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Final Report

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Modeling and Testing of Steel EMT, IMC and RIGID (GRC) Conduit

Part 1

Prepared by

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Disclaimer

This report contains (a) field test data and (b) results obtained with a model computer program. Every effort has been made to ensure accurate instrumentation for the field tests and to validate the computer program. However, the authors disclaim any responsibility relative to the utilization of these results.

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Glossary

EMT	Electrical Metallic Tubing
IMC	Intermediate Metal Conduit
GRC	Galvanized Rigid Conduit
Arc Voltage, $\mathbf{V}_{arc}$	The voltage across the electric arc between two phase conductors or between a phase conductor and a grounding conductor.
Short Circuit Current	The electric current flowing in a circuit whenever a short circuit is applied.
Overcurrent Protective Device, **OPD**	A protective Device which is designed to disconnect a circuit whenever the electric current exceeds a certain value.
Minimum Ground Fault Current, $\mathbf{I}_{GFC}$	The minimum ground fault current which will result in the safe operation of an overcurrent protective device within specified time. This value is normally selected as a multiple of the overcurrent protective device rating.
Maximum Allowable Length, $\mathbf{L}_{max}$	The length of the conduit which will result in a total ground fault current equal to or higher than a specified value, $\mathbf{I}_{GFC}$, with an arc voltage equal or lower than a specified value, $\mathbf{V}_{arc}$.
Permeability	The property of the material which equals the ratio of magnetic flux density to the magnetic field intensity.

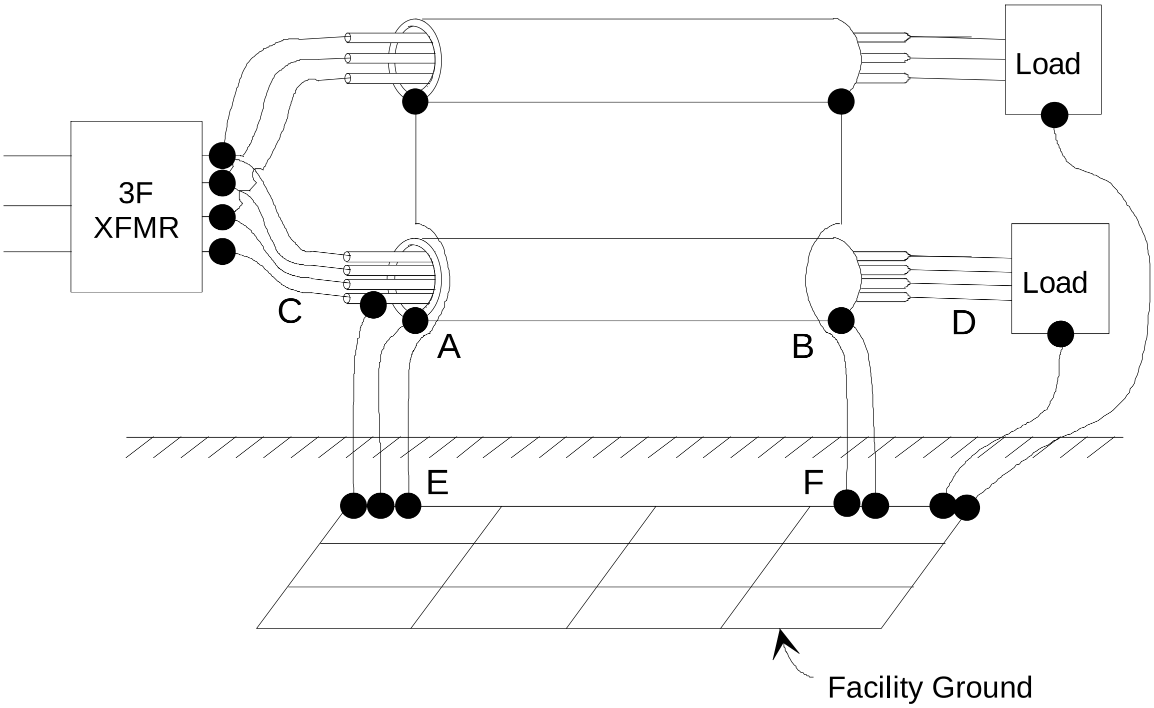
Modeling and Testing of Steel EMT, IMC, and RIGID (GRC) Conduit

1.0 Introduction

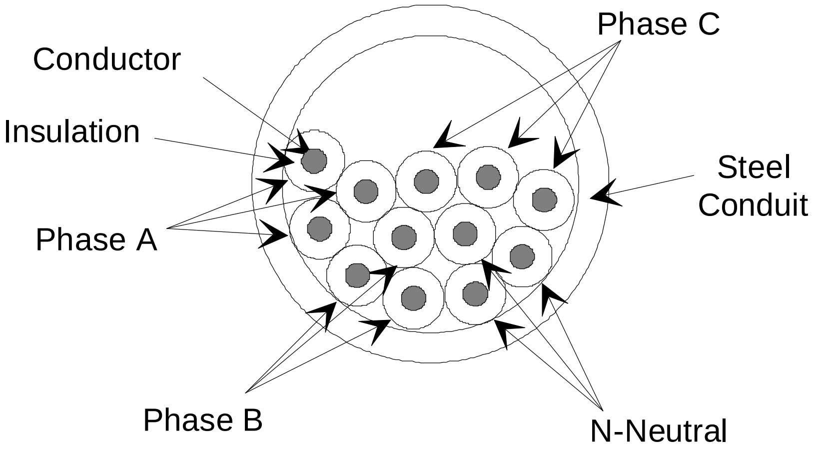
Steel conduit is widely used in secondary power distribution systems, indoors and outdoors. Systems are designed in such a way that the steel conduit does not carry any appreciable electric current under normal operating conditions. Under certain fault conditions, the steel conduit will carry most of the return fault current or in some cases it will be the only return path of the fault current to the source. In reality, the conduit is only one of fault current return paths as illustrated in Figure 1.1a. Specifically, in a practical system the fault current will split among several parallel paths in returning to the source. As an example, for a phase to neutral to ground fault in the bottom conduit of Figure 1.1a the fault current will return to the source through the conduit (path BA), neutral (path DC), and facility ground (path FE). For a phase to conduit fault, the fault current will return to the source through the conduit and facility ground. It is possible that for a phase to conduit fault the only return path for the fault current is the conduit. This is possible for the systems illustrated in Figures 2.1a, 2.1c, and 2.1d. For a single phase to neutral conductor fault, the fault current return path is through the neutral conductor; the neutral conductor may have a higher impedance than the previously noted fault current paths. Therefore, the type of fault becomes the limiting factor. This report is focused on the performance of steel conduit as the equipment grounding conductor so we used the situation where the only fault path is the steel conduit, as the worst case condition.

It is important to discuss other fault conditions which represent worst conditions and determine the design procedure of electrical installations. For this reason consider the simplified installations of Figure 2.1. For a single phase to neutral conductor fault in the systems of Figures 2.1a, 2.1b, and 2.1d, the fault current return path is through the neutral conductor only. The steel conduit does not participate in the fault circuit. For neutral conductor sizes, as recommended in standards, the impedance of the fault current path for these cases is higher than the impedance for a fault to the steel conduit. Consequently, for these cases, the maximum allowable length of the circuit is dictated by the phase to neutral conductor fault.

In recent years fault current levels have increased. For this reason it appeared prudent to reexamine existing parameters for equipment grounding conductors. A program was initiated to evaluate the performance of steel EMT, IMC, or RIGID conduit during faults in secondary distribution systems. A relevant issue is that of grounding of steel conduit. For many technical and safety reasons, electric power installations must be grounded. Two main considerations are: (a) protection in the event of faults and (b) avoidance of electric shocks. As the capacity of the secondary distribution systems increases so does the short circuit capacity and associated protection and safety concerns. Performance of equipment grounding conductors can be best determined by exact modeling and testing of the system under various excitation and fault conditions. This program did exactly that.



(a) Side View with Typical Grounding



(b) Cross Section of a Typical Steel Conduit Enclosed Distribution Circuit

Figure 1.1. Illustration of Steel Conduit Enclosed Secondary Distribution System

For many years, the techniques established by the IAEI Soares Book on Grounding [1] have provided the primary design guidance. Fortunately, computer and analytical means which have developed at a rapid pace have now made it possible to develop and validate a model utilizing current data which can be used with confidence.

This report contains the results of a research project which addressed the critical issues. The report addresses three fundamental issues associated with the use of steel conduit in secondary power distribution systems:

- Does steel EMT, IMC, and RIGID conduit in a specific system perform effectively as equipment grounding conductor with (a) the capacity to safely conduct any fault current likely to be imposed on it; and (b) have sufficiently low impedance to limit the voltage to ground and facilitate the operation of the circuit protective devices, as stated in Article 250-51 of the National Electrical Code (NEC)?

- What length of run using specific steel conduit types and sizes, and specific wires or cables, can be safely installed?

- Are there additional benefits of a supplemental grounding conductor used in these steel conduit enclosed secondary power systems?

The above issues have been investigated by performing the following tasks: (a) modeling of steel conduit enclosed multiconductor systems, (b) laboratory testing of several representative steel conduit types under low currents for the purpose of characterizing the magnetic material, (c) computer simulation of steel conduit enclosed secondary distribution systems, (d) full scale testing of steel conduit enclosed power systems under high fault current, (e) full scale measurement of arc voltage for various fault current levels, and (f) analysis of full scale test results and conclusions. Details of these tasks are included in this report.

A summary of the results of the investigation is as follows:

- A model of steel conduit enclosed power distribution systems has been developed and validated with laboratory and full scale measurements.

- Comparably sized steel EMT, IMC and RIGID conduit will allow the flow of higher fault current than an equipment grounding conductor as listed in NEC Table 250-95.

- Steel EMT, IMC and RIGID conduit, not exceeding the maximum allowable length, meets the requirements of Article 250-51 of the NEC. As a matter of fact, the performance of steel conduit sized in accordance with Chapter 9, Table 1 of the NEC, compared to the minimum size equipment grounding conductors in Table 250-95, allows the flow of higher fault current. This is due to the lower impedance of the steel conduit.

- Steel EMT, IMC and RIGID conduit are of sufficiently low impedance to limit the voltage to ground and facilitate the operation of the circuit protective devices in runs not exceeding the maximum allowable lengths detailed in this report. In most cases, the maximum allowable lengths exceed those permitted by the IAEI Soares Book on Grounding [1] using the same arc voltage and ground fault current.

- The arc voltage of 50 volts and the ground fault current of 500% of the overcurrent device rating, as stated in the IAEI Soares Book on Grounding, 1993 edition [1], is overly conservative as a design guide. Testing for this project confirmed the actual voltage across a fault arc to be up to 30 Volts for an arc length of 75 mils and fault current ranging from 400 to 2500 Amperes.

- A validated computer model has been developed which computes the maximum allowable lengths for specific conductor size enclosed by specific size steel EMT, IMC or RIGID conduit under fault conditions.

- Where lengths do not exceed the maximum allowable computed by the method, supplemental grounding conductors in secondary power systems enclosed in steel EMT, IMC or RIGID conduit are not necessary. The supplemental conductor is sometimes required by the NEC in critical installations such as health care areas, where dual protection for patients is considered prudent.

