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Cable Sizing and Its Effect on Thermal and Ampacity Values in Underground Power Distribution

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Cable Sizing and its Effect on Thermal and Ampacity Values in Underground Power Distribution

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THESIS

A Thesis submitted in partial
fulfillment of the requirements for
the degree of Master of Science in
Electrical Engineering in the College
of Engineering at the University of
Kentucky

By
Obinna Elvis Igwe
Lexington, Kentucky

Director: Dr. Yuan Liao, Professor of Electrical and Computer Engineering

Lexington, Kentucky

2016

ABSTRACT OF THESIS

CABLE SIZING AND ITS EFFECT ON THERMAL AND AMPACITY VALUES IN UNDERGROUND POWER DISTRIBUTION

Over the past decade, underground power distribution has become increasingly popular due to its reliability, safety, aesthetic characteristics, as well as the ever increasing focus on the environmental impacts of the various stages of power generation and distribution. With the technological advances in this area, the process of running these cables have become more economical and efficient.

This thesis explores the practice of grouping multiple three phase cables in a common conduit, using the duct bank process, and analyzes the thermal and ampacity consequences on the individual lines. This analysis is done in an effort to better define and understand the various limitations of the practice and explore future possibilities in its expansion.

KEYWORDS: Cable sizing, duct bank, ampacity, underground power distribution.

Obinna Elvis Igwe

Signature

05/08/2016

Date

CABLE SIZING AND ITS EFFECT ON THERMAL AND AMPACITY VALUES IN UNDERGROUND POWER DISTRIBUTION

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1.1 Background

The power distribution industry has seen a lot of growth over the past couple of decades, as the need for electricity continues to grow. However, there has not been much of change in the techniques used for distribution, but rather, an effort to improve upon what the industry refers to as standard.

There are two major methods of power distribution; the use of overhead, and underground lines. Each of these methods have their own advantages and disadvantages. For example, overhead power lines cost less to build and service when compared to its underground alternative; however, underground power lines, though more expensive, are more aesthetically pleasing, reliable, safe, and require less maintenance due to its lack of exposure to accidents on the road, the harsh elements in nature, as well as the high probability of failure during weather emergencies and natural disasters. Lastly, in terms of accessibility, the overhead option allows for easy repair in case of faults, and one can easily add and modify the lines, while the underground option is favored when trying to run power lines around above-ground obstacles such as buildings, highways etc.

Cables for underground service may be classified either according to the type of insulating material used in their manufacture, or the voltage for which they are manufactured. The latter method of classification is generally preferred. Cables can be divided into the following groups [1]:

(i) Low-tension (L.T.) cables — up to 1000 V

(ii) High-tension (H.T.) cables — up to 11,000 V

(iii) Super-tension (S.T.) cables — from 22 kV to 33 kV

(iv) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(v) Extra super voltage cables — beyond 132 kV [1]

Following the selection of cables required, an underground power distribution project must select between two major methods of laying the underground cables, namely:

(i) Direct-Buried Raceway: In this method, a trench of specified depth is dug, before a bed of fine sand used to prevent moisture from reaching the cables is then laid over it. The power lines are then run directly over this bed of sand. Of the two methods, the direct-buried raceway requires less capital for initial construction, and has superior heat dissipation characteristics; however, maintenance and modification of the lines prove to be very costly as they require excavation. Also, with this method, the process of fault localization (locating faults) becomes challenging. An example of a direct-buried raceway can be seen in Fig. 1.1.

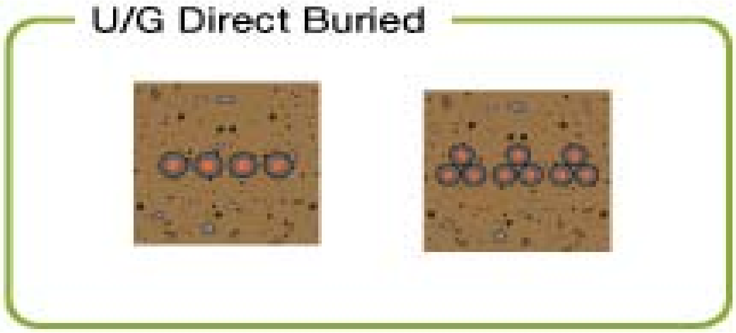


Figure 1.1 Direct Buried Power Lines [15]

(ii) Duct-Bank Raceway: This second method involves the use of a casing, rather than the lines being in direct contact with the earth. Here, a trench is excavated and filled with concrete enclosing spaced conduits (PVC, metal fiber etc.) that contain the power cables. The concrete helps protect the conduit/cables from any moisture in the soil, which in turn, prolongs the life of the materials. The conduits however, apart from helping properly space and separate the cables, also facilitate the cable-pulling process, as well as allow modification and easier fault localization than its direct-buried counterparts.

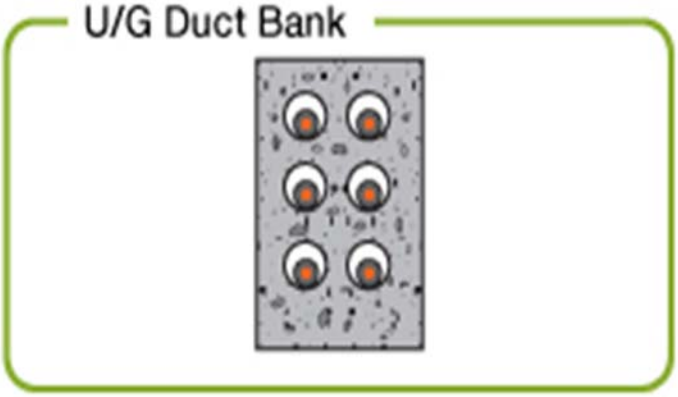


Figure 1.2 Duct-Bank Power Lines [15]

This research primarily focuses on ampacity, which can be defined as the maximum current a power line can operate and still maintain its desired electrical properties; it is sometimes referred to as a cable's current carrying capacity. Basically, the ampacity of power cables is limited or determined by the maximum operating temperature within which the insulation can maintain its best performance. As an example, the cables constructed with a cross-linked polyethylene (XLPE) dielectric are typically restricted to a maximum temperature of 90°C. [3]

The work performed by the authors show that "the major factors affecting cable ampacity calculations, the effects on ampacity of conductor size, ambient temperature, bonding arrangement, duct size, soil thermal resistivity, resistivity and size of backfill (or duct bank) and depth of installation for underground installations were studied, and it was concluded that the three major factors affecting ampacity in underground cable installation are: cable caliber i.e. its physical characteristics, soil thermal resistivity and bonding method." [4]. As the study focuses on cables enclosed in a duct-bank raceway system, the bonding method, and soil thermal resistivity are ignored, leaving cable caliber to be the main factor analyzed.

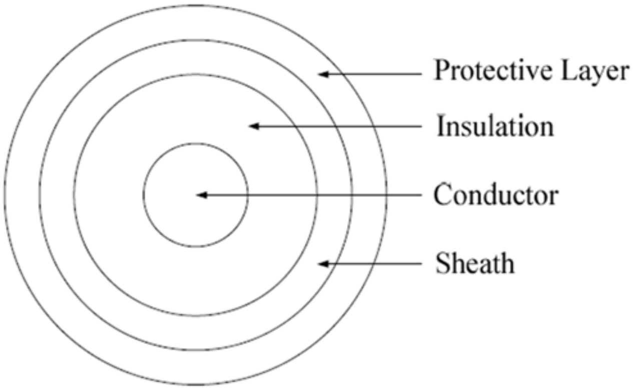


Figure 1.3 Structure of a Power Cable [16]

The inside surface of a conduit receives heat from its enclosed cables by natural convection and radiation, except at the area in direct contact with the cable, which is located at the middle of the bottom surface. In this area, heat transfers by conduction. The radiation heat transfer is ignored due to its minor effect on the tota1 heat dissipation (2-4%) and because of the relatively low temperature levels. The analysis of the conductive heat transfer is based on Laplace's equation in two dimensions [6]. A successful numerical solution of this equation has been achieved by using the finite difference method. A five nodes technique is used. The central nodal temperature T, is determined by the other four surrounding temperatures (T_{i-1j}, T_{i+1j}, $T_{i\,j-1}$, $T_{i\,j+1}$). The finite difference temperature equations are linear equations and have the general following form [6]:

$$T_{ij} = \alpha T_{i-1j} + \beta T_{i+1j} + \gamma T_{1j-1} + \varepsilon T_{1j+1} + \lambda T_{\infty} \quad [6]$$

Equation 1.1 Finite difference temperature general equation

Where α, β, γ, and ε are constants based on the location of the cables in the conduit. In Equation 1.1, the first four terms represent heat by conduction, while the last term is added to the equation for heat when the node is exposed to convection heat transfer with a medium of temperature $T\infty$. At each central node, the temperature equation is determined by using the heat balance method [6].

