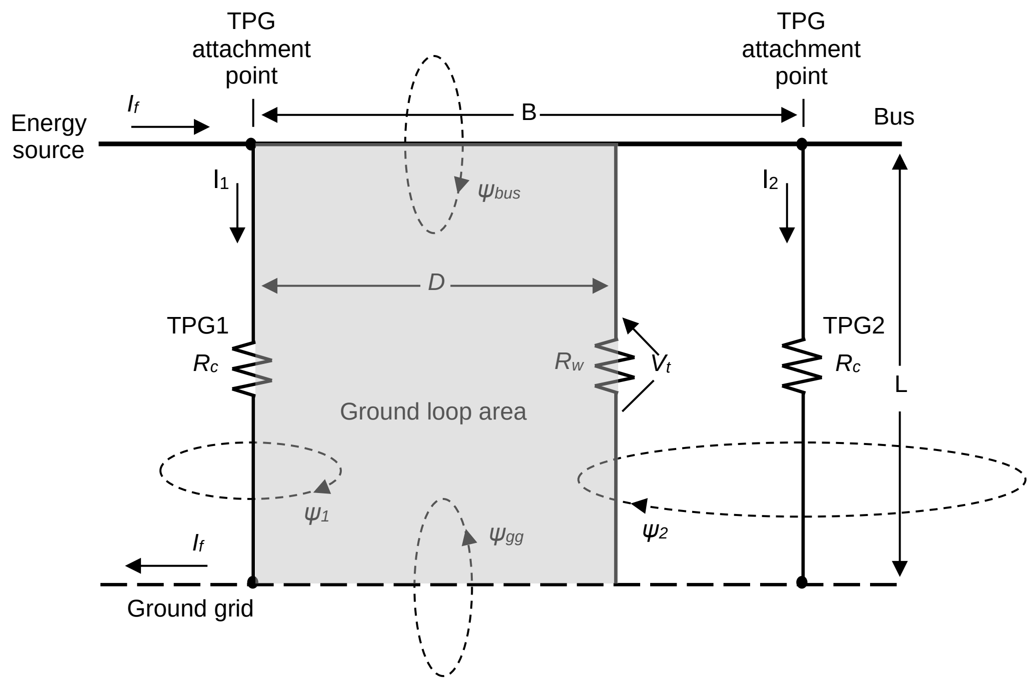


Figure 12. Single-phase schematic representation of bracket TPG grounding. The worker (R_w) contacts station overhead bus anywhere between TPGs. The depth of induction ground loop with worker is distance *D* from the worker to TPG1. (Source: Modified figure C.2 from IEEE 1246 [1])

Circuit parameters for the parallel connected (bracket) TPG model are shown in fig 13. The TPG, bus, and ground grid conductor reactances are shown as lumped circuit elements which represent the actual distributed reactances associated with the flux linkages shown:

where

$X_{1s(b)}$ and $X_{2s(b)}$ = TPG1 and TPG2 self-reactance out to distance *B* (by symmetry $X_{1s(b)} = X_{2s(b)} \stackrel{\text{def}}{=} X_{TPG(b)}$)

X_{bus} = overhead bus length *B* self-reactance

X_{gg} = station ground grid conductor length *B* self-reactance

R_c = TPG conductor length *L* resistance
R_{bus} = overhead bus length *B* resistance
R_{gg} = station ground grid conductor length *B* resistance

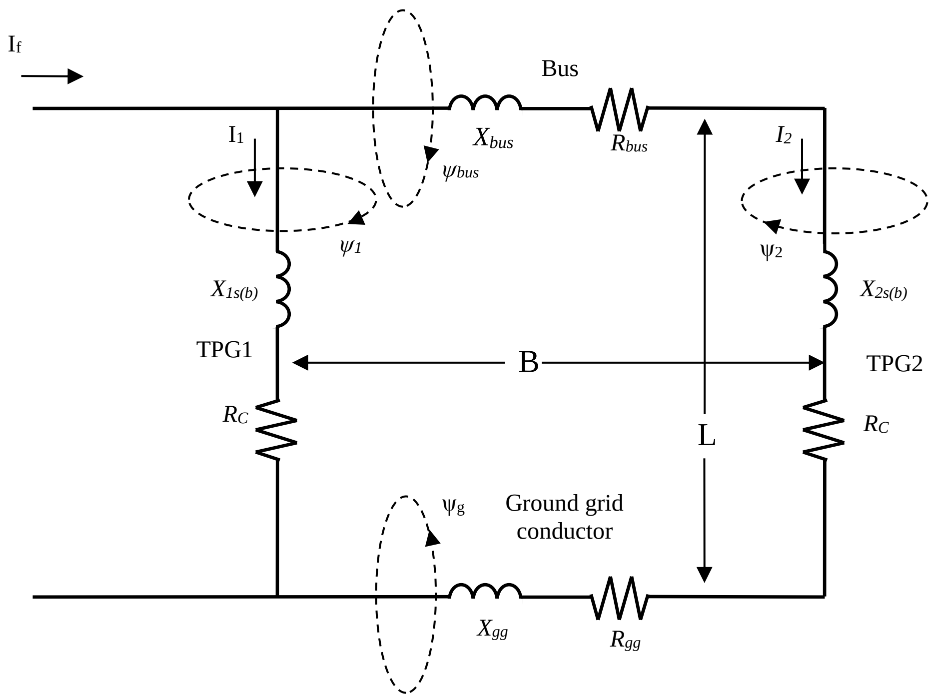


Figure 13. Circuit diagram for determining bracket grounding TPG currents I_1 and I_2. TPGs are constructed of conductors identical in size and length. Magnetic flux ψ_1 is produced by current I_1. All other fluxes shown are produced by current I_2.

For a given conductor length *L*, self-reactance $X_{TPG(b)}$ is a nonlinear function of *B* in the radial dimension to the TPG, due mainly to a 1/*B* relation in magnetic flux density for linkages ψ_1 or ψ_2. Therefore, self-inductance $L_{TPG(b)}$ is determined in a way similar to that described in chapter 2, “Basic Single-Phase TPG Example” section, as well as from equations (6) and (7) of chapter 2, noting that mutual inductance from equation (7) in chapter 2 is determined for $d = B$ as follows:

$$L_{1s} = 2L\left[ln\left(\frac{2L}{r}\right) - 0.75\right]x10^{-9} \quad \text{H} \tag{26}$$

$$L_{m12} = 2L\left[ln\left(\frac{L}{B} + \sqrt{1 + \left(\frac{L}{B}\right)^2}\right) - \sqrt{1 + \left(\frac{B}{L}\right)^2} + \frac{B}{L}\right]x10^{-9} \quad \text{H} \tag{27}$$

with all dimensions in centimeters, and:

$$X_{TPG(b)} = 2\pi f(L_{1s} - L_{m12}) \quad \Omega \tag{28}$$

where

L_{1s} = TPG1 self-inductance out to infinite distance
L_{m12} = TPG1 mutual inductance with TPG2

Conversely, the bus and station ground grid conductor self-reactances approximate a linear function of *B* because their respective magnetic flux density patterns are approximately constant in the axial direction with those conductors. Therefore, the bus and ground grid conductor self-inductances are obtained from equations (24) in chapter 3 and (15) and (6) in chapters 3 and 2, respectively, setting $l = B$ as follows:

$$L_{bus} = 2B\left[ln\left(\frac{2B}{r_b}\right) + ln\xi - 1\right] \times 10^{-9} \quad H \tag{29}$$

where

L_{bus} = self-inductance of straight tubular conductor, H
B = length of tubular conductor
r_b = pipe bus outer radius (one-half outside diameter)
$Ln\xi$ = 0.0416 for schedule 40 pipe bus

$$L_{gg} = 2B\left[ln\left(\frac{2B}{r}\right) - 0.75\right]x10^{-9} \quad H \tag{30}$$

where

L_{gg} = self-inductance at ground grid conductor, H
B = length at ground grid conductor
r = conductor radius

with all dimensions in centimeters.

Bus resistance R_{bus} and station ground grid conductor R_{gg} are calculated from information provided in footnote 1 of chapter 3 for tubular pipe bus and table 1 in chapter 2 for 4/0 AWG copper conductor, respectively.