- We compared the recommended maximum allowable lengths listed in the IAEI Soares Book on Grounding to those computed with the validated model for the same arc voltage and ground fault current. In general, we found that the IAEI Soares Book on Grounding numbers are in reasonable agreement except that in some cases we found errors. The detailed comparison and explanation is given in Section 5.

- The maximum allowable length for a specific system depends on conductor size, steel conduit size and fault type. In many cases, the maximum allowable length for a phase to neutral fault is shorter than the maximum allowable length for a phase to steel conduit fault. Thus in most cases the steel conduit *is not* the limiting factor. In these cases, use of a supplemental grounding conductor will not increase the maximum allowable length. We recommend the use of the validated computer model to compute the maximum allowable length in specific systems.

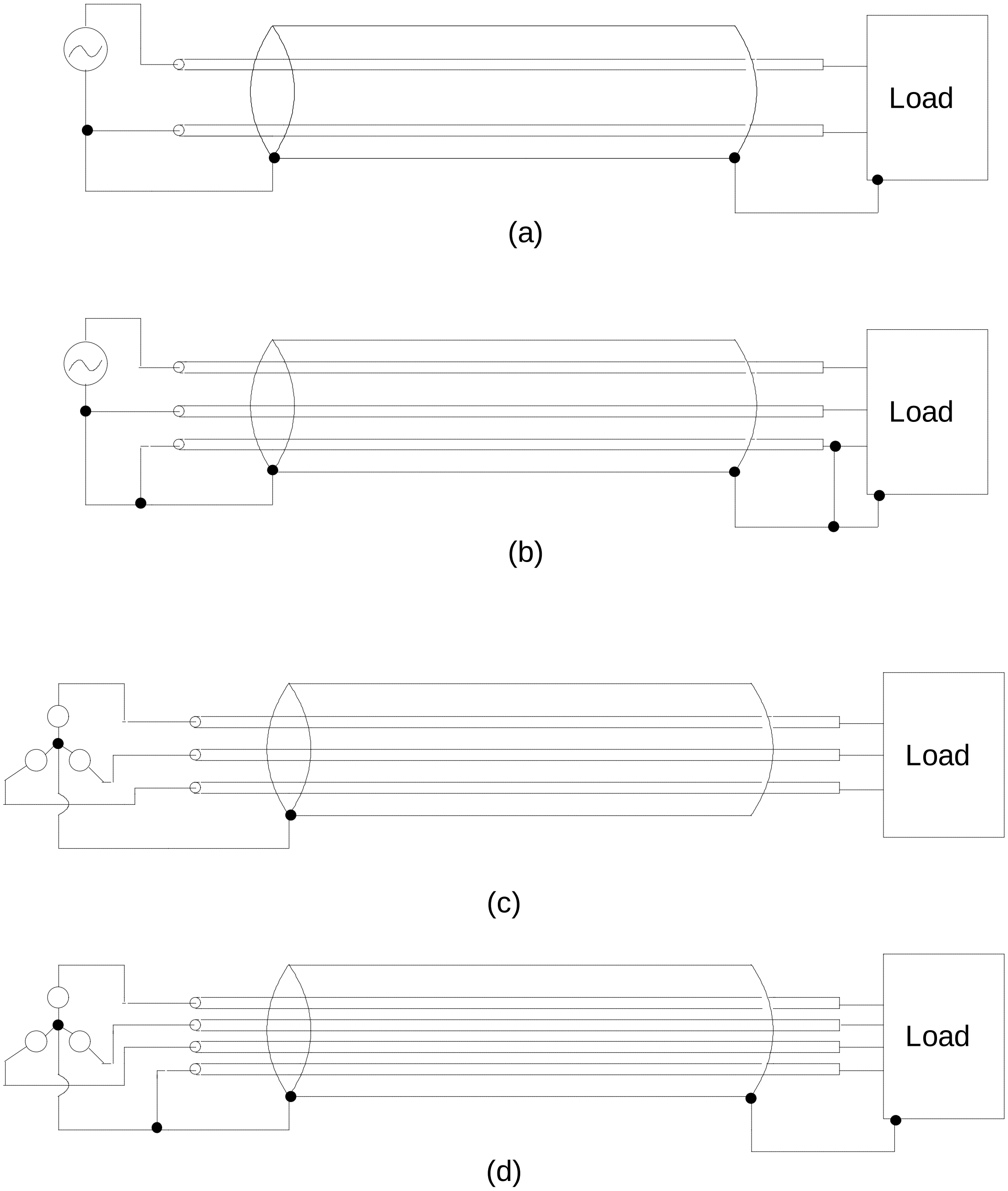


Figure 2.1. Illustration of Simplified Installations
(a) Single Phase Circuit without Ground Conductor
(b) Single Phase Circuit with Ground Conductor
(c) Three Phase Circuit without Neutral
(d) Three Phase Circuit with Neutral

2.0 Determination of Steel Conduit Material Parameters

This section describes the method used to determine the resistivity and permeability of steel conduit material as functions of magnetic field density and temperature. The determination of the required steel conduit material parameters consists of two steps: (a) development of a model of steel conduit and (b) performing measurements from which the parameters of the model are derived.

An illustration of steel conduit enclosed secondary distribution systems is illustrated in Figure 1.1. Modeling of this system consisted of four parts: (a) characterization of the steel conduit material, (b) proper characterization and modeling of the grounding system, (c) modeling of the secondary distribution system conductors, including single conductor per phase distribution systems with or without neutral, as in Figure 1.1a, as well as multiconductor per phase systems as is shown in Figure 1.1b, and (d) modeling of the source.

The objective of characterization of the steel conduit material is to define the parameters of the steel conduit (resistivity and permeability) as functions of magnetic field and temperature. This section describes a procedure by which the steel resistivity and permeability at various magnetic field levels and temperatures is measured. The laboratory setup for this measurement is illustrated in Figure 2.1. Specifically, the laboratory setup consists of a short section of steel conduit, an excitation coil and measurement of the waveform of the magnetization current as well as measurement of the waveform of the applied voltage. From the measured magnetization current, i(t), and the measured excitation voltage, v(t), the B vs. H curve or the steel permeability versus magnetic field intensity inside the steel is derived using the formula:

$$\frac{B(t)}{H(t)} = a\int v(t)dt/i(t)$$

where: a is a constant. This constant is given in Appendix A.

The pertinent mathematical model is also described in Appendix A. Note that the procedure yields the B vs. H curve of the material point by point. The measured permeability data are utilized in the model, see Appendices B and C.

A number of steel conduit samples were cut into two to three inch sections as illustrated in Figure 2.1. Using the samples shown in Figure 2.1, the published characteristics of the steel material were verified within the instrumentation accuracy (1%).

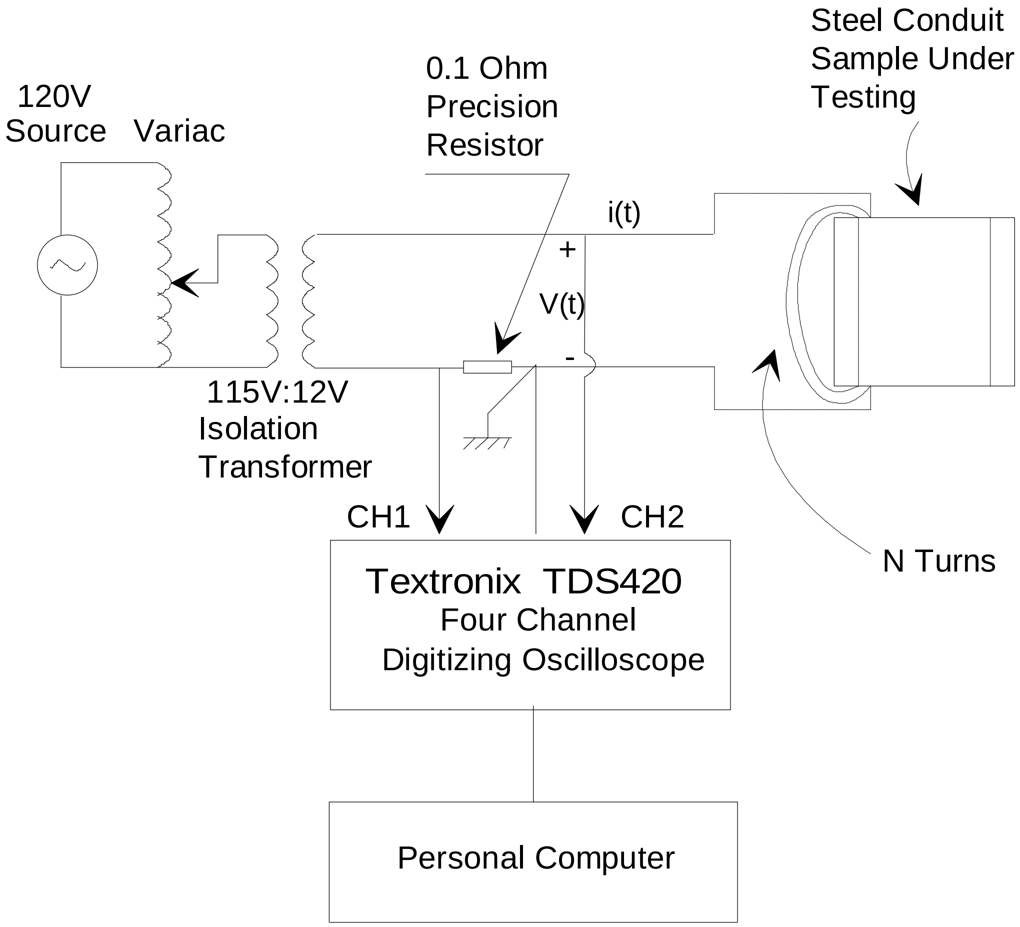


Figure 2.1. Laboratory Setup for Steel Conduit Permeability Measurement

Table 2.1. List of Steel Conduit Samples for Testing

Sample #	Type	Length (inches)	Inner Diameter (inches)	Outer Diameter (inches)
1	EMT	2.5	2.067	2.197
2	EMT	2.0	0.824	0.922
4	IMC	2.5	2.150	2.359
5	GRC	2.5	2.083	2.375
6	IMC	3.0	3.176	3.476
7	EMT	3.0	3.356	3.500

3.0 Computer Modeling of Steel Conduit Enclosed Power Systems

The objective is to model the steel conduit enclosed distribution power systems of the system shown in Figure 1.1. The modeling approach used for deriving a proper circuit model is illustrated in Figure 3.1. The Figure shows a conduit which encloses N cables. Under balanced operating conditions, electric current will flow only in the phase conductors of the system. Unfortunately, most practical systems do not operate under balanced conditions. In this case some electric current will flow in the steel conduit under normal operating conditions. The level of this current depends on the degree of unbalance and the grounding of the neutral. Another condition which results in substantial electric current through the steel conduit is related to the existence of harmonics. Third harmonics may return to the source through the steel conduit if the steel conduit is bonded to the neutral at the two ends. In general, systems are designed in such a way that the electric current through the steel conduit under normal operating conditions is minimized. Under a specific fault condition, however, substantial electric current will flow in the conductors and in the steel conduit. Because of skin effect, proximity of conductors to conduit, and the magnetic properties of steel conduit, the current distribution over the cross section of the conductors and conduit will be nonuniform. The current distribution obeys Maxwell's [15] equations.