Using Equation 1.1, as well as many other factors from the specific materials, the software ETAP®, used for most of this research, is able to perform the various temperature calculations needed for this analysis.

1.2 **Literature Review**

1.2.1 Current Guide to Cable Sizing

There are multiple written guides to cable sizing, however, all methodologies in this field follow the same, or very similar general format as listed below:

i. Firstly, determine the worst-case current profile, including the number of repetitive cycles.
ii. Adjustment of the currents for harmonics, shield losses and dielectric losses.
iii. The rms value is calculated for the profile.
iv. Determine the maximum ambient and peak temperatures.

v. From voltage regulation requirements, select a trial cable size, and calculate the peak rise for high surges and fault currents.

vi. Calculate the steady-state temperature rise from the rms current.

vii. “Consult ampacity tables to select suitable choice below the current and temperature thresholds provided.”[5]

viii. Update selection for a larger (or smaller) conductor size and calculate steady-state and peak temperatures if the first selection is unsatisfactory. [5]

All these steps are very necessary for ensuring the proper cable size selection, however, in step “vii”, consulting the ampacity tables with the required current and temperature thresholds may throw off the actual results if one does not consider the other variables discussed in this research e.g. number of cables.

1.2.2 Modern Ampacity Calculations

Using accurate cable ampacities is critical to electrical power system design. An optimally sized cable results in minimum cost and high reliability. Wind and solar power plants particularly, due to their volatile nature, strive to optimize cable design by using ampacities that closely match maximum generation in order to ensure reliability. This report covered the following three methods used to calculate cable ampacities: the Neher–McGrath method, IEEE Cable Ampacity tables, and commercially available computer programs [9].

(i) Neher–McGrath Method

The first method called the Neher-McGrath Method makes use of the derivation done by J. H. Neher and M. H. McGrath by summarizing previous research into an analytical treatment of the practical problem of heat transfer from power cables. Their article remains a prevalent reference for ampacity deductions [13]. This calculation follows the basic principle that electric current produces thermal heating and transfer to the ambient environment, which requires there to be a difference between the temperatures of the two media. It also adheres to the assumption that in insulated cables, the maximum normal operating temperature is determined by the specific insulation, while in uninsulated cables, the limiting material property is the tensile strength of the cable [13].

(ii) Use of Specialized Tables (Black Books)

This second method involves the use of what the industry refers to as the "Black Books". This refers to the AIEE-IPECEA Power Cable Ampacities [10] first derived and tabulated in 1962. The appeal and convenience of this method is $^{\text{that}}$ it allows engineers and technical designers to easily look up the corresponding cable sizes based on the listed ampacities rather than using the actual Neher-McGrath Method to calculate the respective values [11].

"Considering the number of calculations needed to determine ampacity using the Neher–McGrath method, it is obvious why engineers would prefer using this simplified tabular method." [9] These tables are still used by many engineers today as their primary method of sizing underground cables. It is important to understand that these tables were created with certain base assumptions. These assumptions, for example, include the ambient temperature of the earth being 20°C. "Many locations in the Southwest USA experience the maximum underground soil temperature of 25°C–30°C, which reduces the ampacity by 5%–8% below the tabulated values." [9].

These assumptions are the main reason this research is relevant. Earth characteristics as well as specifications power companies use when laying underground distribution lines vary. As different variations of combinations and specifications change and evolve over the years, so should the assumptions and methods for ampacity calculations.

(iii) Software Method

This research uses software to calculate cable ampacity limits. The software is being used to understand heat and ampacity effects, as more factors can be included in the calculations. The 'rho'/thermal resistivity of the soil or backfill is an important factor, and though there are major rho values provided in the tables, it is important to know that these are just approximations and are sometimes not close enough to the variations actually seen in the real world. Soil depth, and ambient soil temperatures are also approximated. After all these approximations are made, their variations from the actual values add up which may result in significant discrepancies and wrongly sized cables.

1.2.3 Transient Heating of Power Cables

After a power cable is energized, its temperature will climb to a steady state value. Depending on how it is installed and what it is installed in, it will take a few to many hours to reach a steady temperature. "Considering a small cable in free air without wind, the cable will heat up in 1 $^{1}/_{3}$ hours, while a large cable will take about 6 hours. If in conduit buried in the earth, a large cable will take approximately 16 hours." [7].

For a single current-carrying cable in air, its temperature increases exponentially as shown in the equation below:

$$\Phi = \Delta T(1 - e^{-t/K})$$ [7]

Equation 1.2 Exponential temperature change in single current-carrying cable in air

Where:

Table 1.1 Definition of Temperature rise equation

Symbol	Interpretation & Units
Φ	Time varying rise (°C)
ΔT	Steady State Temperature Rise (°C)
t	Time (hrs.)
K	Time constant, equal to R*C (hrs.)
R	Thermal Resistance between wire & free air (°C/W)
C	Thermal Capacitance of Wire (Whr/°C)

"In a combined setting, for example, three conductors spaced together, with each carrying the same current as the conductor above, there is less than three times the exposed cable surface area in the bundle." [7]. In this setting, the value of R for the bundle is greater than $\frac{1}{3}$ the thermal resistance of one wire, so the bundle heats up to a slightly higher temperature rise than for the single wire, however, the capacitance for the bundle is three times the thermal capacitance of one wire, so the value of K is slightly greater than for the single wire. Therefore, the bundle heats up with a slightly longer heating time to the higher temperature rise. For simplicity, this scenario assumes that the small temperature differences through the cross section of the bundle are averaged [7].

A similar, but more complex calculation model can be used for bundles installed in a conduit underground. This complexity is derived from the additional resistances between the bundle and the conduit, as well as the conduit and the conduit and the material surrounding it. In direct buried installation, the material surrounding refers to the trench soil, while in the duct bank method (focus of thesis), it refers to the concrete material enclosing either a single, or multiple spaced conduits.

In addition, the conduit's thermal capacitance affects the heating time. First, the resistance has increased, increasing the heating time. Second, the conduit doesn't begin to heat up in the beginning. It doesn't have heat generated in it like the bundle, so it begins to heat up after the bundle starts to transfer heat to it, which happens only as the bundle heats up. And the conduit's thermal capacitance adds to that of the system. With both resistance and system capacitance increased, the time constant is increased [7].

All these affect the thermal aging of the cables which can be calculated using the IEEE standard proposed Arrhenius Aging Law whose model is as shown below:

$$t = \frac{h}{kT} \quad e^{\left(\frac{\Delta H - T\,\Delta S}{k\,T}\right)}$$

[8]

Equation 1.3 Arrhenius Aging Law

Where:

t = Thermal life (thermal aging) [s]

T= Temperature [°K]

h= Plank constant = 6.62606891x10-34 [J-s]

k= Boltzmann constant = 1.3806505x10-23 [J/°K]

ΔH= Activation enthalpy (material constant) [kcal/mole] [J]

ΔS= Activation entropy (material constant) [kcal/(mol-°K)] [J/°K]

$\Delta G = \Delta H - T\,\Delta S$= Activation energy [kcal/mole] [J]

1.3 Recent Research Status

In the study of underground power distribution, a lot of recent research is focused more on direct burial of cables than the use of duct bank raceways. This creates significantly more variables to study, which differ in location, time of day and even weather. In order to effectively conduct this research, few studies, which involved the use of duct banks, were consulted. The research involving duct banks focus on the effects of the finer details of the duct bank conditions rather than the cable itself.

A lot of research has been conducted on the cooling effects of the types of fillers used in enclosing the conduit. In the paper "Promoting Cable Ampacity by Filling Low Thermal Resistivity Medium in Ducts" [14], the authors experiment with fillers of varying degrees of thermal resistivity in order to judge its effect on temperature of both the cable conductors and the cable skins over a period of time. This research successfully compared the filling media and ascertained which was best for duct bank applications to maximize cable ampacity by significantly improving the radiating environment of the cable and increase the ampacity of the duct laying cable. "By filling the medium in ducts, the ampacity of the single-loop cable can increase by about 8% comparing with the one that is not backfilled."[14]

In the most recent relevant research, which serves as a basis for this thesis, the authors performed various field experiments to prove that the old methods of using "Black Books" were accurate enough for use in more complex underground cable networks. There were various assumptions made including several methods for determining underground cable ampacity. “The older Black Books use an ambient earth temperature of 20 °C, whereas the IEEE 835 tables use an ambient earth temperature of 25 °C. However, the IEEE tables assume that the cable shields are shorted, whereas the Black Books assume that the shields are single-point grounded.” [9] Overall, this results in the IEEE 835 values having a lower ampacity than the Black Books. Designers must understand that the assumptions used in preparing these tables may not match field conditions where cable is to be installed. Soil resistivity and ambient temperatures are particularly variable from site to site. [9].