From basic circuit theory, the ratio of TPG currents is equal to the inverse ratio of their parallel circuit impedances:

$$I_1/I_2 = Z_2/Z_1 \tag{31}$$

and for this bracket grounding example:

$$\widehat{Z_1} = Z_{TPG1} = R_c + 0.0003 + jX_{TPG(b)} \tag{32}$$

$$\widehat{Z_2} = Z_{TPG2} + Z_{bus} + Z_{gg} = R_c + 0.0003 + R_{bus} + R_{gg} + j\left(X_{TPG(b)} + X_{bus} + X_{gg}\right) \tag{33}$$

For simplicity in calculating worker touch voltage V_t (see the section entitled, "Determination of Worker Touch Voltage, V_t," below), the TPG currents are expressed in per-unit of I_f in order to determine K-factors in terms of the station available short-circuit current. The ratio $\frac{\widehat{I_1}}{I_f}$ is found by substituting $\widehat{Z_1}$ and $\widehat{Z_2}$ from equations (32) and

(33) into (31) and replacing I_2 with $I_f - I_1$ in the left side denominator:

$$\hat{I_1}\Big/_{I_f} = \frac{R_c + R_{bus} + R_{gg} + j\left(X_{TPG(b)} + X_{bus} + X_{gg}\right)}{2R_c + R_{bus} + R_{gg} + j(2X_{TPG(b)} + X_{bus} + X_{gg})} \quad (34)$$

Although equation (34) is not reduced to simplest form, it is readily manipulated in software and displayed in polar form as the ratio $\left|\frac{I_1}{I_f}\right| \angle Z$. Ratio $\left|\frac{I_2}{I_f}\right| \angle Y$ is determined from the relation $\frac{I_2}{I_f} = 1 - \frac{I_1}{I_f}$ since the I_1 and I_2 complex current ratios must sum to one per unit of I_f .

Determination of Worker Bracket Touch Voltage V_t

Touch potential V_t is found by summing the resistive and reactive voltage drops around the loop circuit enclosing the shaded area in figure 12. This again implies that all the loop voltage appears across worker resistance R_W. A reactive *IX* voltage drop is calculated for each of the reactances associated with the fluxes (ψ_1, ψ_2, ψ_{bus}, ψ_{gg}), which links only the shaded ground loop area shown in the figure.

The electrical schematic for determining touch voltage V_t is shown in figure 14. The worker contacts the station bus and ground grid conductor at distance *D* from TPG1, completing an induction ground loop circuit with shaded area in the figure. Touch voltage V_t is found by summing the voltage drops around this loop circuit to the contact points with worker. For this purpose, the sectional impedances of station bus and station ground grid conductor included in the shaded loop are approximated by multiplying R_{bus}, R_{gg}, X_{bus}, and X_{gg} by the ratio *D*/*B*.

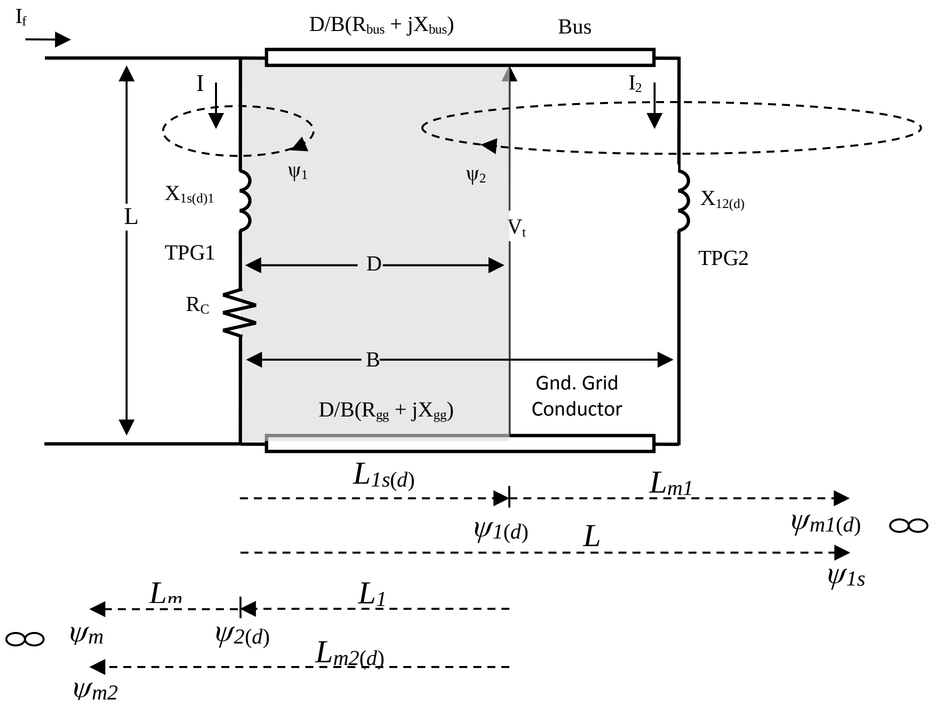


Figure 14. Schematic diagram of a bracket TPG grounded station bus and induction ground loop with worker creating touch voltage V_t. The TPG self- and mutual inductances required to determine V_t are depicted by vectors representing the associated flux linkages with TPGs and worker. TPG2 resistance R_c does not appear in the I_2 branch because it is not involved in calculation of V_t by summation of voltage drops around the shaded portion of the loop.

By inspection of figure 12, flux linkages $\psi_{1(d)}$ produced by current I_1 out to worker distance D induce a voltage in the shaded loop. The TPG1 self-inductance $L_{1s(d)}$ and reactance $X_{1s(d)}$ associated with $\psi_{1(d)}$ produce an equivalent voltage drop in this loop circuit. They are determined by noting that flux linkages ψ_{1s} minus $\psi_{m1(d)}$ are equivalent to $\psi_{1(d)}$ such that self-inductance $L_{1s(d)} = L_{1s} - L_{m1(d)}$. Therefore, self-reactance $X_{1s(d)}$ is calculated in a way similar to $X_{TPG(b)}$, as shown above, with distance D substituted for B in equation (27):

$$L_{m1(d)} = 2L\left[ln\left(\frac{L}{D} + \sqrt{1+\left(\frac{L}{D}\right)^2}\right) - \sqrt{1+\left(\frac{D}{L}\right)^2} + \frac{D}{L}\right]x10^{-9} \quad \text{H} \quad (35)$$

and

$$X_{1s(d)} = 2\pi f\left(L_{1s} - L_{m1(d)}\right) \quad (36)$$

where

L_{1s} = self-reactance out to infinity

$L_{m1(d)}$ = TPG1 mutual inductance with touch point (distance D)

$X_{1s(d)}$ = TPG1 self-reactance to touch point (distance D)

Again, by inspection of figure 14, flux linkages $\psi_{2(d)}$ produced by current I_2 induce a voltage in the shaded loop. The TPG mutual inductance [$L_{12(d)}$ and reactance $X_{12(d)}$] associated with $\psi_{2(d)}$ produce an equivalent voltage drop in this loop circuit. They are determined by noting that flux linkage$L_{12(d)} = L_{m2(d)} - L_{m21}$s $\psi_{m2(d)}$ minus ψ_{m21} are equivalent to $\psi_{2(d)}$ such that mutual inductance . Mutual inductances $L_{m2(d)}$ and L_{m21} are calculated with equation (27) using the appropriate distance between boundaries for the flux linkages:

$$L_{m2(d)} = 2L\left[ln\left(\frac{L}{B-D} + \sqrt{1+\left(\frac{L}{B-D}\right)^2}\right) - \sqrt{1+\left(\frac{B-D}{L}\right)^2} + \frac{B-D}{L}\right]x10^{-9} \quad H \tag{37}$$

where

$L_{m2(d)}$ = TPG2 mutual inductance with touch point (distance *B-D*)

By symmetry $L_{m21} = L_{m12}$; therefore, equation (27) is L_{m21} directly.