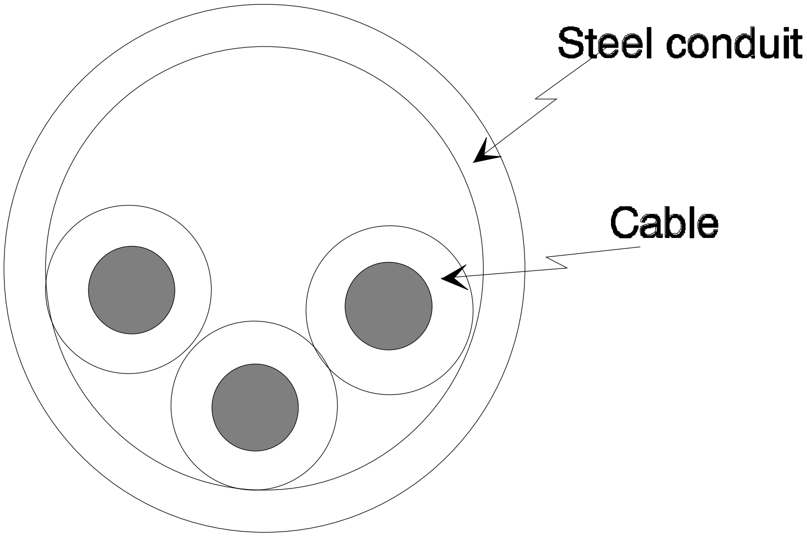


Figure 3.1. Cross Section of a Steel Conduit Enclosed Distribution System

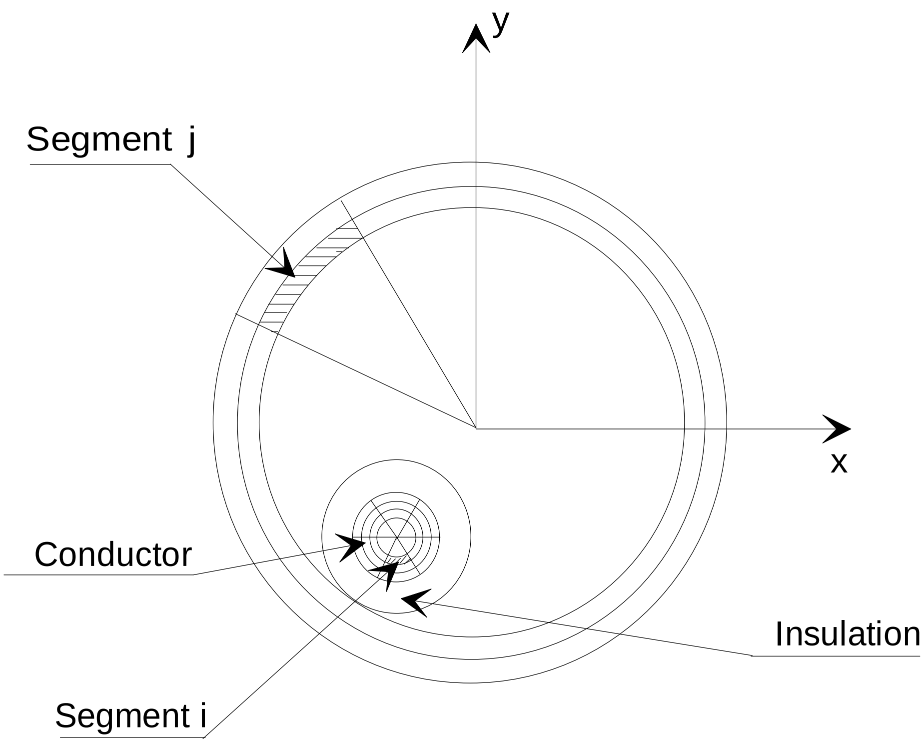


Figure 3.2. Illustration of Partitioning the Metallic Parts of a Steel Conduit Enclosed Power System into *Segments*.

For the purpose of deriving this current distribution, the cross section of the conductors and conduit is partitioned into *segments* as illustrated in Figure 3.2. For simplicity the figure shows only one cable inside a steel conduit. Because the cross section of a segment is small, the current distribution over the surface of a *segment* is uniform. In this case, each *segment*, i, can be characterized with a <u>geometric mean radius</u>, GMR_i, and a <u>geometric mean distance</u>, GMD_{ij}, from any other *segment*, j, in the system. The computational procedure for the quantities GMR_i and GMD_{ij} is presented in Appendix B. Now the voltage across a *segment*, i, is given by the following equation [2]:

$$\tilde{V}_i = \sum_j (r_{ij} + x_{ij}) \tilde{I}_j \qquad (3\text{-}1)$$

where

$$r_{ij}(\Omega/\ m) = \left\{ \begin{array}{ll} 0.9879\text{x}10^{-6}\,f\ (\Omega/\text{m}) & j \neq i \\ \rho_i(T_i)\dfrac{1}{A_i} + 0.9879\text{x}10^{-6}\,f\ (\Omega/\text{m}) & j = i \end{array} \right\}$$

ρ_i is the resistivity of segment i material $(\Omega \cdot \text{m})$

A_i is the cross section area of segment i (m^2)
T_i is the temperature of segment i $(°C)$

$$x_{ij} = \frac{j\omega\mu_i}{2\pi} \ln \frac{D_e}{D_{ij}} \tag{3-2}$$

μ_i is the permeability of *segment* i material

$$D_{ij} = \begin{cases} GMD_{ij} & j \neq i \\ GMR_i & j = i \end{cases}$$

$D_e = 2160\sqrt{\frac{\rho}{f}} \times 0.3048$ in meters
r = soil resistivity in $\Omega \cdot m$
f = frequency of currents in Hz

$$r_i(T_i) = r_{io} + \alpha_i (T_i - T_o) \tag{3-3}$$

α_i is a constant and T_i, T_o in °C

Now assume that the first m_1 *segments* belong to conductor 1, the next m_2 *segments* belong to conductor 2, etc and the last m_k *segments* belong to the steel conduit. Note that k = N+1 where N is the number of conductors. Writing one equation (3-1) for each slice in the above order one obtains the following equation in matrix form:

$$\begin{bmatrix} V^1 \\ V^2 \\ \bullet \\ \bullet \\ \bullet \\ V^k \end{bmatrix} = \begin{bmatrix} Z^{11} & Z^{12} & \bullet\ \bullet\ \bullet & Z^{1k} \\ Z^{21} & Z^{22} & \bullet\ \bullet\ \bullet & Z^{2k} \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ Z^{k1} & Z^{k2} & \bullet\ \bullet\ \bullet & Z^{kk} \end{bmatrix} \begin{bmatrix} I^1 \\ I^2 \\ \bullet \\ \bullet \\ \bullet \\ I^k \end{bmatrix} \tag{3-4}$$

where

V^1 is a vector of voltages across *segments* of conductor 1 (an $m_1 \times 1$ vector).
I^1 is a vector of currents flowing through the *segments* of conductor 1 (an $m_1 \times 1$ vector), etc.
k = N + 1.

Note that the sum of elements in vector I^1 is the total current I_1 through conductor 1, etc. Also note that the voltages in the vector V^1 must be the same and equal to V_1, the voltage along conductor 1, since there is no voltage drop along the cross section of a conductor (otherwise current will flow perpendicular to the conductor).

Equation (3-4) is inverted yielding:

$$\begin{bmatrix} \tilde{I}^1 \\ \tilde{I}^2 \\ \bullet \\ \bullet \\ \bullet \\ \tilde{I}^k \end{bmatrix} = \begin{bmatrix} Y^{11} & Y^{12} & \bullet\ \bullet\ \bullet & Y^{1k} \\ Y^{21} & Y^{22} & \bullet\ \bullet\ \bullet & Y^{2k} \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ Y^{k1} & Y^{k2} & \bullet\ \bullet\ \bullet & Y^{kk} \end{bmatrix} \begin{bmatrix} \tilde{V}^1 \\ \tilde{V}^2 \\ \bullet \\ \bullet \\ \bullet \\ \tilde{V}^k \end{bmatrix} \qquad (3\text{-}5)$$

Next the first m_1 equations are summed yielding one equation, the next m_2 equations are summed yielding another equation, etc. The final result is $k = N+1$ equations where the total current through the conductors and the steel conduit appear, i.e.

$$\begin{bmatrix} \tilde{I}_1 \\ \tilde{I}_2 \\ \bullet \\ \bullet \\ \bullet \\ \tilde{I}_k \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \bullet\ \bullet\ \bullet & y_{1k} \\ y_{21} & y_{22} & \bullet\ \bullet\ \bullet & y_{2k} \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ \bullet & \bullet & \bullet\ \bullet\ \bullet & \bullet \\ y_{k1} & y_{k2} & \bullet\ \bullet\ \bullet & y_{kk} \end{bmatrix} \begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \\ \bullet \\ \bullet \\ \bullet \\ \tilde{V}_k \end{bmatrix} \qquad (3\text{-}6)$$

The above equation represents the model of the steel conduit enclosed power system. This model provides the electric current flowing into the power conductors and the steel conduit for a given set of voltages applied to the steel conduit enclosed system.

4.0 Simulation of Steel EMT, IMC and RIGID Conduit Enclosed Power Systems

The model described in section 3 has been utilized to study the performance of the above steel conduit of various sizes for power systems of different voltage levels with different size phase conductors, grounding conductors and short circuit capacity. The purpose of the simulations was to define meaningful laboratory tests under high current conditions. For the simulation tests, eight typical power systems have been considered as shown in Table 4.1.

Table 4.1. List of Eight Typical Systems Used in the Performance Evaluation

System	Available Fault Current (at main bus)	Nominal Voltage	Source Impedance (ohms)
1	25 kA	480/277	0.0111
2	25 kA	208/120	0.0048
3	50 kA	480/277	0.0055
4	50 kA	208/120	0.0024
5	100 kA	480/277	0.0028
6	100 kA	208/120	0.0012
7	200 kA	480/277	0.0014
8	200 kA	208/120	0.0006

For each one of these power systems, 10 different steel conduit enclosed distribution systems were selected yielding a total of 80 cases. The ten steel conduit enclosed distribution systems are listed in Table 4.2. Table 4.3 illustrates the characteristics of the power conductors listed in Table 4.2. Note also that a typical protective device rating is listed for each conductor in Table 4.2 (indicated as Overcurrent Protective Device Rating) for each one of these systems. Table 4.2 also provides the DC resistance of the steel conduit. The impedance of steel conduit depends on the steel conduit parameters but also depends on power conductor type and size, fault condition and level of fault current. Because the impedance depends on the above factors, the practice of using k factors to account for the impedance of steel conduit is only an approximation. This approximation was justifiably expedient when established several decades ago. Today, with the available information and computer models, it is not appropriate to use k factors and the underlying approximation.