In conclusion, though modern research highlights some discrepancies between the methods, it does not veer towards the cable properties in duct banks. The calculations and analyses performed in this research provide a template of thought for the individuals or groups responsible for cable selection for an underground power distribution project using duct banks; and with the trend of technology-plateau, and shift towards reliability and safety concerns, the use of underground raceway systems will play a bigger part in the field and generate a lot more research material.

1.4 Thesis Objective and Outline

After a thorough review of the present literature available, it is clear that cable sizing is an often overlooked factor as the distribution field progresses. Some current underground power distribution systems model their cable selection process similar to their overhead counterparts regardless of the vast differences in conditions such as cable spacing, ambient temperature, and surrounding materials. This oversight could potentially lead to system failures as well as provide unnecessary expenditures to distribution companies from using cables that cannot handle the conditions, to overcompensating and making use of cables that provide unneeded ampacity ratings.

When selecting and sizing cables for an underground power distribution system, there are a large number of criteria to be considered. These include criteria to ensure that the conductor properties are sufficient to avoid the overheating of the conductor and the terminals of connected equipment, as well as criteria to ensure that the voltage drop will not be excessive. There is a variety of wire and cable materials, and this in addition to the ambient conditions of the raceways and multiple other factors, complicates the cable sizing process. "These pressures have lead many design organizations to reduce the selection and sizing process to the use of a few application tables based on past experience and a simplification of the many criteria." [5]. These simplifications reduce the cost of the design, but can result in errors and/or a life cycle cost that is higher than necessary. Selection tables are convenient, but the built-in assumptions are almost always overlooked [5].

The objective of this thesis is to investigate the current cable sizing methodology for medium-voltage underground power distribution, and provide an assessment and solutions to their consequences (good or bad) on the cables' ampacity and temperature values. This will be done through the modelling of a 'test' medium voltage power system, and using the software ETAP ®, to simulate a combination of these cables in a single conduit, and observe the changes in temperature and ampacity values. All this will be performed with reference to the variations in cable size for normal steady state operation, transient operation, and short-circuit scenarios.

Chapter 2 System Network Overview

2.1 Network Design and One-Line Diagram

To setup the proposed medium-voltage distribution network to be analyzed, a One-Line-Diagram was designed as shown in the figure below:

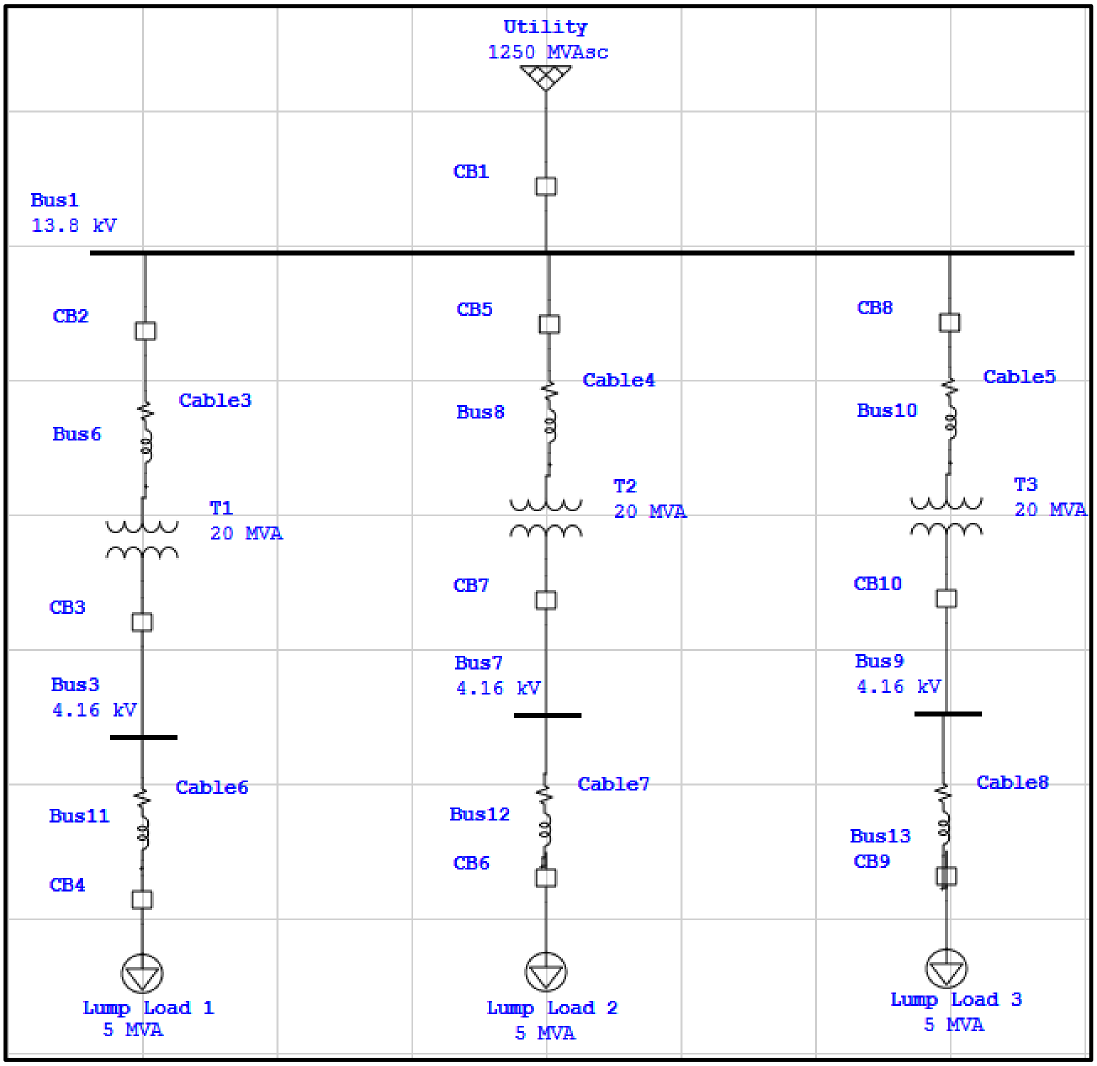


Figure 2.1 Power system network used

Here, we consider a utility in swing operation mode with a 3-Phase short circuit rating of 1250MV at 13.8kV. The proposed investigation involves the presence of three 3-Phase cables of similar current loading grouped in a common conduit, and the operating voltages chosen for analysis are 13.8kV and 4.16kV. At the end of the distribution, the power generated is consumed by a lumped load which can be best used to simulate further step-down processes for distribution purposes and other high-voltage applications. For this thesis, residential power supply shall be used as the load description, with low load growth.

2.2 Cable Properties and Setup

This research is focused on the cables and their corresponding properties when bundled, and deployed together in an underground raceway conduit, and subject to its normal mode of operation, as well as fault scenarios. Thus, using the proposed collective of cable features as well as project characteristics provided by Owen Electric Cooperative as standard, the cables 3 -5 as shown in figure 2.1 were assigned the following characteristics.