Finally,

$$X_{12(d)} = 2\pi f(L_{m2(d)} - L_{m21})\ \Omega \tag{38}$$

where

$X_{12(d)} =$ TPG1 mutual reactance with touch point (distance *D*) due to TPG2 current I_2.

Summation of the voltage drops around the shaded loop circuit in figure 14 gives:

$$\widehat{V_t} = \widehat{I_1}\left(R_c + 0.0003 + jX_{1s(d)}\right) - \widehat{I_2}\left[jX_{12(d)} + \frac{D}{B}\left(R_{bus} + R_{gg} + jX_{bus} + jX_{gg}\right)\right] \tag{39}$$

$\widehat{I_1}$ and $\widehat{I_2}$ are complex currents in terms of I_f. As before, 0.3 milliohm is added to TPG conductor resistance R_c to account for cable clamps and ferrules.

The bus X_{bus} and ground grid X_{gg} reactances are produced from flux linkages (ψ_{bus}, ψ_{gg}) that are at a predominant right angle to dimension *D* and, therefore, do not have similar mathematical forms as for $X_{1s(d)}$. Therefore, ratio *D*/*B* in equation (39) provides a linear resistance and reactance relationship for the overhead bus and ground grid conductor segments versus dimension *D* of the ground loop with TPG1 and worker.

Determination of K-factor results from dividing both sides of equation (39) by I_f, giving the TPG1 composite complex impedance $\widehat{Z_g} = \widehat{V_t}/I_f$. Division by I_f on the right side of the equation is accomplished by substituting per-unit quantities $\left|\frac{I_1}{I_f}\right| \angle Z$ and $\left|\frac{I_2}{I_f}\right| \angle Y$ for currents $\widehat{I_1}$ and $\widehat{I_2}$, respectively. Currents $\widehat{I_1}$ and $\widehat{I_2}$ are solved in per unit of I_f and converted to rectangular form for computation of composite impedance $\widehat{Z_g}$. The magnitude of Z_g is then readily determined after collecting real and imaginary terms. This magnitude represents the effective composite impedance of TPG1 in terms of the station-available, short-circuit current and worker position between TPGs. The K-factors are then found, as before, by dividing the composite impedance magnitude Z_g by TPG conductor resistance R_c.

Note that the choice of determining K-factors for TPG1 is arbitrary (closest to source); K-factors for TPG2 would produce the same touch voltage at a given location on the bus.

Bracket TPG Grounding Example

A family of bracket grounding TPG impedance correction K-factor curves for various bracket spacing B is shown in figure 15.

Values for magnitude Z_g and TPG impedance correction K-factor $K = Z_g/R_c$ are given in table 6 for one bracket distance $B = 24$ meters in figure 15.

The associated K-curve from Table 6 is replotted in figure 16, along with TPG per-unit currents $\frac{I_1}{I_f}$ and $\frac{I_2}{I_f}$ versus TPG bracket separation distance *B* for comparison. The steep portion of the K-curve to the left of the vertical dashed line in figure 16 is due to the rapid nonlinear change in self-reactance $X_{1s(d)}$ near TPG1 relative to the linear changing overhead bus and ground grid conductor impedances. In the region to the right of the dashed line, $X_{1s(d)}$ becomes fairly constant, and the linear impedances of the bus and ground grid conductor dominate.

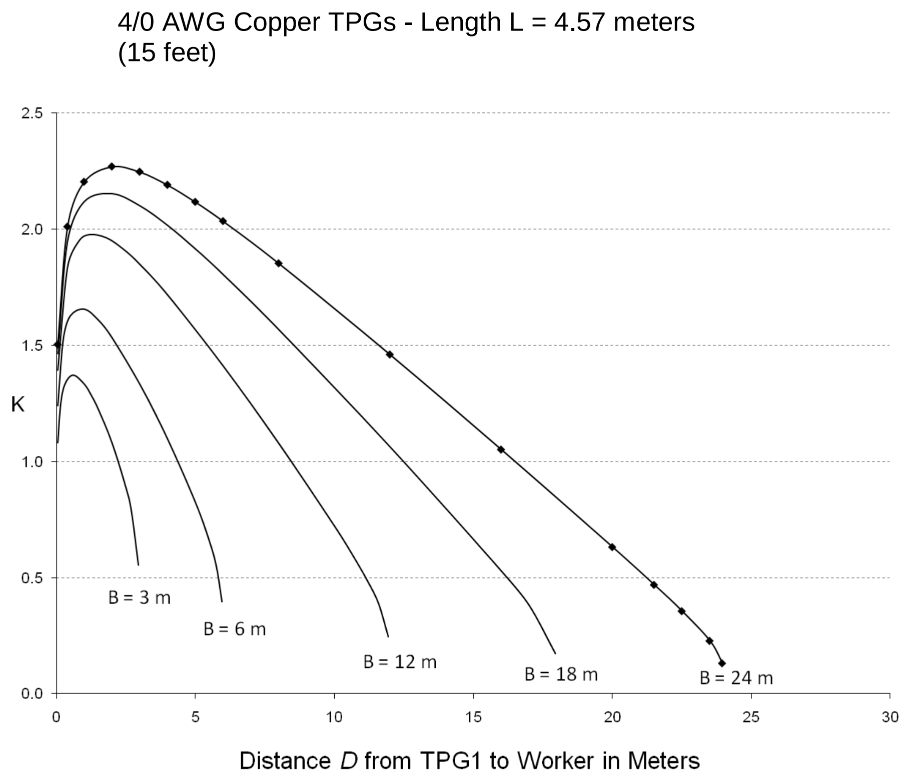


Figure 15. Family of 60-Hz TPG impedance correction K-factor curves for single-phase, bracket grounded overhead station bus. *B* = bracket distance between TPGs. Worker contacts bus between TPGs. Curves include effect of impedance for a single 4/0 AWG station ground grid conductor current return path below the bus. Refer to figure 12 (figure C.21 in IEEE 1246).

Table 6. Sample Data Spreadsheet for Bracket TPG Grounding K-Curve (*B* = 24 meters) in Figure 15

TPG size	rad. (cm)	L (m)		R_c	R_b	B (m)	X_{bus}	X_{gg}	R_{gg}
4/0	0.819	4.57	K_{24}	7.998E-04	6.408E-04	24	1.090E-02	1.434E-02	4.200E-3
$D_{(m)}$	Z_g	$X_{1s(d)}$	$X_{12(d)}$	K	$X_{m\,1(d)}$	$X_{m\,2(d)}$			
0.05	1.203E-03	7.058E-04	6.788E-08	1.50	1.454E-03	3.278E-05			
0.4	1.609E-03	1.397E-03	5.510E-07	2.01	7.631E-04	3.326E-05			
1	1.763E-03	1.670E-03	1.413-06	2.20	4.892E-04	3.412E-05			
2	1.816E-03	1.846E-03	2.953E-06	2.27	3.137E-04	3.566E-05			
3	1.798E-03	1.930E-03	4.639E-06	2.25	2.301E-04	3.735E-05			
4	1.753E-03	1.979E-03	6.491E-06	2.19	1.809E-04	3.920E-05			
5	1.694E-03	2.011E-03	8.535E-06	2.12	1.485E-04	4.124E-05			
6	1.628E-03	2.034E-03	1.080E-05	2.04	1.258E-04	4.351E-05			
8	1.483E-03	2.064E-03	1.617E-05	1.85	9.597E-05	4.888E-05			
12	1.169E-03	2.095E-03	3.214E-05	1.46	6.485E-05	6.485E-05			
16	8.417E-04	2.111E-03	6.326E-05	1.05	4.888E-05	9.597E-05			
20	5.060E-04	2.120E-03	1.482E-04	0.63	3.920E-05	1.809E-04			
21.5	3.761E-04	2.123E-03	2.330E-04	0.47	3.649E-05	2.657E-04			
22.5	2.855E-04	2.125E-03	3.494E-04	0.36	3.487E-05	3.821E-04			
23.5	1.832E-04	2.126E-03	6.607E-04	0.23	3.340E-05	6.934E-04			
23.95	1.061E-04	2.127E-03	1.421E-03	0.13	3.278E-05	1.454E-03			
$X_{tpg(b)}$	I1/f	Angle Z	I2/If	*Angle Y*	$X_{m\,12}$	X_{1s}			
2.127E-03	9.236E-01	1.178	7.895E-02	-13.919	3.271E-05	2.160E-03			