Table 4.2. Steel Conduit Systems Targeted for Full Scale Testing

Steel Conduit Type and Size	Conductors (2)	*Overcurrent Protective Device Rating (Copper)	**Steel Conduit Resistance (Ohms per 1000 ft)
GRC 3/4"	2×#8	50	0.2442
GRC 2"	2×3/0	200	0.0757
GRC 3"	2×350kcmil	310	0.0365
IMC 3/4"	2×#8	50	0.2915
IMC 2"	2×3/0	200	0.0961
IMC 3"	2×350kcmil	310	0.0456
EMT 1/2"	2×#10	30	0.7489
EMT 3/4"	2×#8	50	0.4881
EMT 2"	2×3/0	200	0.1507
EMT 3"	2×350kcmil	310	0.0846

* Based on 1993 NEC Table 310-16, Column 75°C

** DC Resistance at 25°C

Table 4.3. Electrical Characteristics of Power Conductors Used in the High Fault Current Tests.

Conductors	DC Resistance(@75°C)* (Ohms/Mft) Copper	Area (cir mils)	Diameter (inches)
10	1.24	10,380	0.116
8	0.778	16,510	0.146
3/0	0.0766	167,800	0.470
350 kcmil	0.0367	350,000	0.681

*From NEC, Chapter 9, Table 8.

For each one of the listed systems, the maximum allowable length of steel conduit, L_{max}, has been computed. The definition of L_{max} has been given in the Glossary and repeated here.

Maximum Allowable Length of Steel Conduit: It is the length of the conduit which will result in a total ground fault current equal to or higher than a specified value, I_{GFC}, with an arc voltage equal or lower than a specified value, V_{arc}

As it is apparent from the definition, the maximum allowable length of steel conduit is dependent upon the arc voltage, V_{arc}, of the fault and the ground fault current, I_{GFC}. It appears that the currently accepted practice driven by the IAEI Soares Book on Grounding, 1993 edition [1] is to assume that the arc voltage, V_{arc}, is 50 volts and the ground fault current, I_{GFC}, is 500% of the overcurrent protective device rating. However, based on the tests performed under the present project, even the values of 40 volts for arc voltage and 400% of overcurrent device rating for ground fault current are conservative. *The values in the IAEI Soares Book on Grounding have been used here for all computations to enable direct comparison between the model of this report and the IAEI Soares Book on Grounding*. Tables 4.4 and 4.5 illustrate the computed maximum allowable steel conduit length using the assumption as per Soares Book on grounding. Specifically, the maximum steel conduit length is computed as follows: First, the impedance, Z_C, of the power conductor and steel conduit is computed per unit length for a ground fault. Next, it is assumed that the arc voltage is 50 volts resistive. With this assumption, the maximum allowable length of steel conduit, is given by the following equation:

$$L_{max} = \left(V - V_{arc} - Z_s(5I_p)\right) / (5I_pZ_c) \qquad \text{(in meters)} \qquad (4.1)$$

where: Z_S is the source impedance (in Ohms)

Z_C is the cable/conduit impedance (in Ohms/m)

I_p is the protective device rating (in Amps)

V is the source voltage (in Volts)

V_{arc} is the voltage across the fault arc (in Volts).

The results of Table 4.4 assume a 25^oC operating temperature of the conductor prior to the fault. The results of Table 4.5 assume a 75^oC operating temperature of the conductor prior to the fault. The results are consistent with the field tests under high current excitation. Note that the temperature of the conductor plays an important role.

Table 4.4. Computed Maximum Allowable Length of Steel Conduit Run for an Arc Voltage of 50 Volts and a Ground Fault Current 5´I_p,Operating Temperature Prior to Fault: 25$^{\mathrm{O}}$C

Steel Conduit Type and Size	Conductor Size (Copper)	Maximum Steel Conduit Length (feet)	
		480V System	208V or 240V System
GRC 3/4"	2×#8	803	248
GRC 2"	2×3/0	889	274
GRC 3"	2×350kcmil	866	267
IMC 3/4"	2×#8	834	257
IMC 2"	2×3/0	960	296
IMC 3"	2×350kcmil	893	276
EMT 1/2"	2×#10	822	253
EMT 3/4"	2×#8	767	236
EMT 2"	2×3/0	921	284
EMT 3"	2×350kcmil	968	299

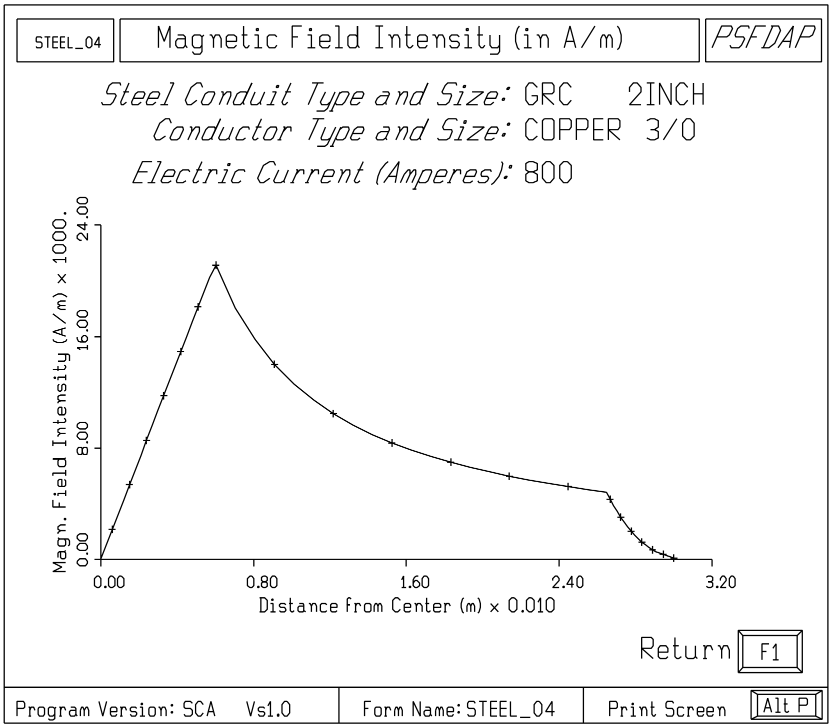
Table 4.5. Computed Maximum Allowable Length of Steel Conduit Run for an Arc Voltage of 50 Volts and a Fault Current 5´I_p,Operating Temperature Prior to Fault: 75$^{\mathrm{O}}$C

Steel Conduit Type and Size	Conductor Size (Copper)	Maximum Steel Conduit Length (feet)	
		480V System	208V or 240V System
GRC 3/4"	2×#8	724	223
GRC 2"	2×3/0	854	264
GRC 3"	2×350kcmil	843	260
IMC 3/4"	2×#8	748	231
IMC 2"	2×3/0	919	284
IMC 3"	2×350kcmil	869	268
EMT 1/2"	2×#10	740	228
EMT 3/4"	2×#8	692	213
EMT 2"	2×3/0	879	271
EMT 3"	2×350kcmil	937	289

4.1 Effect of Electric Current Magnitude on Maximum Allowable Length

Because of the nonlinear magnetic excitation characteristics of the steel conduit, the maximum allowable length defined in the previous section is dependent upon the electric current magnitude. Specifically, as the electric current magnitude increases, the steel conduit is driven toward 'saturation'. This causes a reduction of the steel conduit impedance and therefore an increase of the maximum allowable length. The phenomena are complex because the saturation of the steel conduit is not uniform. To illustrate the point, Figure 4.1 shows the magnitude of the magnetic field intensity and the apparent relative permeability as a function of radial distance for a system comprising one conductor at the center of a steel conduit for a certain magnitude of electric current. The conductor chosen was a 3/0 Copper conductor with a GRC 2" steel conduit. The magnetic field intensity and the relative permeability are shown in Figures 4.1a and 4.1b respectively for an electric current magnitude of 800 Amperes. Note in Figure 4.1b the relative magnetic permeability is constant (μ_r = 1.0) outside the conduit. The relative permeability decreases as the magnetic field increases. At small magnetic fields (near the outside surface of the steel conduit) the relative permeability is high (μ_r=1300). For points internal to the steel conduit, the relative permeability decreases depending upon the saturation level of the steel at the observation point. The profile of the magnetic flux density, B, for the system of Figure 4.1 is shown in Figure 4.2. Inside the conductor and in the gap, the magnetic flux density is proportional to the magnetic field intensity ($B=\mu_0 H$). However, inside the steel conduit the relationship between B and H becomes nonlinear ($B=\mu_0\mu_r(H)H$), and for high magnetic fields (high current levels) the B profile deviates significantly from the H profile. This effect makes the total impedance of the system dependent upon the electric current magnitude.

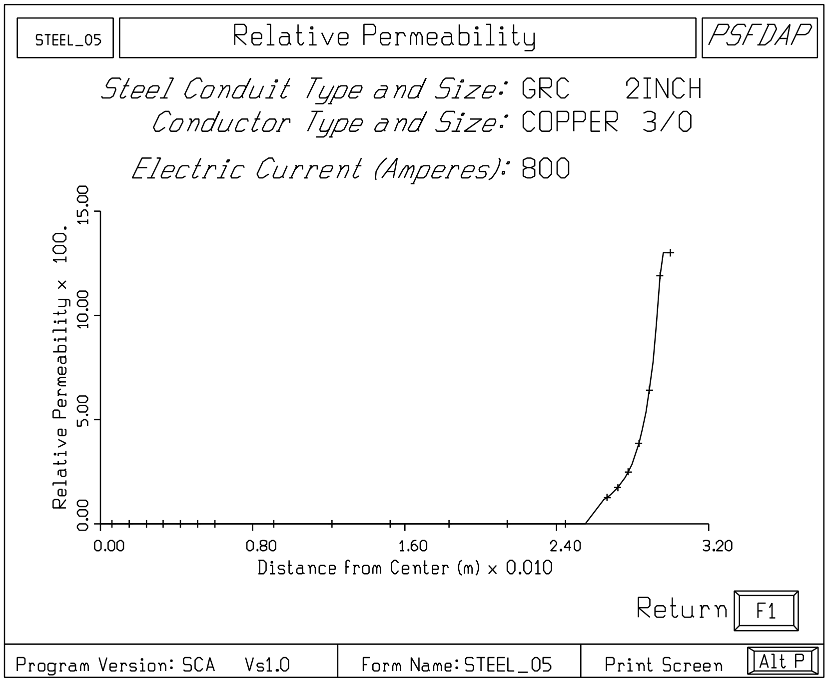
Using the developed model (described in Appendix C), the impedance of a simple conductor/steel conduit system was computed at different electric current magnitudes. The steel conduit systems of Table 4.6 with the Copper conductors of Table 4.3 were computed for current levels of $3I_p$, $4I_p$, and $5I_p$, where I_p is given in Table 4.2 as the overcurrent protective device rating. The results are summarized in Tables 4.7 and 4.8.