Table 2.1 Characteristics of cables used in network

Cable Material	Copper
Cable Size	500 kcmil
Cable Rating	15kV
Core Type	1/3 Concentric Neutral
Conduit Material	Non-Magnetic Metal (Stainless Steel)
Cable Length	400 feet
Conduit Depth	10 feet
Cable Insulation	Cross-linked Polyethylene (XLPE 100%)
Cable Jacket	PVC
Cable Orientation	Cradled

The conduit is assumed set at a 6 inch diameter, and this assumption is held for all the analyses performed in this research; thus, with these characteristics in mind, the cross-section cable layout for cables 3 -5 (13.8kV) can be illustrated in Figure 2.2:

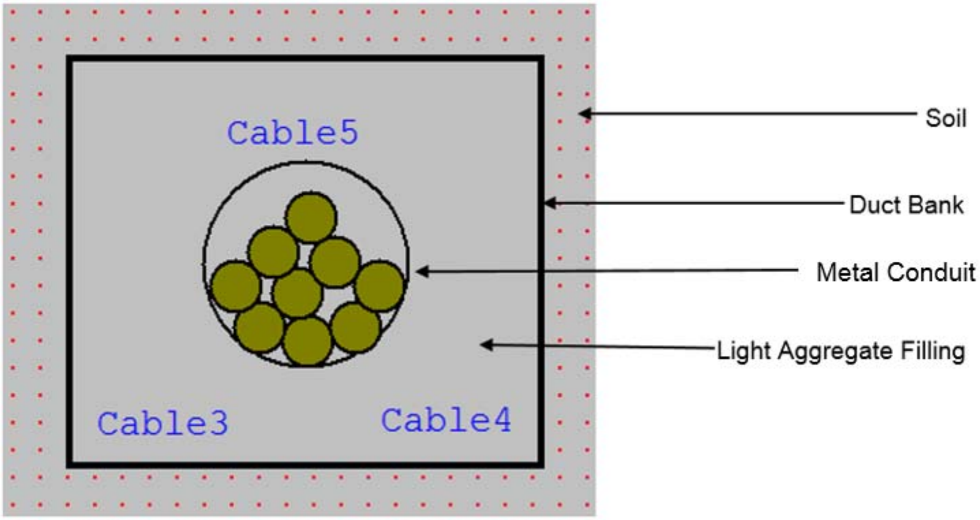


Figure 2.2 15kV Cable layout in common conduit

To begin the investigative process, a power flow analysis was conducted in order to ascertain the loading characteristics of the various elements in the network. For the cables in question shown above, the operating load/current is similar due to the one-line diagram construct, and is highlighted below:

Table 2.2 Operating Load Current and Power Factors of Cables

	Average	Phase A	Phase B	Phase C
Current (Amps)	209.2	209.2	209.2	209.2
Power Factor (%)	79.23	79.23	79.23	79.23

Chapter 3 Steady State Temperature Analysis

3.1 Analysis Overview

This steady state temperature analysis is run as an iterative method. For all the analyses performed, the following temperature standard was observed:

Table 3.1 Legend of set temperature value ranges in thermal analysis

	Legend
🟩	Ambient Temperature (< 80°C)
🟪	Warning Temperature (80°C ≤ T < 90°C)
🟥	Alert Temperature (T ≥ 90°C)

This was done according to the cable insulation material selected. XLPE-insulated cables have a rated maximum conductor temperature of 90 °C and an emergency rating up to 140 °C, depending on the standard used. They also have a conductor short-circuit rating of 250 °C. This was chosen because XLPE has the lowest maximum conductor temperature, making it the ideal material on which to base all the analyses on. “This cable is predominantly used for primary underground distribution; suitable for use in wet or dry locations, direct burial, underground duct, and where exposed to sunlight.” [12] It is to be used at 15kV or less, and at conductor temperatures of less than 90°C in normal operation. Therefore, the thermal analysis was based on cable sizes and combinations that allow for normal operation (T < 90°C). Lastly, with all these cable constraints set, the conduit was chosen to be a 6 inch diameter steel pipe.

3.2 Results & Analysis

3.2.1 Power Company Proposed Size: 500 kcmil

Owen Electric proposed the use of 500 kcmil cables for this application. The results from the steady state analysis shows that this choice, however appropriate and safe for the cable to maintain temperatures well below its limit, can be argued as oversized. The company intended to combine three 3-phase cables of similar voltage rating and loading in a common conduit. The results shown in Figures 3.1 – 3.3 highlight a progression of temperature increase over the course of adding each additional cable (Cable 3, 4 and 5).

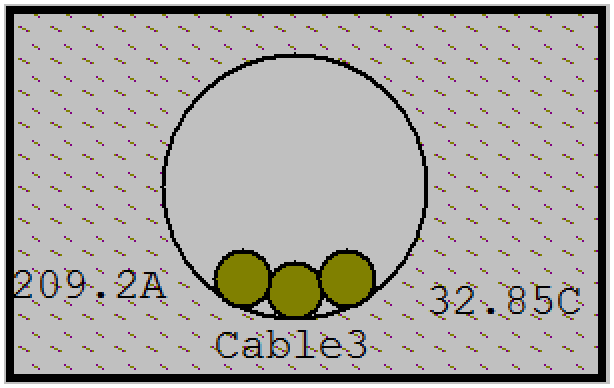


Figure 3.1 Single 3-Phase 15kV Cable at 500 kcmil

From Figure 3.1, it can be seen that the single cable in the conduit allows a steady state temperature of 32.85°C. This is well below the 80°C warning temperature setting, thus its green shading. With an alarm temperature of 90°C, the temperature for this iteration is less than half of its limit.

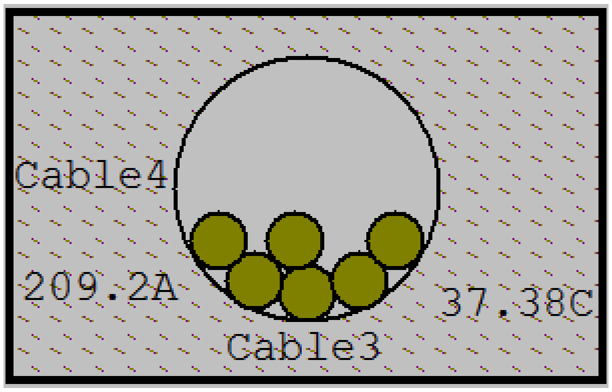


Figure 3.2 Two 3-Phase 15kV Cables at 500 kcmil

In the iteration shown in Figure 3.2, the temperature rises about 5°C from the corresponding single cable value. The value of 37.38°C is still less than half of the limit and can therefore easily handle the temperature due to the current.

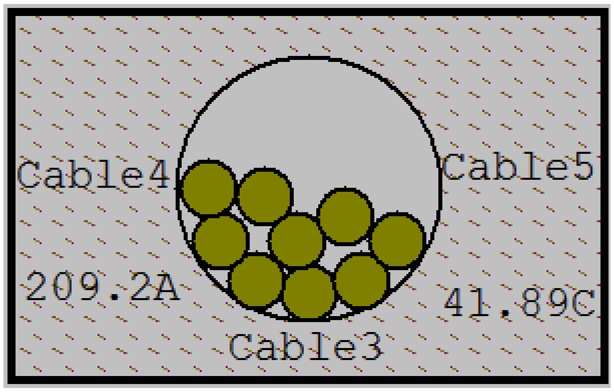


Figure 3.3 Three 3-Phase 15kV Cables at 500 kcmil

In the final iteration of this case study highlighted in Figure 3.3, all three cables were added to the conduit and the steady state temperature analysis revealed a temperature value of 41.89°C. This, like the previous two iterations, is well below half of the limit and this temperature is easily handled by the chosen cable size and materials.