$X_{m\,1(d)}$ = TPG1 mutual reactance with touch point (distance D), Ohm
$X_{m\,2(d)}$ = TPG2 mutual reactance with touch point (distance B-D), Ohm
$X_{m\,12}$ = Xm21 = TPG1 mutual reactance with TPG2, Ohm
X_{1s} = TPG1 self-reactance out to infinity, Ohm
$X_{1s(d)}$ = TPG1 self-reactance to touch point (distance D), Ohm
$X_{12(d)}$ = TPG1 mutual reactance with touch point (distance D) due to TPG2 current I2, Ohm
$X_{tpg(b)}$ = TPG self-reactance out to distance B, Ohm
R_c = TPG conductor length L resistance, Ohm
R_{bus} = station overhead bus length B resistance, Ohm
R_{gg} = 4/0 copper station ground grid conductor length B resistance, Ohm
X_{bus} = station overhead bus length B self-reactance, Ohm
X_{gg} = 4/0 copper station ground grid conductor length B self-reactance, Ohm
Z_g = TPG1 composite impedance, Ohm
K = TPG impedance correction factor
All reactances at 60 Hz.

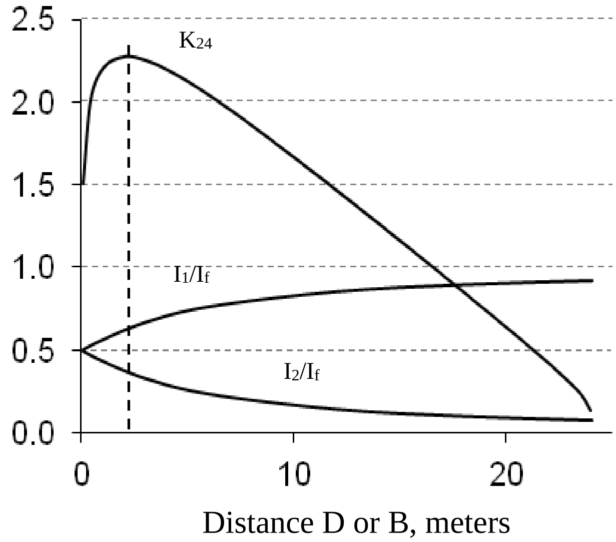


Figure 16. 60-Hertz TPG K-factor curve from Fig. 15 for B = 24 m, shown with associated TPG currents. Current ratio traces show range of TPGs current division for $0 < B \le 24$ m. At B = 24 m, TPG1 carries 92% of total short-circuit current I_f . Refer to Fig. 1.

Chapter 5

Power Line Grounding

Power Line Grounding Introduction

A method to predict worker touch voltage in substations using TPGs impedance correction K-factors has been developed in the previous chapters. Similar analysis of touch potential can be applied to workers aloft in contact with power line conductors at a support structure. Ground potential rise at the structure footings, guy wire anchors, etc., are not addressed in this analysis. Two examples for single-point protective grounding at a high-voltage transmission and utility line structure are presented. These examples are simple in layout: TPGs lie in the same plane as the structure, and the source of short-circuit current is from either side of the structure.

Transmission Line Structure Grounding

Figure 17 shows a simple TPG worksite grounding application for a H-frame, wood pole, transmission line structure. The structure and TPGs lie in the same plane (i.e., the TPGs are connected to the line conductors near the insulators). A worker contacts the line conductor and pole ground down-lead wire at the elevation of the line conductor, forming a rectangular induction ground loop (shaded area) with the A-phase TPG and ground down-lead of dimensions D and H. This model lends itself to analysis of touch voltage V_t using mutual induction formulas that are similar to those for the substation models in the previous chapters. Other, more complicated structure grounding configurations (e.g., worksite bracket grounding) are beyond the scope of this chapter.

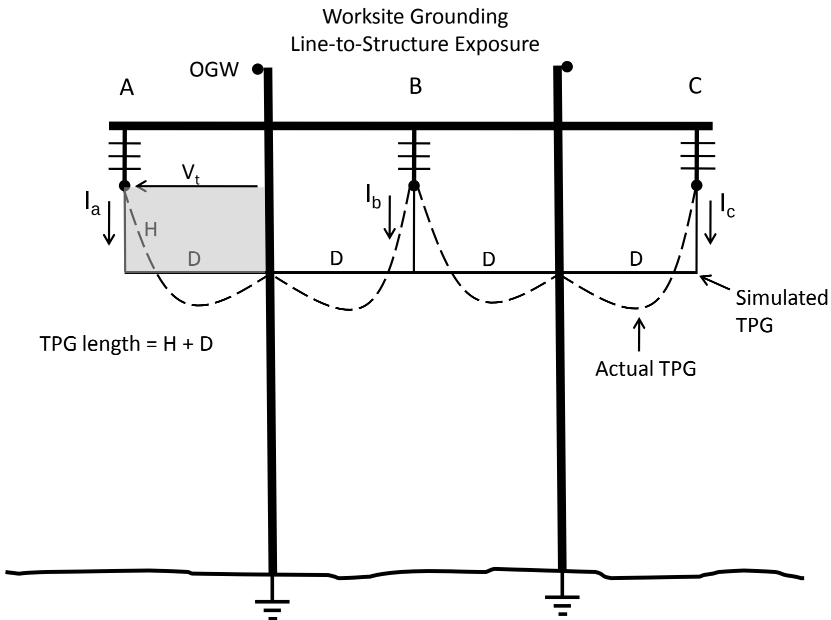


Figure 17. Graphic representation of three-phase, TPG worksite grounding at high-voltage, transmission line, H-frame wood pole structure. Line conductors are perpendicular to plane of page. Pole ground down-lead wires connect overhead ground/shield wires to pole footing earth electrodes. Four TPGs of length D+H connect the line conductors to the down-leads. Structure and TPGs lie in the same plane. Worker contacts touch voltage V_t between line conductor and pole ground down-lead wire. Structure height is not to scale.

Figure 18 shows the circuit model for obtaining expressions for the self and mutual reactances. The three line currents are again balanced, and no current is assumed in the pole ground down-lead wires. For modeling purposes, the TPG2 and TPG3 horizontal conductor segments combine, as shown in a single conductor of the same radius, which carries line current I_b. The horizontal segments of TPG3 and TPG4 are shown without magnetic flux encircling the conductors because flux linkages with the ground loop are insignificant. Each of the four TPGs has conductor resistance R_c (not shown), but only the TPG1 conductor produces a resistive IR voltage drop component in the ground loop.

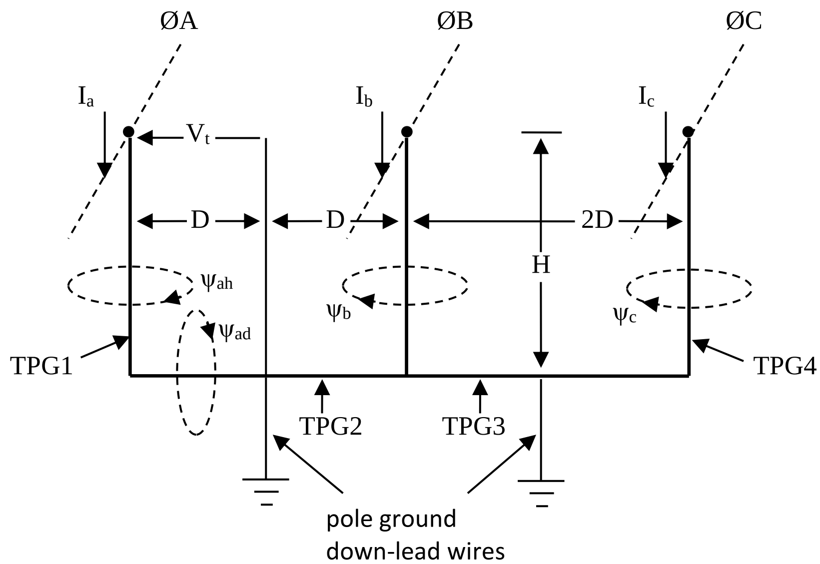


Figure 18. Circuit representation for transmission line, three-phase, TPG worksite grounding at H-frame, wood pole structure. Four TPGs of length $D + H$ connect the line conductors to the pole ground down-leads (ground down-lead associated with touch voltage V_t is shown extending from TPGs up to level of line conductor). Touch voltage exposure is between A-phase line conductor and pole ground down-lead wire. No current is assumed in the ground down-leads. Structure and TPGs lie in the same plane. Using the right-hand rule, fluxes ψ_{ad} and ψ_{ah} penetrate the ground loop out of the plane of the page, while fluxes ψ_b and ψ_c penetrate the ground loop into the page.