Steel Conduit Type and Size: GRC 2INCH
Conductor Type and Size: COPPER 3/0
Electric Current (Amperes): 800

Program Version: SCA Vs1.0
Form Name: STEEL_04

(a)

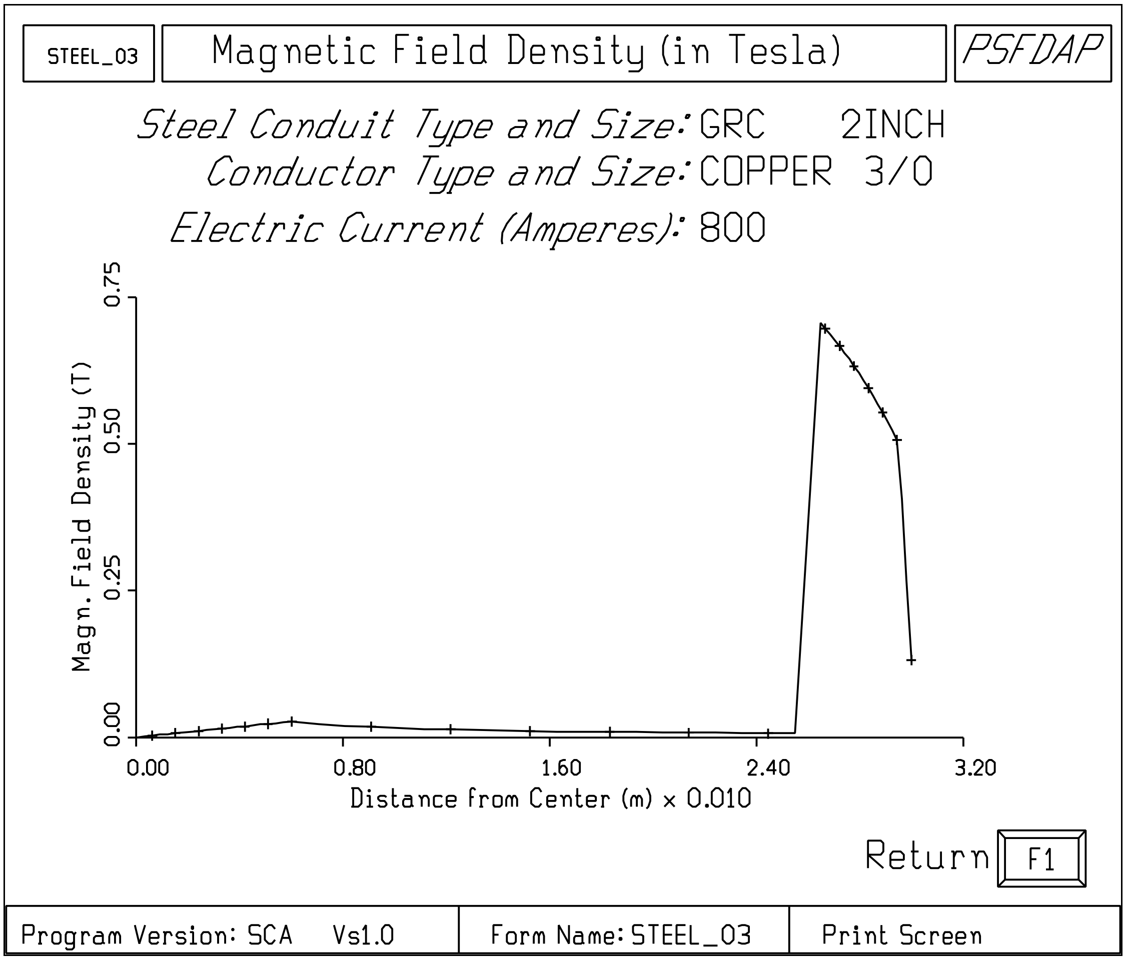


Steel Conduit Type and Size: GRC 2INCH
Conductor Type and Size: COPPER 3/0
Electric Current (Amperes): 800

Program Version: SCA Vs1.0
Form Name: STEEL_05

(b)

Figure 4.1 Illustration of Magnetic Field in a Single Conductor/Steel Conduit System.
(a) Magnetic Field Magnitude Along a Radial Line
(b) Relative Permeability in Steel Conduit



Steel Conduit Type and Size: GRC 2INCH
Conductor Type and Size: COPPER 3/0
Electric Current (Amperes): 800

Program Version: SCA Vs1.0
Form Name: STEEL_03

Figure 4.2 Illustration of Magnetic Field Density in a Single Conductor/Steel Conduit System.

Using the computed impedance of the steel conduit/power conductor system, the maximum allowable length can be computed with equation 4.1. In this equation, the impedance must be computed at the ground fault current. This analysis indicates that two very important parameters which define the maximum allowable length of steel conduit as an equipment grounding conductor are:

- Arc Voltage
- Ground Fault Current

The variation of the maximum allowable steel conduit length versus these parameters is illustrated in Figure 4.3 for a specific steel conduit (EMT 1/2), specific power conductor (COPPER #10) and specific operating temperature (50^{o}C). This graphical representation has been generated for all the systems listed in Table 4.2 for two different operating temperatures 25^{o}C and 75^{o}C. These graphs are given in Appendix G. *All indicated temperatures are in degrees Celsius.*

Table 4.6 Characteristics of the Steel Conduit Systems Tested.

Steel Conduit Type and Size	I.D. (inches)	O.D. (inches)	Area (sq.in)	R ($\Omega/10^3$ ft)	ρ ($10^{-6}\Omega\cdot$m)
GRC 3/4”	0.836	1.050	0.31699	0.2442	0.163873
GRC 2”	2.083	2.375	1.02283	0.0757	0.163873
GRC 3”	3.090	3.500	2.12207	0.0365	0.163873
IMC 3/4”	0.864	1.029	0.24532	0.2915	0.151304
IMC 2”	2.149	2.359	0.74369	0.0961	0.151304
IMC 3”	3.176	3.476	1.56734	0.0456	0.151304
EMT 1/2”	0.622	0.706	0.08761	0.7489	0.138860
EMT 3/4”	0.824	0.922	0.13439	0.4881	0.138860
EMT 2”	2.067	2.197	0.43536	0.1507	0.138860
EMT 3”	3.356	3.500	0.77539	0.0846	0.138860

Table 4.7 Impedance in mOhms per 100 Feet of Steel Conduit Enclosed Copper Power Conductor, 25^{o}C

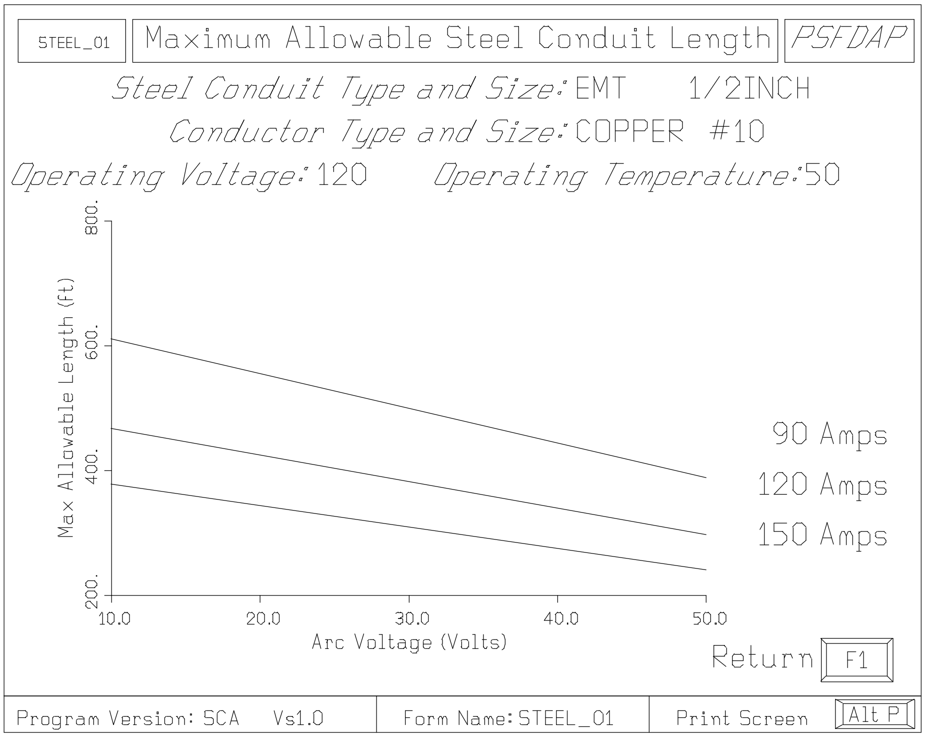
Steel Conduit Type and Size	Conductor Size	Electric Current		
		$3I_p$	$4I_p$	$5I_p$
GRC 3/4"	#8	119.54 + j47.43	111.87 + j42.43	106.35 + j38.52
GRC 2"	3/0	24.52 + j17.66	22.27 + j16.14	20.57 + j15.12
GRC 3"	350kcmil	15.12 + j13.08	13.64 + j12.00	12.63 + j11.26
IMC 3/4"	#8	114.13 + j45.04	107.42 + j38.56	103.55 + j33.70
IMC 2"	3/0	22.96 + j17.23	20.62 + j15.25	19.27 + j13.69
IMC 3"	350kcmil	14.50 + j12.65	13.12 + j11.66	12.12 + j11.03
EMT 1/2"	#10	185.03 + j44.03	182.69 + j35.57	181.49 + j30.19
EMT 3/4"	#8	118.98 + j32.96	117.07 + j26.91	116.11 + j23.05
EMT 2"	3/0	23.52 + j13.83	22.74 + j11.75	22.35 + j10.42
EMT 3"	350kcmil	13.36 + j11.07	12.68 + j9.67	12.33 + j8.76

I_p is the rating of the Overcurrent Protective Device.

Table 4.8 Impedance in mOhms per 100 Feet of Steel Conduit Enclosed Copper Power Conductor, 75^{o}C

Steel Conduit Type and Size	Conductor Size	Electric Current		
		$3I_p$	$4I_p$	$5I_p$
GRC 3/4"	#8	132.58 + j47.43	124.91 + j42.43	119.39 + j38.52
GRC 2"	3/0	25.80 + j17.66	23.55 + j16.14	21.85 + j15.12
GRC 3"	350kcmil	15.73 + j13.08	14.25 + j12.00	13.24 + j11.26
IMC 3/4"	#8	127.17 + j45.04	120.46 + j38.56	116.59 + j33.70
IMC 2"	3/0	24.24 + j17.23	21.90 + j15.25	20.55 + j13.69
IMC 3"	350kcmil	15.11 + j12.65	13.73 + j11.66	12.74 + j11.03
EMT 1/2"	#10	205.83 + j44.03	203.49 + j35.57	202.29 + j30.19
EMT 3/4"	#8	132.02 + j32.96	130.12 + j26.91	129.15 + j23.05
EMT 2"	3/0	24.80 + j13.83	24.02 + j11.75	23.63 + j10.42
EMT 3"	350kcmil	13.97 + j11.07	13.29 + j9.67	12.94 + j8.76

I_p is the rating of the Overcurrent Protective Device.