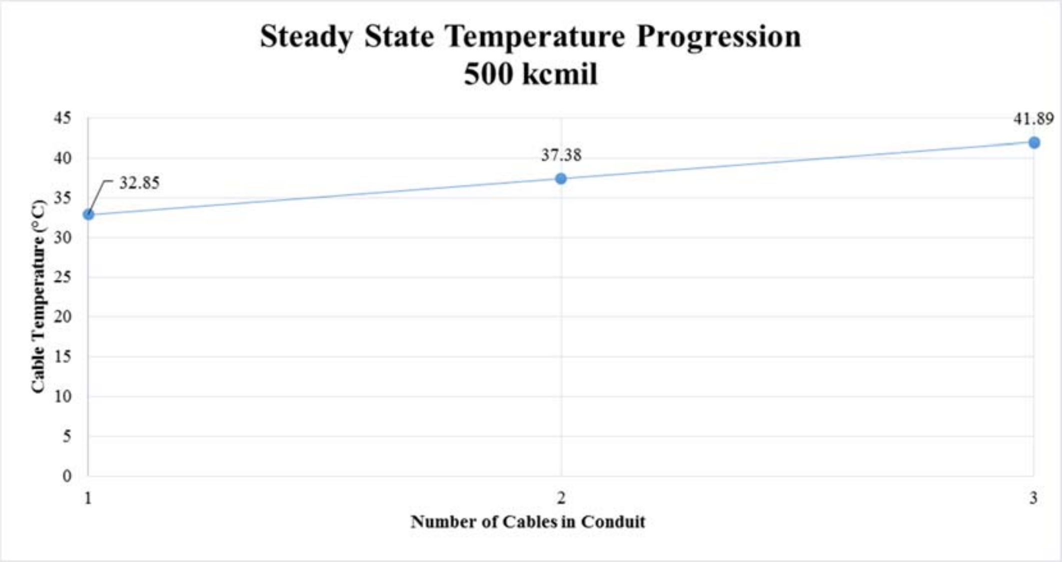
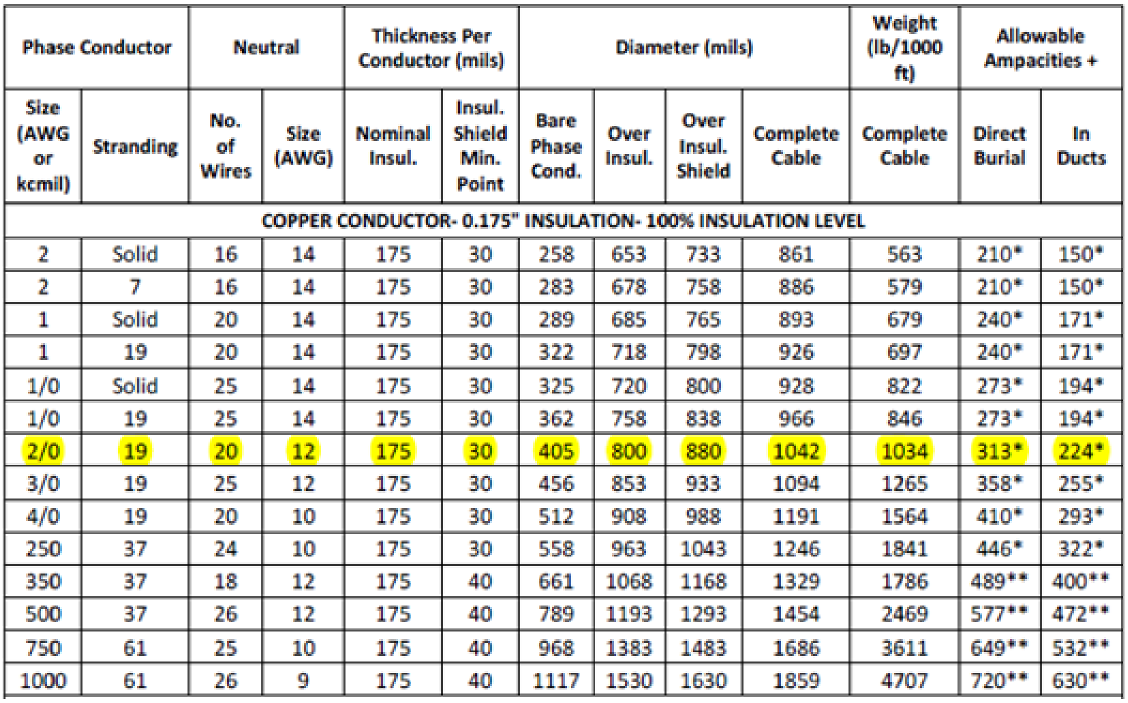


Figure 3.4 Steady state temperature progression at 500kmcil

3.2.2 Cable Manufacturer Proposed Size: 2/0 AWG [12]

For this section of the analysis, a major cable manufacturer was selected - SouthWire Company, LLC. Most, if not all, cable manufacturers use the National Electric Code (NEC) ampacity table as a guide for deriving their company specific cable ampacities, while the rest use the actual NEC table as a reference for the customer. This company as examined, used the NEC table as a guide, and slightly varied their values slightly according to their individual specifications, however, the main ranges provided are still the same, and the discrepancies insignificant.

According to a data sheet provided by SouthWire, the proposed size for the loading current (209.2 Amps) calculated during the power flow analysis of the network, is 2/0 AWG, as shown in Figure 3.5:



Phase Conductor		Neutral		Thickness Per Conductor (mils)		Diameter (mils)				Weight (lb/1000 ft)	Allowable Ampacities +	
Size (AWG or kcmil)	Stranding	No. of Wires	Size (AWG)	Nominal Insul.	Insul. Shield Min. Point	Bare Phase Cond.	Over Insul.	Over Insul. Shield	Complete Cable	Complete Cable	Direct Burial	In Ducts
COPPER CONDUCTOR- 0.175" INSULATION- 100% INSULATION LEVEL												
2	Solid	16	14	175	30	258	653	733	861	563	210*	150*
2	7	16	14	175	30	283	678	758	886	579	210*	150*
1	Solid	20	14	175	30	289	685	765	893	679	240*	171*
1	19	20	14	175	30	322	718	798	926	697	240*	171*
1/0	Solid	25	14	175	30	325	720	800	928	822	273*	194*
1/0	19	25	14	175	30	362	758	838	966	846	273*	194*
2/0	19	20	12	175	30	405	800	880	1042	1034	313*	224*
3/0	19	25	12	175	30	456	853	933	1094	1265	358*	255*
4/0	19	20	10	175	30	512	908	988	1191	1564	410*	293*
250	37	24	10	175	30	558	963	1043	1246	1841	446*	322*
350	37	18	12	175	40	661	1068	1168	1329	1786	489**	400**
500	37	26	12	175	40	789	1193	1293	1454	2469	577**	472**
750	61	25	10	175	40	968	1383	1483	1686	3611	649**	532**
1000	61	26	9	175	40	1117	1530	1630	1859	4707	720**	630**

Figure 3.5 SouthWire Sizing Chart for 15kV Primary Underground XLPE [12]

The asterisk (*) beside the values in the highlighted row provides the following connotation:

“Ampacities shown assume use of 100% load factor, 60 Hz current, 36" burial depth, 20°C ambient temperature, 90°C conductor temperature, earth RHO 90, insulation and shield RHO 400.”[12]

As shown in the highlighted row, for the current 224 A in ducts (above the 209.2 A loading current), corresponds with 2/0 AWG, and this would be adequate, were it only one cable per conduit similar to the first iteration shown in Figure 3.6:

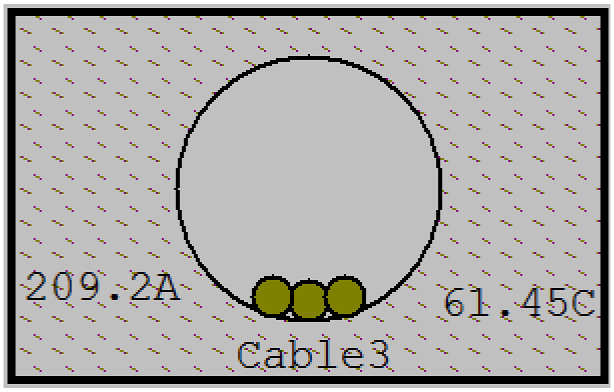


Figure 3.6 Single 3-Phase 15kV Cable at 2/0 AWG

For this first iteration at 2/0 AWG, the single cable steady state thermal analysis provides a resultant temperature value of 61.45°C. Given that this cable has the warning temperature of 80°C, the shading remains green, and this setup can be expected to operate normally.

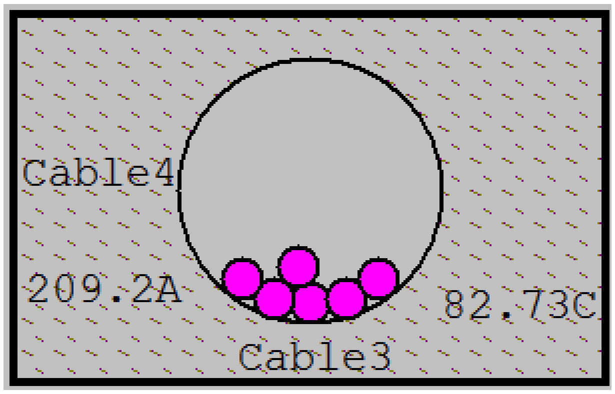


Figure 3.7 Two 3-Phase 15kV Cables at 2/0 AWG

In the second iteration, two cables of the specified sizing were used and the resulting steady state temperature was calculated to be 82.73°C. This value is higher than the warning temperature, but less than the alarm temperature; hence, the purple shading. With this result, the cable can operate normally at this current; however, the temperature change does show a jump of approximately 20°C with the addition of an extra cable of equal loading.