The A-phase, TPG1 self-inductance associated with the voltage induced in the worker ground loop creating touch voltage V_t is determined in two parts. This TPG forms two sides of the worker ground loop; therefore, flux linkages ψ_{ad} and ψ_{ah} must be accounted for when determining the self-inductance. These fluxes are at a predominant right angle to each other; therefore, they can be evaluated separately, and their associated self-inductances can be combined by superposition. The TPG1 self-inductance associated with flux linkages ψ_{ah} (flux produced by I_a in length H of TPG1) is determined in a similar way to that described in the "Basic Single-Phase TPG Grounding Model" section in chapter 2, as well as from equations (6) and (7) in chapter 2. As described in that section, the method of determining self-inductance for a specified radial distance from a conductor involves finding the mutual inductance of two equal length parallel conductors; in this case, the vertical segments of TPG1 and pole ground down-lead of length H, separated by distance D. Therefore:

$$L_{1sH} = 2H\left[ln\left(\frac{2H}{r}\right) - 0.75\right] x10^{-9} \text{ H} \tag{40}$$

$$L_{1mH(d)} = 2H\left[ln\left(\frac{H}{D} + \sqrt{1+\left(\frac{H}{D}\right)^2}\right) - \sqrt{1+\left(\frac{D}{H}\right)^2} + \frac{D}{H}\right] x10^{-9} \text{ H} \tag{41}$$

where
r = the conductor radius and all dimensions in centimeters

Then:

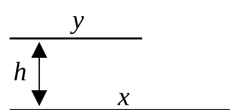
$$X_{1sH(d)} = X_{1sH} - X_{1mH(d)} = 2\pi f\left(L_{1sH} - L_{1mH(d)}\right) \ \Omega \tag{42}$$

where
$X_{1sH(d)}$ = A-phase TPG1 length H self-reactance to pole ground down-lead (distance D)
L_{1sH}, X_{1sH} = A-phase TPG1 length H self-inductance (reactance) out to infinite distance

$L_{1mH(d)}, X_{1mH(d)}$ = A-phase TPG1 length H mutual-inductance (reactance) with pole ground down-lead (distance D)

The TPG1 self-inductance associated with flux linkages ψ_{ad} (flux produced by I_a in length D of TPG1) is determined in the same manner as for $X_{1sH(d)}$, noting that the worker position (of length D) is parallel with the I_a current in the horizontal segments of TPG1 and TPG2 of length $2D$. Therefore, the desired mutual inductance is for two unequal length parallel conductors. From Grover [2], the mutual inductance of two unequal length parallel conductors with their ends on a common perpendicular is found from the relation:

$$2L_{mxy} = L_{m(x)} + L_{m(y)} - L_{m(x-y)} \tag{43}$$



where

L_{mxy} = the mutual inductance of the two unequal length parallel conductors of lengths x and y, having $x > y$

$L_{m(x)}$ = the mutual inductance of two parallel conductors of equal length x

$L_{m(y)}$ = the mutual inductance of two parallel conductors of equal length y

$L_{m(x-y)}$ = the mutual inductance of two parallel conductors of equal length $x - y$

and all parallel conductors are separated the same distance h.
The TPG-worker ground loop in figure 18 is a special case of one conductor (TPG current I_a) twice the length of the other (worker),

making $L_{m(y)} = L_{m(x-y)}$ and, therefore, $L_{mxy} = \frac{1}{2} L_{m(x)}$. The required mutual inductance is then:

$$L_{1mD(h)} = 2D\left[ln\left(\frac{2D}{H} + \sqrt{1 + \left(\frac{2D}{H}\right)^2}\right) - \sqrt{1 + \left(\frac{H}{2D}\right)^2} + \frac{H}{2D}\right] x10^{-9} \text{ H} \quad (44)$$

where the 1/2 factor for $L_{m(x)}$ results in the 2D term (rather than 4D) in front of the bracket.

The TPG1 approximate self-inductance[2] of length D is:

$$L_{1sD} = 2D\left[ln\left(\frac{2D}{r}\right) - 0.75\right] x10^{-9} \text{ H} \quad (45)$$

Finally:

$$X_{1sD(h)} = X_{1sD} - X_{1mD(h)} = 2\pi f\left(L_{1sD} - L_{1mD(h)}\right) \quad \Omega \quad (46)$$

where

$X_{1sD(h)}$ = A-phase TPG1 length D self-reactance to worker position (distance H)

L_{1sD}, X_{1sD} = A-phase TPG1 length D self-inductance (reactance) out to infinite distance

$L_{1mD(h)}, X_{1mD(h)}$ = A-phase TPG1 andTPG2 segments length 2D mutual-inductance (reactance) with worker position (distance H)

The total self-reactance X_a of the A-phase TPG1 associated with the area enclosed by the worker ground loop is:

---

[2] Approximate self-inductance of horizontal segment of TPG1 based on self-inductance formula for I_a current-carrying conductor of length D, which ignores influence of flux linkages due to the same current in adjacent horizontal segment of TPG2. This results in slightly lower K-factor values.

$$X_a = X_{1sH(d)} + X_{1sD(h)} \quad \Omega \tag{47}$$

Flux linkages ψ_b and ψ_c, and their associated mutual reactances X_{ab} and X_{ac}, influence touch voltage V_t to a much lesser extent than X_a. This is due to the distant locations of the vertical portions of the I_b and I_c TPG conductors with the worker induction ground loop (I_c has the least effect). Calculated values for mutual reactance X_{ac} will show it insignificant and, therefore, will be ignored when determining composite TPG impedance Z_{g1} below.

The ψ_b flux linkages with the A-phase TPG1-worker ground loop are similar in physical arrangement to those for linkages ψ_{2d} in figure 14 in chapter 4, where TPG1 in that figure becomes the vertical portion A-phase TPG1, and TPG2 becomes the common vertical portion of the B-phase TPG. Thus, the mutual reactance term X_{ab} is of similar form as $X_{12(d)}$ from equation (38) in chapter 4. Due to symmetry (pole ground down-lead centered between TPGs), mutual reactance $L_{m2(d)}$ in equation (38) in chapter 4 is equivalent to $L_{1mH(d)}$ in equation (41); therefore:

$$X_{ab} = X_{1mH(d)} - X_{mab} = 2\pi f\left(L_{1mH(d)} - L_{mab}\right)\Omega \tag{48}$$

where

X_{ab} = mutual reactance of the vertical portion of TPG1 with the pole ground down-lead due to current I_b in the common vertical portion B-phase TPG

From modified equation (27) in chapter 4:

$$L_{mab} = 2H\left[ln\left(\frac{H}{2D} + \sqrt{1 + \left(\frac{H}{2D}\right)^2}\right) - \sqrt{1 + \left(\frac{2D}{H}\right)^2} + \frac{2D}{H}\right]x10^{-9} \quad \mathrm{H} \tag{49}$$

with all dimensions in centimeters.

Derivation of mutual reactance X_{ac}, if it were to be evaluated, would follow a similar process as for X_{ab} in determining the mutual reactances of the vertical portions of the C- and A-phase TPGs, and of the C-phase TPG with the pole ground down-lead. A single value of X_{ac} is given in the sample data spreadsheet below for comparison with X_{ab}.