Steel Conduit Type and Size: EMT 1/2INCH

Conductor Type and Size: COPPER #10

Operating Voltage: 120 Operating Temperature: 50

Figure 4.3 Illustration of Maximum Allowable Length vs. Arc Voltage Indicated Electric Current Values Represent Ground Fault Currents of 300%, 400%, and 500% of Overcurrent Protective Device Rating Respectively.

Note: Operating Temperature is in degrees Celcius.

5.0 High Current Laboratory Tests

The high current laboratory tests to validate the model were performed at Kearney Laboratories in McCook, IL. The tests consisted of low and high fault current injection on representative steel conduit enclosed distribution systems with several grounding options and measurement of transfer voltages and current division among steel conduit, grounding system, and neutral. The representative systems are listed in Table 4.6. These systems consisted of UL listed materials and were installed by a licensed electrical contractor in accordance with the 1993 National Electrical Code. Products tested were: three brands and types of conduit; cables from two manufacturers; several brands and types of EMT couplings (zinc diecast setscrew; steel setscrew, steel compression and zinc compression); standard electrogalvanized steel coupling for IMC and RIGID. This section defines the design, type and number of the performed tests.

Figure 5.1 illustrates the laboratories' facility. The steel conduit runs were placed along the line AB. The layout of the steel conduits is illustrated in Figure 5.2. Note that 10 different runs of steel conduit were tested. Each steel conduit contained two conductors as defined in Table 4.2. The electrical connections of the power conductors and steel conduit are illustrated in Figure 5.3. Three specific tests were performed for each steel conduit. These are:

Test 1: The switch S (see Figure 5.3) is open. A ground fault is placed between the power conductor and the conduit at location B of Figure 5.1. The fault was initially generated with a 'guillotine' as it is illustrated in Figure 5.3. During this test, the voltage and current at point A were recorded for further analysis, as well as the arc voltage as is illustrated in Figure 5.4. During the tests it was determined that the voltage across the guillotine was not appreciable. For this reason, it was replaced with direct connection. The electric fault was terminated by opening a breaker by electronic timing.

Test 2: This test is similar to test 1 except that the switch S is closed (see Figure 5.3).

Test 3: This test is identical to test 1 except that the steel conduit is connected to ground at locations A and B shown in Figure 5.1.

The first test evaluated the performance of steel conduit as the only grounding conductor for the ground fault. The second test evaluated the effects of a supplementary grounding conductor inside the steel conduit. The third test evaluated the performance of a typical steel conduit enclosed power system with multiple grounding points. All results were utilized to validate the computer model. Note that a total of 30 tests were performed.

The source utilized for the tests had the following short circuit characteristics:

at the 120 volt tap:	85 kAmperes
at the 277 volt tap	83 kAmperes

The waveforms of the electric current and voltage were recorded by means of a strip chart recorder as well as by means of a digitizing scope and subsequent transfer of the data to a personal computer for further analysis. Georgia Tech provided the digitizing oscilloscope and personal computer. Figure 5.4 illustrates the instrumentation for each steel conduit and enclosed wires.

The above described tests were performed on May 12-14, 1993.

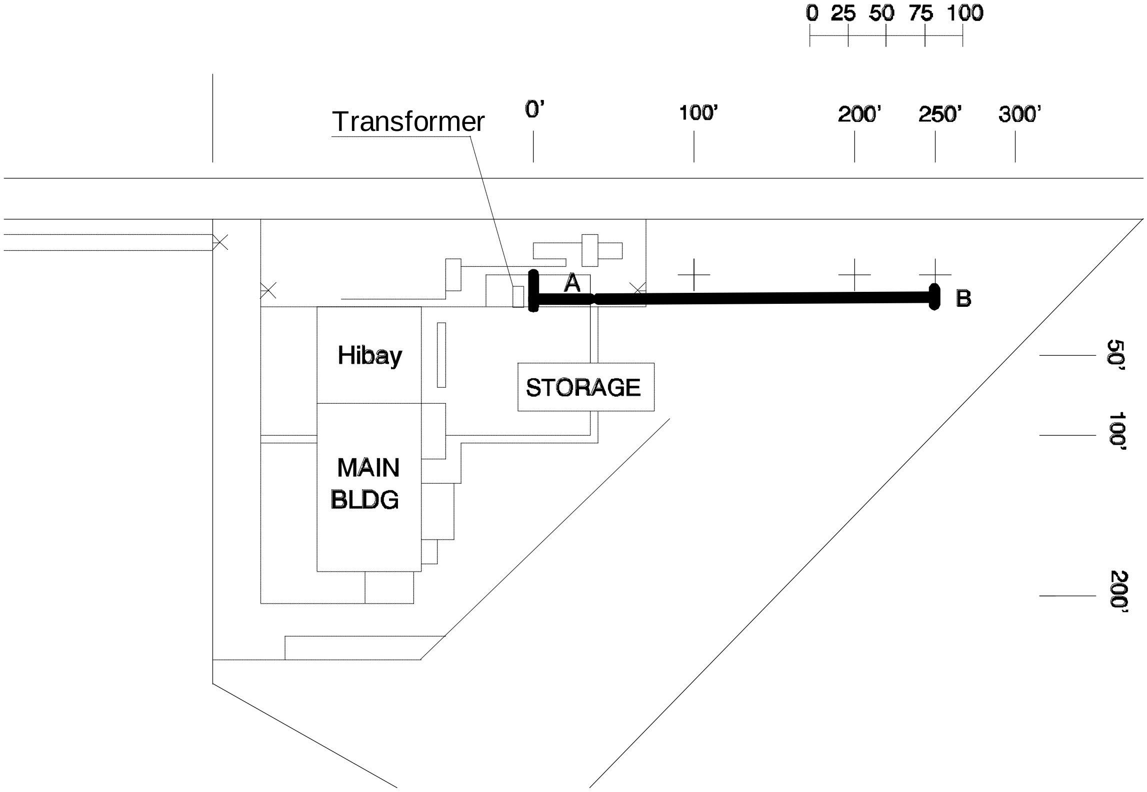


Figure 5.1. Illustration of Kearney Laboratories' Facility

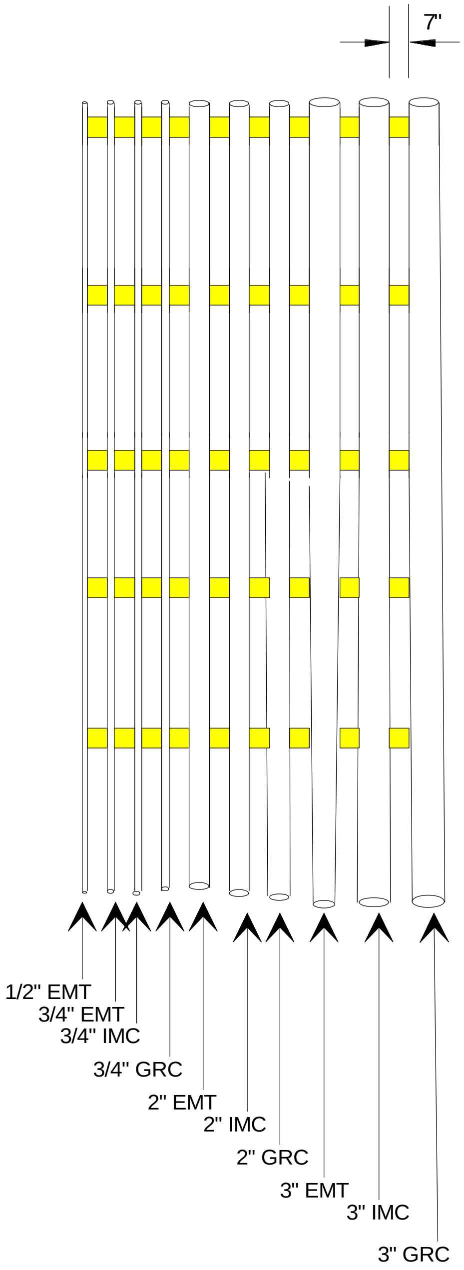


Figure 5.2. Illustration of the Layout of Ten Runs of Steel Conduit. Power Conductors Were Enclosed But Not Shown. Total Length of Each Conduit Run is 256 Feet. Wood Blocks Were Used to Space the Steel Conduit Systems.

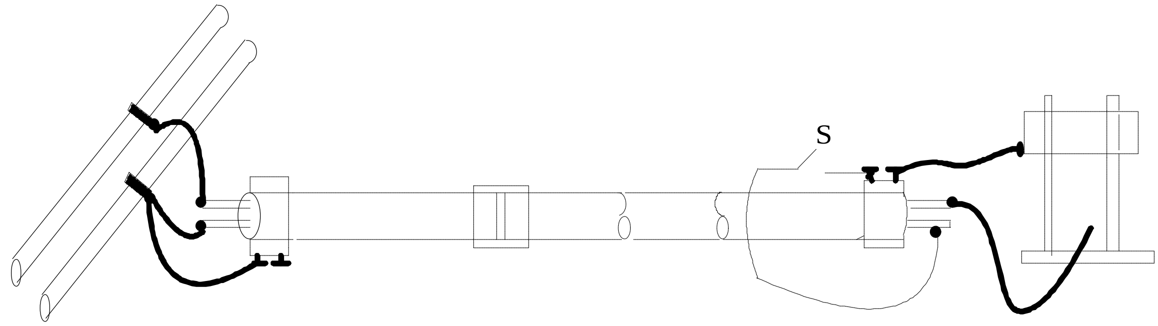


Figure 5.3 Illustration of Installation and Connections for One Steel Conduit With Two Enclosed Conductors.