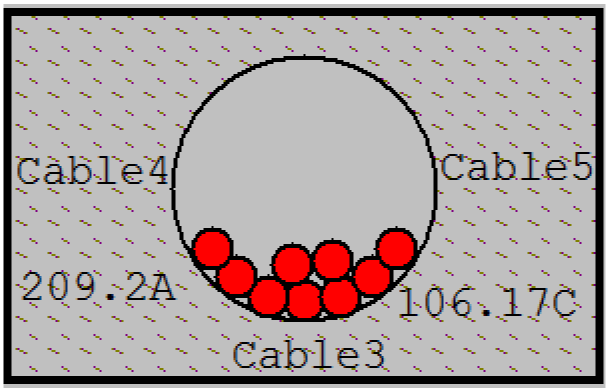


Figure 3.8 Three 3-Phase 15kV Cables at 2/0 AWG

The final iteration for this case, like the previous one, involves the addition of one more equally loaded cable to the conduit. It can be observed in Figure 3.8 that with the red shading, the temperature is above the normal operation thermal limit for this cable (106.17°C < 90°C). This proves that although the values given by the cable manufacturer may hold true in some cases, the scenario is unsafe for three or more cables in a common conduit. Over the course of this case, the temperature increases by more than 20°C per additional cable added.

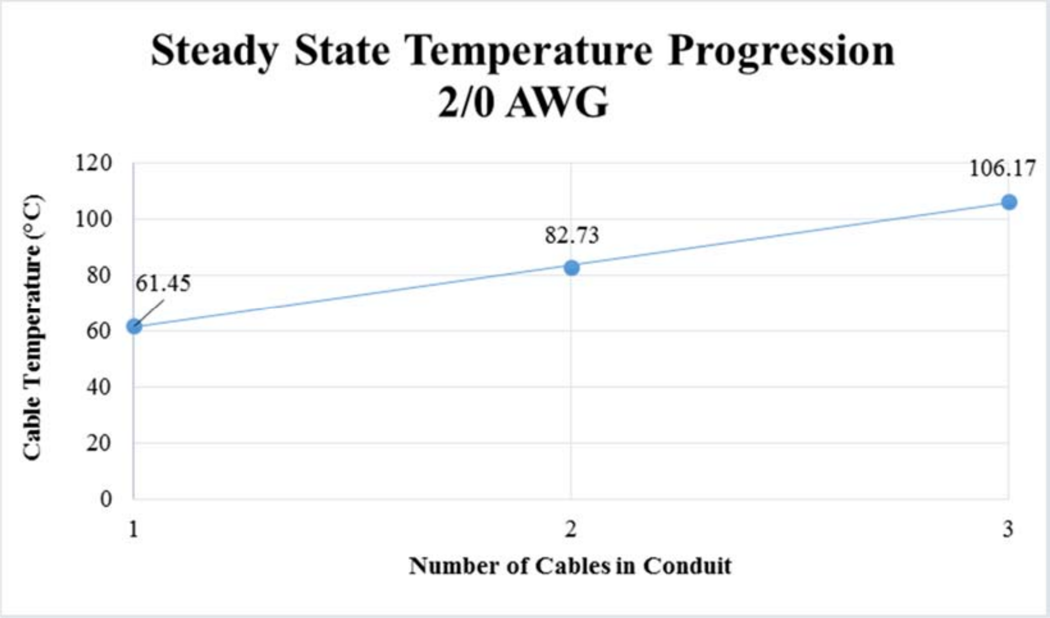


Figure 3.9 Steady state temperature progression 2/0 AWG

3.2.3 Analysis Proposed Size: 3/0 AWG

After dealing with the previous two case studies, it was found that 500 kcmil proposed by the power company is an overcompensation for the current due to the significantly low steady state temperature values. The results gotten from adhering to the cable manufacturer’s data sheet recommendations had better values; however, overheated with the addition of a third cable to the conduit. Thus, through the use of the software, another case was studied; this involved the use of the size immediately larger than the manufacturer, which is 3/0 AWG.

As seen in Figure 3.10, the presence of a single cable in the conduit produced a steady state temperature of 52.2°C, which is above half the limit, but still below the warning.

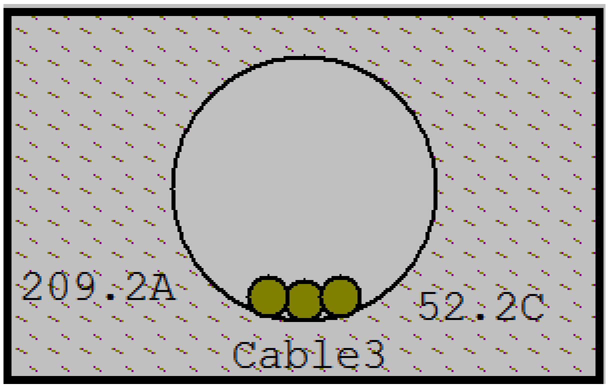


Figure 3.10 Single 3-Phase 15kV Cable at 3/0 AWG

The next iteration shown in Figure 3.11 involved the introduction of a second cable which resulted in a temperature of 67.66°C. This is still below warning, though above its ambient temperature of 25°C.

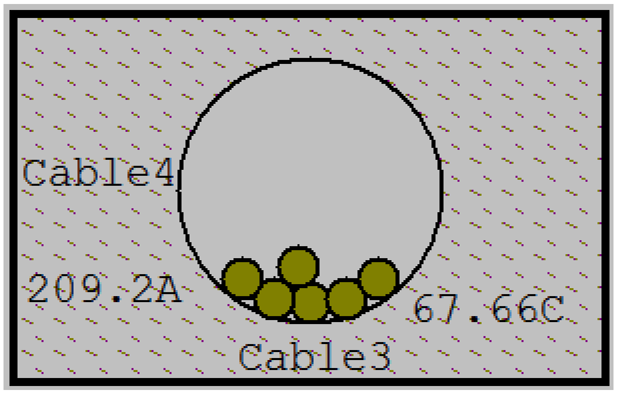


Figure 3.11 Two 3-Phase 15kV Cables at 3/0 AWG

Finally, the addition of a third cable shown in Figure 3.12 brought the temperature to 84.13°C, which is above the warning temperature but still below the alarm/maximum allowable temperature.

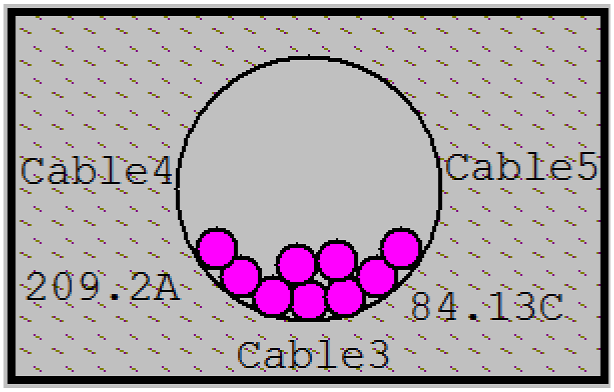


Figure 3.12 Three 3-Phase 15kV Cables at 2/0 AWG

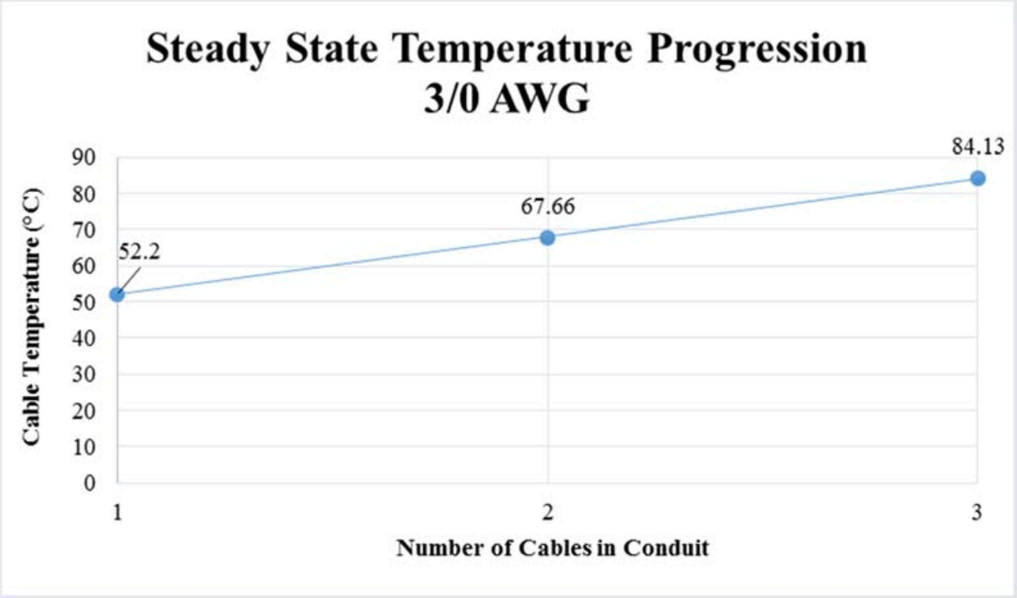


Figure 3.13 Steady state temperature progression at 3/0 AWG

These results can be used to illustrate that 3/0 AWG is better suited than 2/0 AWG, and 500 kcmil is an overcompensation for the required loading. The drawbacks for the overcompensation lie in the economics of underground distribution as seen in Appendix G. The table in Appendix G shows the significant price difference between the three sizes investigated; 2/0 AWG being \$3,920.51 per 1000ft, and 3/0 AWG and 500kcmil being \$ 4,940.18 and \$14,536.73 per 1000ft respectively. As previously mentioned, the use of underground raceways, or direct buried conduits is a significantly more expensive method of power distribution than its overhead counterpart, and the unnecessary use of more expensive underground cables such as the 500 kcmil as well as conduit and duct bank materials, which are used to properly house the bigger wire sizes, add up to the overwhelming costs of this convenient mode of distribution.