The expression for touch voltage V_t is similar to equation (10) in chapter 3, except that the B- and C-phase currents' mutual reactance terms are subtractive:

$$\widehat{V_t} = \widehat{I_a}(R_C + 0.0003 + jX_a) - j\widehat{I_b}X_{ab} - j\widehat{I_c}X_{ac} \qquad (50)$$

where

X_a = self-reactance of A-phase TPG bounding shaded area of ground loop with worker, ohm

X_{ab} = mutual reactance of vertical segment of A-phase connected TPG with pole ground down-lead due to current I_b, ohm

X_{ac} = mutual reactance of vertical segment of A-phase connected TPG with pole ground down-lead due to current I_c, ohm

Subtraction of the B- and C-phase current terms in equation (50) accounts for the opposing direction those magnetic fluxes penetrate the worker ground loop relative to the A-phase flux. The X_{ac} mutual reactance term is also shown to be insignificant and can be eliminated from equation (50).

The A-phase TPG1 composite impedance magnitude Z_{g1}, due to balanced three-phase currents in the TPGs of figures 17 and 18, is found by substituting the rectangular form of short-circuit currents into equation (50), collecting real and imaginary terms and converting to magnitude, then dividing by I_f. However, assuming the C-phase current term is insignificant and can be neglected in solving for Z_{g1}, we get:

$$Z_{g1} = \frac{V_t}{I_f} = \sqrt{(R_c + 0.0003 - 0.866X_{ab})^2 + (X_a + 0.5X_{ab})^2} \qquad (51)$$

Dividing equation (51) by R_c gives the desired TPG impedance correction K-factor formula:

$$K = \frac{\sqrt{(R_c + 0.0003 - 0.866X_{ab})^2 + (X_a + 0.5X_{ab})^2}}{R_c} \qquad (52)$$

Transmission Line Grounding Example

Three families of K-factor curves for three-phase TPG worksite grounding (figure 17) plotted from equation (52) are shown in figure 19 for No. 2, No. 1/0, and No. 4/0 AWG copper TPGs. Values for TPG conductor resistance R_c are calculated from table 1 in chapter 2 for conductor length $D + H$. These curves have noticeably different shapes compared to the curves in figure 9 in chapter 3 for three-phase grounding substation bus and do not converge to a minimum value of K for $D < 2$ m. This is due primarily to the influence of resistance R_c dependency on TPG length $D + H$.

These K-curves are not necessarily applicable to single-phase grounding or single-phase line energization with three-phase grounding. In those cases, significant current may be present in the pole ground down-lead wires.

A sample data spreadsheet, table 7, is provided for No. 4/0 AWG copper TPGs for $H = 6$ m. It includes a single value for mutual reactance X_{ac} and $\%X_{ac}$ (in percent of X_a) for $D = 0.5$ m to show that it is insignificant (< 5%). The values for K_s represent K-factors for the A-phase TPG based only on current I_a and the TPG self-impedance (resistance and self-reactance) for length $L = H + D$.

Note that the average value of K_s is approximately 2.9 over the entire combined ranges of D and H for No. 4/0 AWG conductor in figure 19.

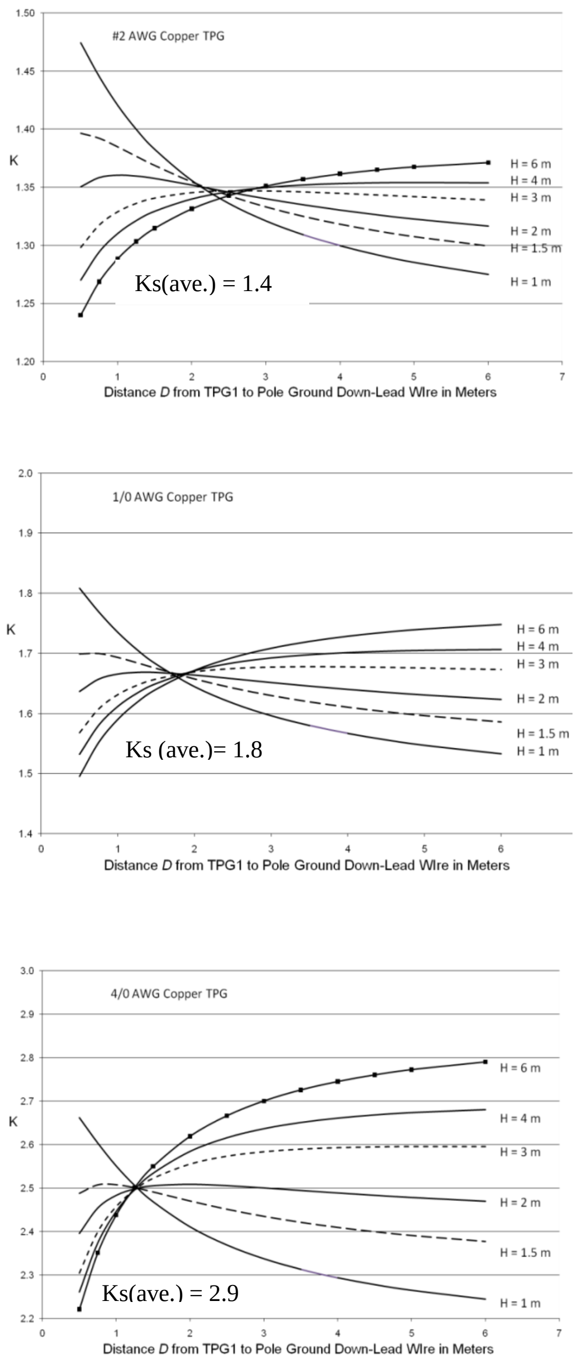


Figure 19. 60-Hz TPG impedance K-factor curves for transmission line three-phase worksite grounding.

Table 7. Sample Data Spreadsheet for Transmission Line 3-Phase TPG Worksite Grounding in Figure 17

TPG size	*H(m)*	X_{1sH}	*rad (cm)*	R_c *(Ω/m)*			X_{mac} *(0.5)*	X_{ac} *(0.5)*	$\%X_{ac}$ *(0.5)*			
4/0	*6*	*2.959E-03*	*0.819*	*0.000175*			*4.966E-04*	*9.783E-05*	*4.7*			
$D_{(m)}$	X_{mab}	$X_{1mH(d)}$	$X_{1sH(d)}$	K_{1sD}	$X_{1mD(h)}$	$X_{1sD(h)}$	X_a	X_{ab}	$\%X_{ab}$	Z_{g1}	K	K_s
0.5	7.440E-04	1.022E-03	1.936E-03	1.529E-04	3.134-06	1.497E-04	2.086E-03	2.782E-04	13.3	2.526E-03	2.22	3.01
0.75	5.944E-04	8.567E-04	2.102E-03	2.522E-04	7.033E-06	2.452E-04	2.347E-03	2.623E-04	11.2	2.777E-03	2.35	2.99
1	4.966E-04	7.440E-04	2.215E-03	3.580E-04	1.245E-05	3.455E-04	2.560E-03	2.474E-04	9.7	2.987E-03	2.44	2.98
1.25	4.265E-04	6.602E-04	2.298E-03	4.685E-04	1.937E-05	4.492E-04	2.748E-03	2.337E-04	8.5	3.174E-03	2.50	2.97
1.5	3.735E-04	5.944E-04	2.364E-03	5.829E-04	2.773E-05	5.551E-04	2.919E-03	2.209E-04	7.6	3.347E-03	2.55	2.96
2	2.984E-04	4.966E-04	2.462E-03	8.205E-04	4.861E-05	7.719E-04	3.234E-03	1.982E-04	6.1	3.667E-03	2.62	2.96
2.5	2.477E-04	4.265E-04	2.532E-03	1.068E-03	7.473E-05	9.930E-04	3.525E-03	1.788E-04	5.1	3.966E-03	2.67	2.96
3	2.113E-04	3.735E-04	2.585E-03	1.323E-03	1.057E-04	1.217E-03	3.802E-03	1.622E-04	4.3	4.253E-03	2.70	2.97
3.5	1.840E-04	3.319E-04	2.627E-03	1.584E-03	1.411E-04	1.443E-03	4.069E-03	1.479E-04	3.6	4.531E-03	2.73	2.98
4	1.628E-04	2.984E-04	*2.660E-03*	1.850E-03	1.805E-04	1.670E-03	4.330E-03	1.356E-04	3.1	4.803E-03	2.74	2.99
4.5	1.458E-04	2.708E-04	*2.688E-03*	2.121E-03	2.238E-04	1.898E-03	4.585E-03	1.250E-04	2.7	5.071E-03	2.76	3.00
5	1.320E-04	2.477E-04	*2.711E-03*	2.397E-03	2.705E-04	2.126E-03	4.837E-03	1.157E-04	2.4	5.336E-03	2.77	3.01
6	1.109E-04	2.113E-04	*2.747E-03*	2.959E-03	3.735E-04	2.585E-03	5.332E-03	1.004E-04	1.9	5.858E-03	2.79	3.04
$X_{tpg(b)}$	I1/f	Angle Z	I2/If	*Angle Y*	X_{m12}	X_{1s}						
2.127E-03	9.236E-01	1.178	7.895E-02	-13.919	3.271E-05	2.160E-03						