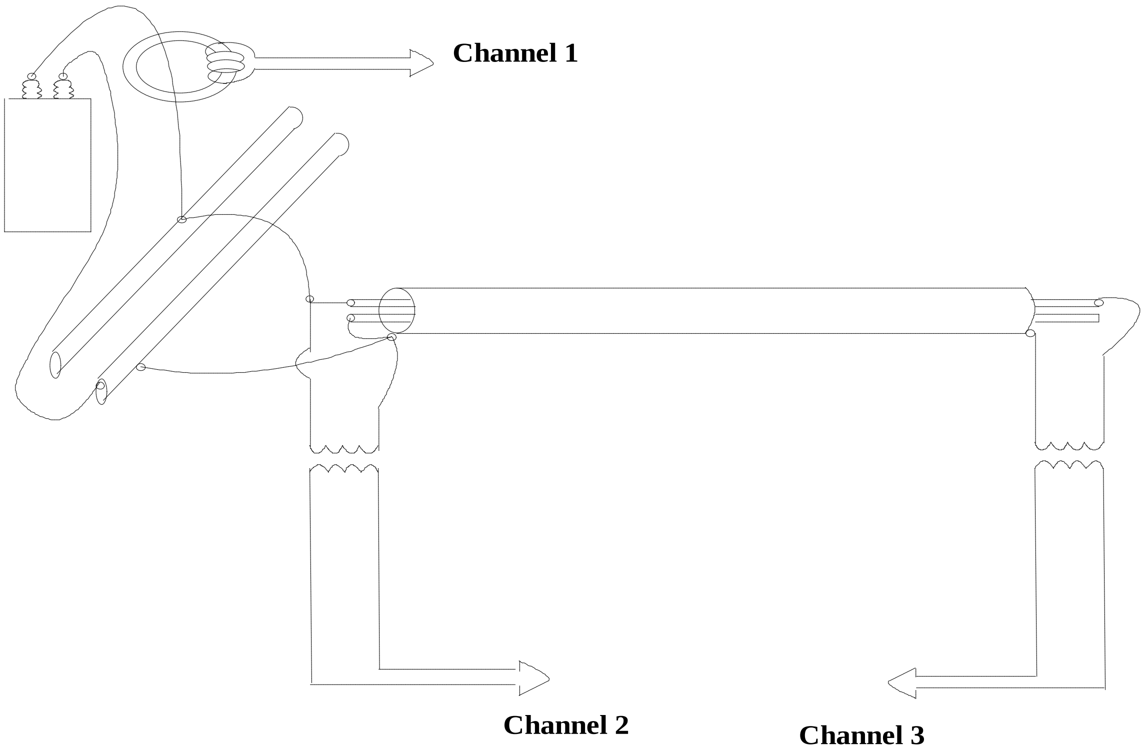


Figure 5.4 Illustration of the Instrumentation for One Steel Conduit With Two Enclosed Conductors. Channel 1 - Fault Current, Channel 2 - Source Voltage, Channel 3 - Fault Voltage

Following the analysis of the test results, it was requested that the sponsor have a small number of additional tests run to complete validation of the model. It was decided at that time to add another electric quantity, i.e., the amount of current return through the soil; and to also determine if there was any appreciable difference between using a steel set-screw coupling or a zinc diecast set-screw coupling on an identical conduit type. The instrumentation was modified as it is illustrated in Figure 5.5 to reflect the new measurements. The tests were repeated for two runs of EMT 1/2 (using two different couplings) and one run of EMT 3/4. The layout is illustrated in Figure 5.6. These tests were performed at Kearney Laboratories, McCook, IL, on August 9 - 10, 1993. The tests were identical to the tests on May 12 - 14, 1993, as described in this report with the exception that a fourth test was added. The fourth test consisted of a direct fault to the external ground, i.e., the only fault current return path was the external grounding system.

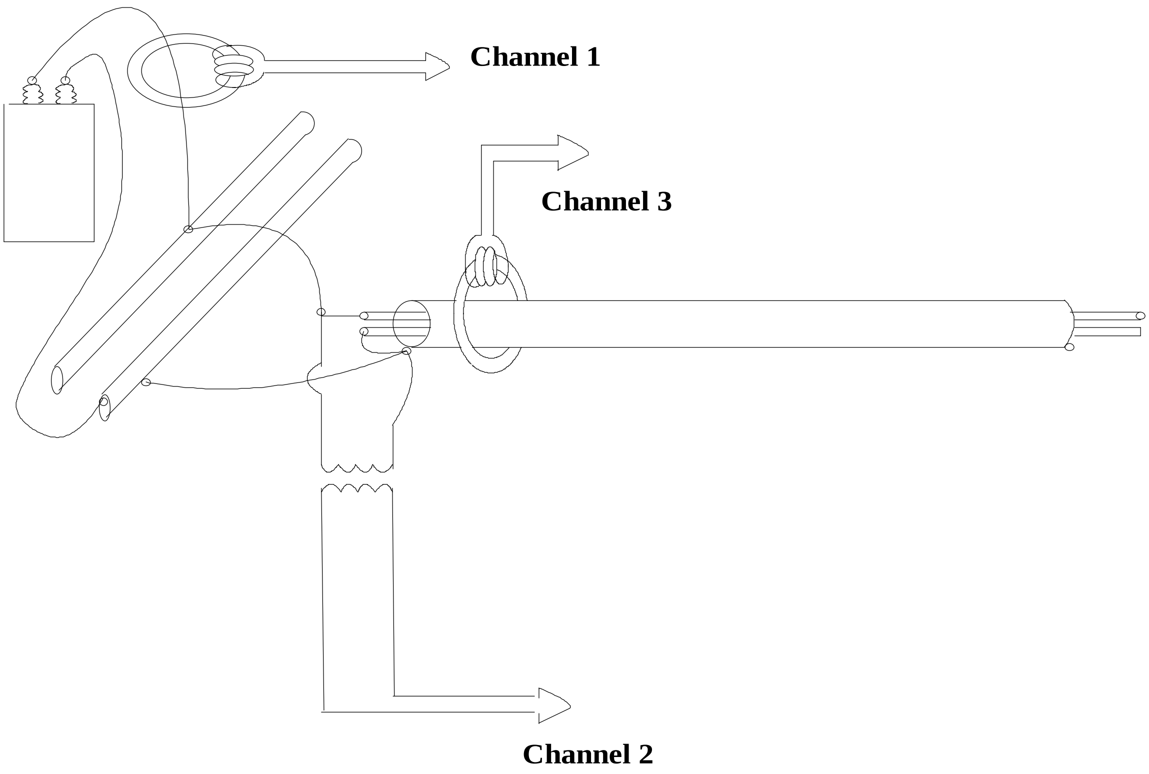


Figure 5.5 Illustration of the Instrumentation for One Steel Conduit With Two Enclosed Conductors. Channel 1 - Fault Current, Channel 2 - Source Voltage, Channel 3 - Earth Return Current

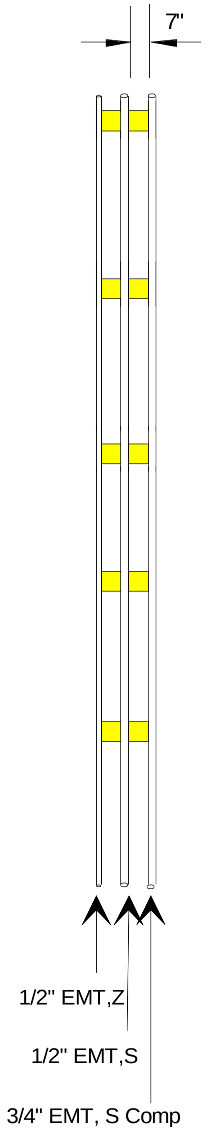


Figure 5.6. Illustration of Layout of Three Runs of Steel Conduit. Power Conductors Were Enclosed But Not Shown. Total Length of Each Conduit Run is 256 Feet.

After each set of tests, the conductors and conduits were physically examined. No damage of any kind was observed. Appendix E shows the captured data from the tests as well as analysis of the data.

For each case, there are five figures as follows:

- A plot of the actual captured voltage and current waveforms. We refer to this data as RAW data.

- A plot of the voltage and current total rms (root mean square) value computed over a sliding window of one cycle (1/60 second). We refer to this data as RMS values.

- A plot of the voltage and current rms (root mean square) value of the 60 Hz component computed over a sliding window of one cycle (1/60 second). We refer to this data as the 60 Hz RMS values.

- A plot of the estimated* total resistance and inductance values computed over a sliding window of one cycle (1/60 second). We refer to this data as the estimated R and L values.

- A plot of the estimated* resistance and inductance values for the 60 Hz component computed over a sliding window of one cycle (1/60 second). We refer to this data as the 60 Hz R and L values.

* The estimation was performed in the least squares sense [17].

The resistance and inductance values were compared to those predicted by the model. For completeness, Appendix G contains the computed impedance values of a steel conduit enclosed power distribution system at various current levels and two temperatures. For each case, two Figures are provided. The first Figure provides the impedance per 100 feet of steel conduit at different current levels. The impedance is listed with its magnitude and phase as well as a resistance and reactance. The second Figure provides the maximum allowable length of steel conduit for three different interrupting currents (equal to 3, 4, and 5 times rated current) versus arc voltage ranging from 10 to 50 volts.

Note that all computations of maximum run and conclusions are based on the impedance of the steel conduit enclosed power distribution system. For this reason, it is expedient to base the comparison of the experimental results and the modeling results on the impedance of the steel conduit enclosed distribution system. This comparison is summarized in Tables 5.1 and 5.2 for systems with 120 and 277 volt nominal voltage, respectively. In addition, Tables 5.3 and 5.4 summarize the measured data for all cases. The Tables represent the summary of all tests done at Kearney Laboratories in McCook, IL (the May 1993 and August 1993 tests).

In addition to the above tests, measurements of arc voltage at various current levels and separation distances comparable to insulation thickness of 600 volt cables were obtained. The analysis of these results is shown in Appendix F.

Table 5.1. Summary of Test Results and Model Comparison for 120 Volt Systems. Steel Conduit is the Only Return Path. Impedance Values are Given in mOhms per 100 Feet.

Steel Conduit Type and Conductor Size	Electric Current Level (Amperes)	Measured Impedance R, X	Computed Impedance R, X
EMT - 1/2Z CU-#10	247	187.9, 30.55	188.71, 24.72
EMT - 1/2S CU-#10	228	199.3, 32.15	189.05, 26.65
EMT - 3/4 CU-#8	345	130.1, 25.33	121.11, 21.59
IMC - 3/4 CU-#8	437	102.0, 29.63	105.29, 27.55
GRC - 3/4 CU-#8	417	106.8, 30.13	105.31, 31.65
EMT - 2 CU-3/0	1822	21.56, 10.64	22.37, 8.96
IMC - 2 CU-3/0	1849	19.78, 12.89	18.83, 12.56
GRC - 2 CU-3/0	1758	21.22, 13.04	18.82, 13.41
EMT - 3 CU-350	2578	13.15, 9.86	13.02, 10.44
IMC - 3 CU-350	2609	12.69, 10.21	11.56, 10.43
GRC - 3 CU-350	2433	13.98, 10.86	11.81, 10.41

Z	zinc diecast coupling
S	Steel coupling
CU	Copper Conductor

Table 5.2. Summary of Test Results and Model Comparison for 277 Volt Systems. Steel Conduit is the Only Return Path. Impedance Values are Given in mOhms per 100 Feet.

Steel Conduit Type and Conductor Size	Electric Current Level (Amperes)	Measured Impedance R, X	Computed Impedance R, X
EMT - 1/2Z CU-#10	537	193.1, 17.76	187.49, 14.84
EMT - 1/2S CU-#10	546	193.7, 18.6	187.47, 14.66
EMT - 3/4 CU-#8	851	123.9, 15.5	119.64, 12.20
IMC - 3/4 CU-#8	1066	95.1, 18.98	100.79, 15.57
GRC - 3/4 CU-#8	997	95.9, 20.25	97.63, 18.36
EMT - 2 CU-3/0	4628	20.39, 7.28	21.95, 6.17
IMC - 2 CU-3/0	5422	15.78, 8.40	16.64, 7.53
GRC - 2 CU-3/0	5271	15.71, 9.59	15.12, 8.15
EMT - 3 CU-350	7092	11.33, 6.94	11.72, 6.84
IMC - 3 CU-350	6775	9.71, 8.35	8.69, 7.52
GRC - 3 CU-350	6920	10.18, 8.68	8.40, 7.87

Z	zinc diecast coupling
S	Steel coupling
CU	Copper Conductor

Table 5.3. Summary of Test Results and Model Comparison for 120 Volt Systems. Effect of Other Parallel Fault Current Return Paths. Impedance Values are Given in mOhms per 100 Feet.