Also, the use of a smaller cables due to outdated ampacity calculations with assumptions that are not tailored to the specific scenario (depth, number of conductors in common conduit) can result in overheating and degradation of the cables.

Figure 3.14 shows a chart constructed with values compiled from running the steady state temperature analysis of the same cable loading current conditions with varied cable number and size combinations. The chart highlights the vast difference cable sizing provides in terms of temperature when dealing with the same system.

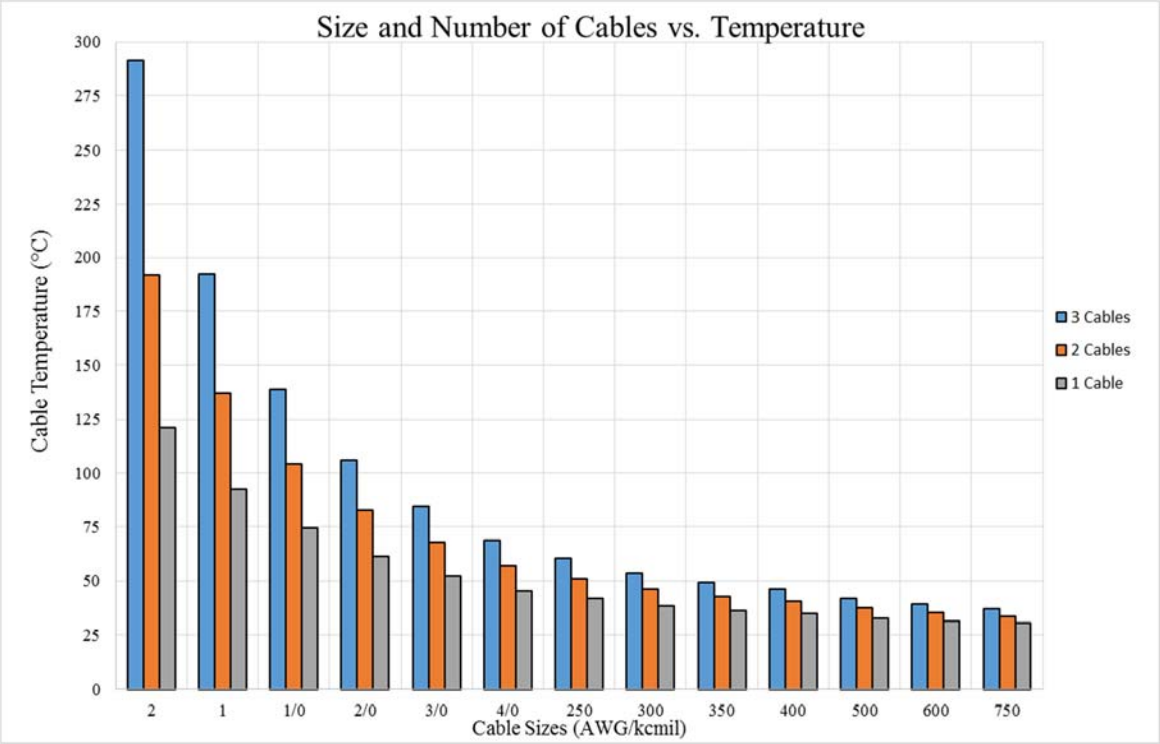


Figure 3.14 Summary of variation of cable temps at different sizes and combinations

3.2.4 Effect of Conduit Material (3/0 AWG)

For this thesis, the conduit material was chosen as a non-magnetic metal (stainless steel), and this was in order to ignore the electromagnetic and heating effects from the current flow through the conduit. However, it was also chosen due to the superior heat dissipating properties when compared to the following other materials as can be seen in Fig. 3.15.

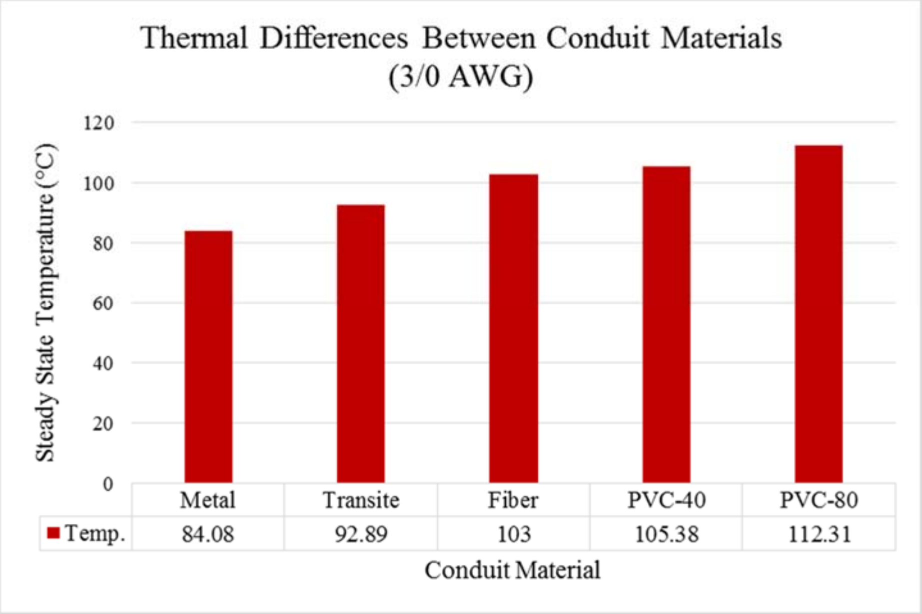
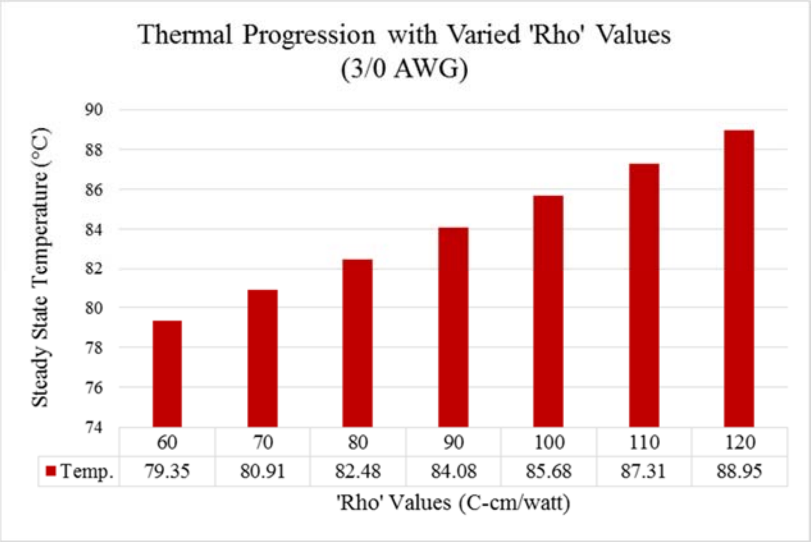


Figure 3.15 Steady state thermal comparison of different conduit materials

Therefore, from Figure 3.15, it can be seen that the heat dissipating properties of the other potential conduit materials are not as high as that of metal. The alternative materials may be preferred in direct burial use due to their lower cost, as well as resistance to rust. In the duct bank raceway method, conduits are encapsulated by a concrete filler, thereby removing any moisture concerns. There is no specific preference to suggest one material's popularity; the choice is mostly based on financial, and regulation reasons.