R_c = TPG cable resistance (excluding clamps and ferrules)
X_{1sH} = TPG1 self-reactance for length H
$X_{1mH(d)}$ = TPG1 mutual reactance for length H out to D
$X_{1sH(d)}$ = TPG1 self-reactance for length H out to D
X_{1sD} = TPG1 self-reactance for length D
$X_{1mD(h)}$ = TPG mutual reactance for length 2D out to H of unequal length conductors D and 2D
$X_{1sd(h)}$ = TPG1 self-reactance for length D out to H
X_a = TPG1 self-reactance for rectangle of dimensions H and D
X_{mab} = mutual reactance of vertical portion of TPG1 with common BØ TPG
X_{ab} = mutual reactance of vertical portion of TPG1 with pole ground down-lead due to current I_b in common BØ TPG
$\%X_{ab}$ = X_{ab} in percent of X_a (information)
Z_{g1} = A-phase TPG1 equivalent impedance (includes R of cable, clamps, ferrules) producing touch potential at worker position during balanced 3-phase short-circuit current
K = TPG1 impedance correction factor
K_s = TPG1 impedance correction factor based only on self-reactance (R_c + 0.0003 + jX_{1sD})
All reactance values at 60 Hz

This suggests that, for conservative results, the TPG self-impedance can be used to determine touch voltage. Likewise, average values of K_s for each size conductor over the entire combined ranges of *D* and *H* are shown on all the graphs of figure 19.

Utility Line Structure Grounding

The grounding scheme from figure 17 is modified for utility pole grounding in figure 20, with only line and TPG conductors shown; distance *D* between line conductors is usually less than 2*D* for the transmission line. Two TPGs are connected in a line-to-line (chain) grounding configuration. Simulated TPGs for modeling purposes are the solid lines of length $2H + D$. The vertical segments of TPGs connected to the B-phase line conductor are separated $D/3$ to account for the hang of the actual TPGs. A third TPG typically connects from the center B-phase line to the neutral and/or pole ground down-lead wire or other temporary earth electrode. Balanced three-phase line currents are assumed with no current in a neutral or earth ground wire.

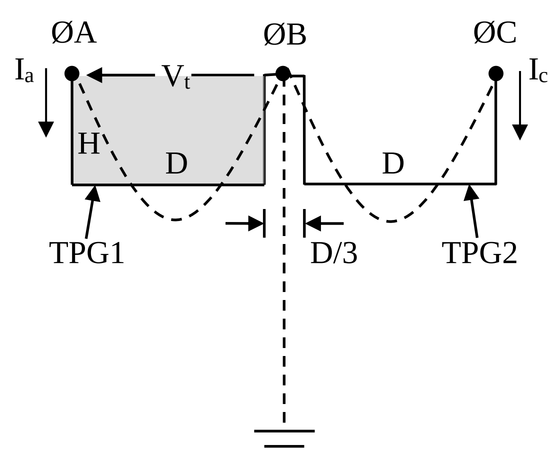


Figure 20. Graphic representation of three-phase TPG chain grounding circuit at utility line pole. Actual TPGs are depicted by dashed lines, and simulated TPGs are depicted by solid lines of length *2H + D.*

Worker touch voltage V_t in figure 20 is found using a similar calculation procedure as for the transmission line model, except induced touch voltage components are calculated for each current (I_a and I_c) in the vertical segments of the TPG connections to the B-phase line conductor. This is necessary for adequate modeling of the magnetic coupling with the ground loop bounded by the current-carrying conductor at B-phase. In the transmission line case, the ground loop was bounded by the noncurrent-carrying ground down-lead wire, making the model less sensitive to the conductor shape chosen to carry current I_b.

The derivation of the K-factor expression for the AB-phase connected TPG1 (or BC-phase connected TPG2 due to symmetry) is left to the reader. It has the same form as equation (52) for the transmission line case:

$$K = \frac{\sqrt{(R_c + 0.0003 - 0.866X_{12-b})^2 + (X_{hd} + 0.5X_{12-b})^2}}{R_c} \qquad (53)$$

where

X_{12-b} = mutual reactance of TPG1, due to current I_c in adjacent (ØB) vertical segment of TPG2, ohm

X_{hd} = TPG self-reactance of shaded rectangle sides $2H+D$, ohm

and, again, noting that the contribution to induced voltage V_t, due to current I_c in the vertical segment of TPG2 connected to the C-phase line conductor, is neglected.

Utility Line Structure Grounding Example

Three families of K-factor curves for three-phase TPG worksite chain grounding (figure 20) plotted from equation (53) are shown in figure 21 for No. 2, No. 1/0, and No. 4/0 AWG copper TPGs.

A sample data spreadsheet, table 8, is provided for No. 4/0 AWG copper TPGs for H = 3 m. The values for K_s represent K-factors for the A-phase TPG based only on current I_a and the TPG self-impedance (resistance and self-reactance) for length $L = H + D$. Values for K_s are also shown for each size conductor in figure 21, and they apply to all curves in a family. The range of K for each family of curves is relatively small; an average value K-factor could be chosen to adequately represent each TPG conductor size.

Table 8. Sample Data Spreadsheet for Utility Line 3-Phase (Chain) Worksite Grounding in Figure 4, for No. 4/0 Copper TPGs

4/0	*H(m)*		*rad (cm)*	*R_c (Ω/m)*												
	3		*0.819*	*0.000175*												
$D_{(m)}$	X_{sh}	X_{mh}	X_h	K_{sd}	X_{md}	X_d	X_{hd}	$X_{12\text{-}b}$	$\%X_{12\text{-}b}$	Z_g	K	X_{12m}	K_s	A	B
0.5	1.323E-03	3.720E-04	9.505E-04	1.529E-04	3.134E-06	1.497E-04	2.051E-03	2.785E-04	1.358E+01	2.255E-03	1.98	5.968E-04	2.77	2.209E+00	8.022E-01
1		2.483E-04	1.074E-03	3.580E-04	1.245E-05	3.455E-04	2.494E-03	2.484E-04	9.960E+00	2.708E-03	2.21	4.520E-04	2.75	1.550E+00	6.499E-01
1.5		1.868E-04	1.136E-03	5.829E-04	2.773E-05	5.551E-04	2.827E-03	2.228E-04	7.883E+00	3.064E-03	2.33	3.720E-04	2.75	1.195E+00	5.352E-01
2		1.492E-04	1.173E-03	8.205E-04	4.861E-05	7.719E-04	3.119E-03	2.011E-04	6.450E+00	3.382E-03	2.42	3.183E-04	2.76	9.671E-01	4.491E-01
2.5		1.239E-04	1.199E-03	1.068E-03	7.473E-05	9.930E-04	3.390E-03	1.827E-04	5.388E+00	3.679E-03	2.47	2.788E-04	2.77	8.089E-01	3.837E-01
3		1.057E-04	1.217E-03	1.323E-03	1.057E-04	1.217E-03	3.650E-03	1.669E-04	4.572E+00	3.965E-03	2.52	2.483E-04	2.79	6.931E-01	3.333E-01
3.5		9.201E-04	1.230E-03	1.584E-03	1.411E-04	1.443E-03	3.904E-03	1.533E-04	3.928E+00	4.242E-03	2.55	2.238E-04	2.80	6.052E-01	2.937E-01
4		8.139E-04	1.241E-03	1.850E-03	1.805E-04	1.670E-03	4.152E-03	1.416E-04	3.410E+00	4.513E-03	2.58	2.036E-04	2.82	5.364E-01	2.620E-01
4.5		7.292E-04	1.250E-03	2.121E-03	2.238E-04	1.898E-03	4.397E-03	1.313E-04	2.986E+00	4.781E-03	2.60	1.868E-04	2.84	4.812E-01	2.361E-01
5		6.601E-04	1.256E-03	2.397E-03	2.705E-04	2.126E-03	4.639E-03	1.223E-04	2.636E+00	5.045E-03	2.62	1.724E-04	2.86	4.360E-01	2.146E-01
6		5.545E-04	1.267E-03	2.959E-03	3.735E-04	2.585E-03	5.119E-03	1.073E-04	2.095E+00	5.566E-03	2.65	1.492E-04	2.90	3.667E-01	1.813E-01