Steel Conduit Type and Conductor Size	Electric Current Level (Amperes)	Measured Impedance R, X	Measured Impedance with a Supplementary Conductor	Measured Impedance with a Supplementary Conductor and Earth Return
EMT - 1/2Z CU-#10	247	187.9, 30.55	157.2, 17.53	137.77, 62.59
EMT - 1/2S CU-#10	228	199.3, 32.15	163.8, 17.53	137.8, 62.6
EMT - 3/4 CU-#8	345	130.1, 25.33	105.6, 15.56	99.2, 60.05
IMC - 3/4 CU-#8	437	102.0, 29.63	89.84, 16.53	90.43, 16.33
GRC - 3/4 CU-#8	417	106.8, 30.13	91.19, 15.87	91.69, 16.08
EMT - 2 CU-3/0	1822	21.56, 10.64	11.34, 10.34	11.38, 10.35
IMC - 2 CU-3/0	1849	19.78, 12.89	11.29, 10.57	11.30, 10.58
GRC - 2 CU-3/0	1758	21.22, 13.04	11.42, 10.46	11.44, 10.43
EMT - 3 CU-350	2578	13.15, 9.86	6.89, 10.15	6.93, 10.20
IMC - 3 CU-350	2609	12.69, 10.21	6.95, 9.96	7.03, 10.00
GRC - 3 CU-350	2433	13.98, 10.86	6.89, 10.15	6.94, 10.13

Z	zinc diecast coupling
S	Steel coupling
CU	Copper Conductor

Table 5.4. Summary of Test Results and Model Comparison for 277 Volt Systems. Effect of Other Parallel Fault Current Return Paths. Impedance Values are Given in mOhms per 100 Feet.

Steel Conduit Type and Conductor Size	Electric Current Level (Amperes)	Measured Impedance R, X	Measured Impedance with a Supplementary Conductor	Measured Impedance with a Supplementary Conductor and Earth Return
EMT - 1/2Z CU-#10	537	193.1, 17.76	161.92, 13.77	135.88, 48.66
EMT - 1/2S CU-#10	546	193.7, 18.6	161.4, 13.86	134.6, 48.62
EMT - 3/4 CU-#8	851	123.9, 15.5	102.44, 12.51	89.70, 47.00
IMC - 3/4 CU-#8	1066	95.1, 18.98	88.48, 15.14	88.54, 15.55
GRC - 3/4 CU-#8	997	95.9, 20.25	88.16, 15.91	90.06, 15.23
EMT - 2 CU-3/0	4628	20.39, 7.28	11.87, 8.87	11.90, 8.87
IMC - 2 CU-3/0	5422	15.78, 8.40	11.23, 8.97	11.18, 8.95
GRC - 2 CU-3/0	5271	15.71, 9.59	11.23, 9.23	11.28, 9.24
EMT - 3 CU-350	7092	11.33, 6.94	7.15, 8.63	7.11, 8.59
IMC - 3 CU-350	6775	9.71, 8.35	6.74, 8.32	6.81, 8.36
GRC - 3 CU-350	6920	10.18, 8.68	7.14, 8.70	6.91, 8.69

Z	zinc diecast coupling
S	Steel coupling
CU	Copper Conductor

6.0 Comparisons and Discussion

In this section, the validated computer model is used to determine the maximum allowable steel conduit lengths for two specific fault conditions and to compare the results to the IAEI Soares Book on Grounding, 1993 edition. In order to make the comparison meaningful, the assumptions of the Soares Book on Grounding have been used: (a) an arc voltage of 50 volts, and (b) the ground fault current is 500% of overcurrent device rating. The results are summarized in Table 6.1. The only fault conditions considered are LC1 and LN1 which are defined in the subnotes of the table. Note that for the LN1 fault, a full neutral is assumed.

For comparison purposes, Table 6.2 has been generated which tabulates maximum system length, as computed with the validated model using 40 volts for arc voltage and fault current equal to 400% of protective device rating. The data of the Table 6.2 are self explanatory.

In a specific applications, all the possible fault conditions must be considered and the maximum allowable length for the reliable interruption of the fault must be computed. Note in Tables 6.1 and 6.2 that the minimum allowable length many times is determined by the possible line to neutral faults. The results of Tables 6.1 and 6.2 are given for the specific purpose of (a) comparing the model to the IAEI Soares Book on Grounding, 1993 edition, and (b) to emphasize the need to consider other possible faults.

Table 6.1 Maximum System Length (Predicted by Model for Comparison to Soares - 50 Volt Arc and 500% of Protective Device Rating)

Conduit Size (inches)	Conductors AWG No.	Overcurrent Device Rating Amps. 75 °C	Ground Fault Current 500% of I_p	Maximum Length of Conduit Run, Soares (feet)	Maximum Length of EMT Run for LC1* (feet)	Maximum Length of IMC Run for LC1* (feet)	Maximum Length of GRC Run for LC1* (feet)	Maximum Length for LN1** Fault (feet)
1/2	3-#12	20	100	350	280	290	280	208
	4-#12	20	100	345	280	290	280	208
3/4	4-#10	30	150	355	289	292	282	221
	4-#8	50	250	315	236	257	247	211
1	4-#8	50	250	335	265	266	256	211
	3-#4	85	425	266	262	285	268	309
1 1/4	3-#2	115	575	265	284	294	275	358
1 1/2	3-#1	130	650	265	296	303	283	393
	3-#2/0	175	875	220	263	284	265	447
2	3-#3/0	200	1000	255	283	296	274	479
	3-#4/0	230	1150	230	266	285	263	503
2 1/2	3-250 kcmil	255	1275	265	299	276	267	516
	3-350 kcmil	310	1550	235	274	259	249	534
3	3-500 kcmil	380	1900	230	271	255	246	529
	3-600 kcmil	420	2100	230	258	247	236	518
3 1/2	3-700 kcmil	460	2300	230	267	246	237	501
	3-800 kcmil	490	2450	230	260	241	231	490
4	3-900 kcmil	520	2600	235	262	241	233	477
	3-1000 kcmil	545	2725	235	257	238	229	467
5	3-1500 kcmil	625	3125	245	-	-	230	439
	3-1750 kcmil	650	3250	240	-	-	229	430

This table for comparisons only. All other possible fault paths must be considered to establish the limiting condition.

* LC1 fault - Line to conduit fault, conduit is the only return path

** LN1 fault - Line to neutral fault, neutral is the only return path, **full neutral**

Table 6.2 Maximum System Length (Predicted by Model - 40 Volt Arc and 400% of Protective Device Rating)

Conduit Size (inches)	Conductors AWG No.	Overcurrent Device Rating Amps. 75 °C	Ground Fault Current 400% of I_p	Maximum Length of EMT Run for LC1* (feet)	Maximum Length of IMC Run for LC1* (feet)	Maximum Length of GRC Run for LC1* (feet)	Maximum Length for LN1** Fault (feet)
1/2	3-#12	20	80	395	398	384	298
	4-#12	20	80	395	398	384	298
3/4	4-#10	30	120	404	399	386	316
	4-#8	50	200	334	350	334	301
1	4-#8	50	200	370	362	350	301
	3-#4	85	340	365	382	357	441
1 1/4	3-#2	115	460	391	392	365	512
1 1/2	3-#1	130	520	407	402	377	562
	3-#2/0	175	700	364	377	348	639
2	3-#3/0	200	800	390	389	363	685
	3-#4/0	230	920	367	375	347	719
2 1/2	3-250 kcmil	255	1020	406	368	356	737
	3-350 kcmil	310	1240	374	342	331	763
3	3-500 kcmil	380	1520	370	338	327	756
	3-600 kcmil	420	1680	353	325	314	740
3 1/2	3-700 kcmil	460	1840	360	325	315	716
	3-800 kcmil	490	1960	351	318	307	701
4	3-900 kcmil	520	2080	353	320	310	682
	3-1000 kcmil	545	2180	347	314	304	668
5	3-1500 kcmil	625	2500	-	-	308	627
	3-1750 kcmil	650	2600	-	-	306	615

This table for comparisons only. All other possible fault paths must be considered to establish the limiting condition.

* LC1 fault - Line to conduit fault, conduit is the only return path

** LN1 fault - Line to neutral fault, neutral is the only return path, **full neutral**

7.0 Summary and Conclusions

A computer model has been developed which computes the impedance of steel conduit with enclosed power conductors. The computer model has been validated with full scale tests. The model is capable of predicting the effect of temperature on the total impedance. The measured impedances during the full scale tests are within the values predicted with the model in the temperature range 25^{o}C to 55^{o}C. It is important to note that the full scale tests consisted of repeated short circuit test on samples of steel conduit systems and therefore the prefault temperature was different for each test but generally in the above stated range of temperatures.

Tests of arc voltage were performed. These tests consisted of generating an arc between two electrodes. The current through the arc was controlled by a current limiting impedance. The separation distance between the two electrodes was measured before and after the test. This separation distance was always longer than the thickness of power conductor insulation and therefore represent worst case (or conservative results). The voltage between the two electrodes was measured. The test results which are given in Appendix F, indicate that even for the conservatively long electrode separation of 80 mils, the arc voltage never exceeded 40 volts. For shorter electrode separation distances, the arc voltage did not exceed 30 volts.

Full scale tests were performed with and without supplementary grounding conductors. Supplementary grounding conductors, when participating in the fault circuit, reduce the overall impedance. *However, it is important to note that the limiting factor in the capability of the system to interrupt a fault is the size of the phase conductor and neutral. Specifically, for systems designed with present standards, the fault circuit for a phase conductor to neutral fault (steel conduit or supplementary ground conductor is not involved in the fault) presents the maximum impedance and therefore will draw the minimum fault current as compared to other faults at the same location. Use of supplementary grounding conductors does not add to the safety of the systems in these instances*. The maximum allowable length of a steel conduit run can be increased to some degree by the addition of a supplemental grounding conductor. This varies by size and system designs. An additional project is undertaken to expand the model to compute the maximum allowable length in these cases.

In this report we examined the practice as dictated by the Soares Book on Grounding. We found the recommendation to use 500% of the protective device rating as the ground fault current for interruption of the fault to be overly conservative. Present industry experience with protective devices indicates that a fault current of 300% of protective device rating will result in a reliable operation of the protective device. Current practice of protective device testing is to test the protective device for an electric current up to 300% of its rating. Based on these observations, one could conclude that even the value of 400% of the protective device rating for ground fault current would be conservative.

Finally, it is important to stress that the maximum allowable length of a steel conduit enclosed secondary distribution system may be limited by the size of the power conductor and neutral conductor and not the steel conduit. As an example, for a system comprizing a copper #8 conductor, a copper #8 neutral conductor, enclosed in a 3/4 inch EMT conduit and operating at 120 volts, the maximum allowable length for a conductor to neutral fault is 17% lower than the maximum allowable length for a conductor to steel conduit fault. *In the design process, the maximum allowable length for all possible faults must be computed. The allowable length of the run should be the minimum of all.*

8.0 References

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