Rc = TPG cable resistance (excluding clamps and ferrules)

Xsh = TPG self-reactance for length H

Xmh = TPG mutual reactance for length H out to D

Xh = TPG reactance for length H out to D

Xsd = TPG self-reactance for length D

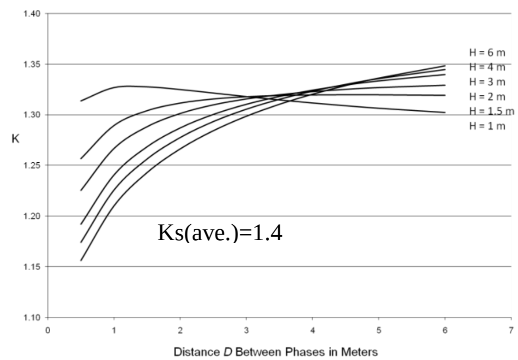
Xmd = TPG mutual reactance for length D out to H

Xd = TPG reactance for length D out to H
Xhd = TPG reactance for rectangle of dimensions H and D due to self-current
X12m = mutual reactance of vertical segment of BCØ TPG connected to BØ line conductor

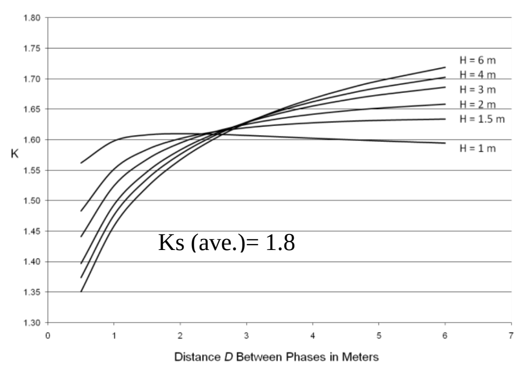
X12-b = coupled reactance of TPG1 (ABØ) due to current in adjacent TPG2 (BCØ)

%X12-b = X12 in percent of Xhd (informational)
Zg = 3-ph balanced fault composite impedance of ABØ TPG due to currents in A and B phases; C neglected)
K = TPG impedance correction factor
Ks = TPG impedance correction factor based only on self-reactance (Rc+0.0002+jXsh+jXsd)
All reactance vales at 60 Hz
Note: For calculation of X12m, A, and B mutual reactance variables the distance between the vertical segments of A- and C-phase TPGs connected to B-phase line conductor is D/3. This accounts for some spreading of the A- and C- phase TPGs as D increased.
The A and B variables break Grover's mutual inductance formula into two parts for the calculation of the mutual reactance of C-phase TPG vertical segments at B-phase line conductor with A-phase TPG vertical segment at A-phase line conductor.

No. 2 AWG Copper TPG length = 2*H* +



No. 1/0 AWG Copper TPG length = 2*H* + *D*



No. 4/0 AWG Copper TPG length = 2*H*

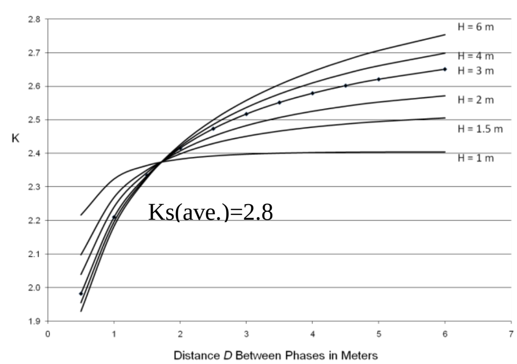


Figure 21. 60-Hz TPG impedance K-factor curves for utility line -phase (chain) worksite grounding line-to-line exposure.

Chapter 6

Conclusion

Electrical grounding models for six temporary protective grounding scenarios covered in this book illustrate the effect magnetic induction has on worker touch voltage when a worksite is accidentally energized. The underlying induction principles are presented and developed into touch voltage equations in terms of the self- and mutual reactances for the TPGs. These grounding models are the basis for applying TPG impedance correction K-factors that appear in IEEE 1246.

Temporary protective grounding staged-fault field tests [3] [4] confirm the model predictions of higher value touch voltages due to TPG induction ground loops formed with the worker.

The induction ground loop effect is demonstrated in [3] for the case of a grounded generator bus with TPGs between worker and energy source. The measured touch voltage remote from the point of attachment of the TPGs to the bus is two or more times the fault voltage drop measured directly across the TPGs (refer to figures 1 and 3, as well as table 1, in [3]). For the transmission line grounding tests [3] [4], the measured touch voltages from line conductor to structure are approximately three times the fault voltage drop directly across the TPG forming the ground loop with the worker (refer to figures 9 and 10 in [3] and Test 6, figure 3, and table 2 in [4]). The above-referenced field test examples do not precisely fit the grounding models presented in this paper; however, the test data generally confirm the model predictions and are useful for study.

In the previous chapters, impedance correction K-factors are described which adjust the resistance of the TPG conductor to an equivalent shunt impedance across the worker's body. This equivalent impedance, multiplied by the worksite available short-circuit current, approximates the actual touch voltage due to the physical layout of the TPGs, creating an induction ground loop with the worker. In some cases, touch voltage calculation can be further simplified by using the TPG conductor self-impedance (resistance and self-reactance) to determine K-factors, making it independent of the physical layout at the worksite.

Touch (exposure) voltage is shown to be approximately three times higher, depending on the physical arrangement of TPGs with the worker, if the reactive IX voltage drop of the cable is included with the resistive IR voltage drop; however, for the case of working between an energy source and TPGs, the touch voltage (and K-factors) continues to rise with worker distance from the TPGs.

References

[1] The Institute of Electrical and Electronics Engineers, IEEE Standard No. 1246-2011, *IEEE Guide for Temporary Protective Grounding Systems Used in Substations*, 2011.

[2] Grover, Frederick W., *Inductance Calculations*, Dover Publications, Inc., Mineola, New York, 2004.

[3] Atwater, P.L., and J.M. DeHaan, "Staged Fault Test Evaluation of Safety Grounding For High-Voltage Equipment and Transmission Lines," *Proceedings of 2000 T&D World Expo*, p. 317-338, 2000.

[4] Atwater, P.L., J.M. DeHaan, and A. Roman, "Evaluation of Safety Grounding Practices for Maintenance Work on De-Energized Transmission Lines," Proceedings of 2001 IEEE/PES Transmission and Distribution Conference, Distribution System Maintenance and Operation Session, 2001.

Biography

Philip L. Atwater received a B.S. degree in electrical engineering from Michigan State University, East Lansing, Michigan in 1977, and is a registered Professional Engineer.

He is retired from the Bureau of Reclamation and is currently a consultant with over 37 years of experience in the electric power fields of plant controls design, power system equipment diagnostics, research, and field testing. Philip has performed several research-related, staged fault protective grounding tests on high-voltage transmission lines and equipment. In addition, he served on the IEEE Substations Safety Working Group for the 1246-2011 Standard [1] revision.

James M. DeHaan received a B.S. degree in electrical engineering from Dordt College, Sioux Center, Iowa in 1989, and M.S. degree in electric power engineering from Iowa State University, Ames, Iowa in 1991. He is a registered Professional Engineer.

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