3.2.5 Effect of RHO (3/0 AWG)

Regardless of whether a cable is laid using the direct buried or duct bank method, the ‘rho’, which is defined as the soil/backfill material thermal resistivity, is a very important component that is not to be overlooked. The National Electric Code highlights it as an indicator of the heat transfer capability of a homogenous filler, through conduction and it is expressed in C-cm/watt. The average ‘rho’ value for soil in 90% of the United States is 90 C-cm/watt; however, it can go as low as 60 C-cm/watt in coastal areas with high water table, and 120 C-cm/watt in very rocky, dry, and sandy areas [17]. The filler chosen for this research has the rho value of 90 C-cm/watt, therefore, mimicking common soil; however, Figure 3.16 shows the significant change in steady state temperature for this scenario with varied ‘rho’ values.



	60	70	80	90	100	110	120
🟥 Temp.	79.35	80.91	82.48	84.08	85.68	87.31	88.95

Figure 3.16 Thermal progression with varied ‘rho’ values

Chapter 4 Cable Ampacity Calculations

Chapter 4 focuses on the calculation of the cable ampacity using two main methods:

(i) Uniform Temperature Option

(ii) Uniform Ampacity Option

In both methods, the analysis will only be using the cable of size 3/0 AWG, which was ascertained as the best sizing option for the proposed cable combination model in a common conduit. The aim of this calculation is to provide a final analytical look at the difference in the values between the older methods and current calculation values, which consider more variables to fine-tune the results for each specific calculation. As previously stressed, these differences are important to note in order to ensure the safe sizing in future cable networks.

4.1 Cable Ampacity with Uniform Temperature

4.1.1 Analysis Process Breakdown

The uniform-temperature ampacity calculation involves an iterative process, which adjusts cable loading current in each iteration so that the cable temperature approaches the temperature limit. In this ETAP cable ampacity module, the load adjustment in each step is determined based on the gradient of cable temperature change and therefore, offers fast convergence to the solution. [18]

4.1.2 Results and Analysis

The calculated results for the variation of 1 – 3 cables in a common conduit are shown in Figures 4.1 – 4.3:

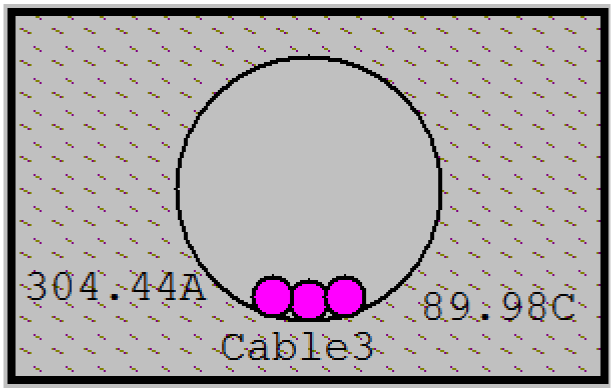


Figure 4.1 Single cable ampacity with uniform temperature

Figure 4.1 shows the first iteration results (single cable). Due to the nature of the calculation, the cable is shown to be right at the temperature limit initially set. The maximum current that can maintain that temperature is 304.44 Amperes.

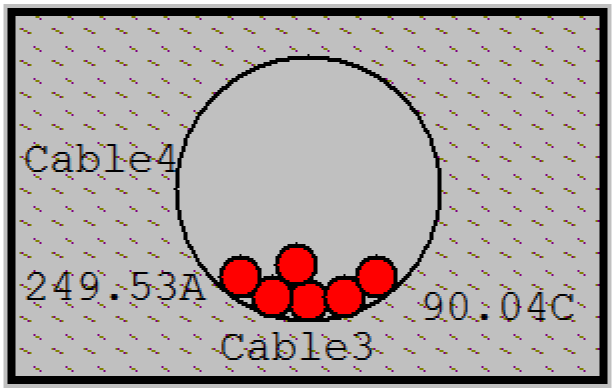


Figure 4.2 Double cable ampacity with uniform temperature

For the second iteration, shown in Figure 4.2, the temperature was also put at the limit (as best as it could), and the maximum current was now decreased to 249.53 Amperes, thus highlighting the drop in more than 50 A of ampacity with the addition of an extra cable to the conduit.

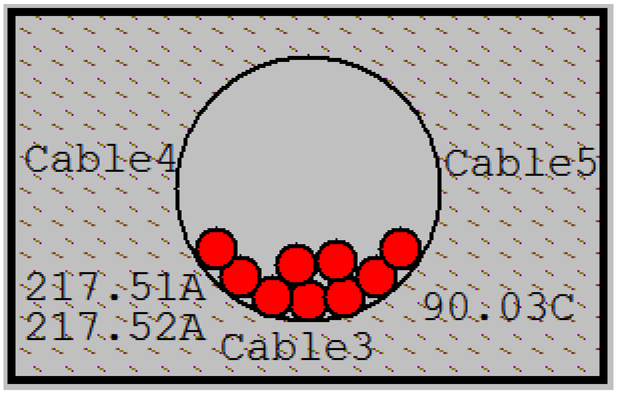


Figure 4.3 Triple cable ampacity with uniform temperature

For this last iteration, shown in Figure 4.3, the same calculations were performed, and as expected, this resulted in a further decrease in cable ampacity.

4.2 Cable Ampacity with Uniform Ampacity

4.2.1 Analysis Process Breakdown

This cable ampacity calculation approach is based on the equal temperature criterion for ampacity calculation. It determines the maximum allowable load currents when all the cables in the system have their temperature within a small range of the temperature limit. Since all the conductors in a cable branch are assumed to equally share the load current, in the case where these conductors are not located in the same conduit/location, they may not have the same temperature. When this situation occurs, the temperature of the hottest conductor in this cable branch will be used to represent this cable branch. [18]

4.2.2 Results and Analysis

Figures 4.4 – 4.6 show the result of this iteration with 1 – 3 cables using the Uniform Ampacity Method. As can be seen, these values are very similar to that of the previous method, highlighting the point made that the ampacities considered should be varied according to the number of cables in a common conduit. Thus, individuals tasked with cable selection should note the decreasing trend of cable ampacity values as the number of cables are increased i.e. they are inversely proportional.

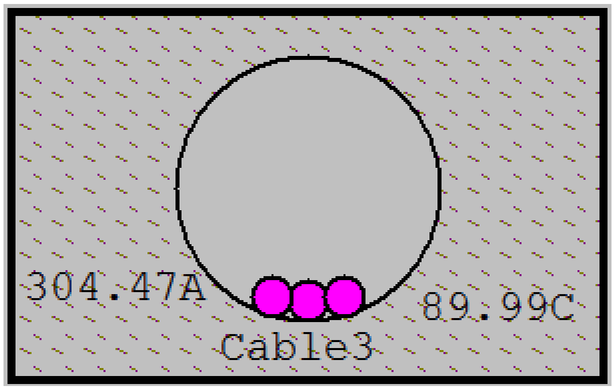


Figure 4.4 Single cable ampacity with uniform ampacity

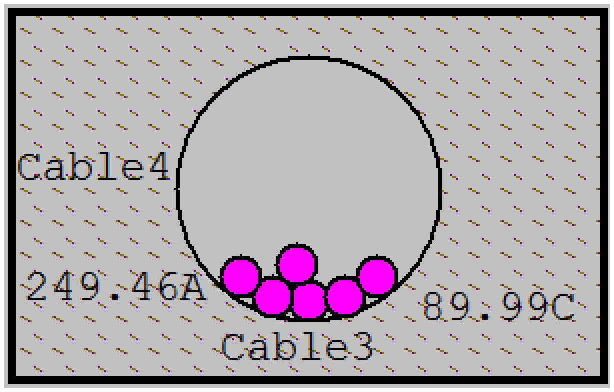


Figure 4.5 Double cable ampacity with uniform ampacity

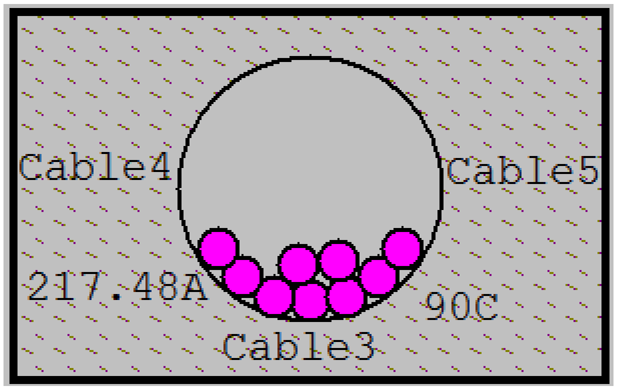


Figure 4.6 Triple cable ampacity with uniform ampacity

Chapter 5 Short Circuit Fault Analysis

5.1 Short Circuit Overview

A short circuit can be described as low impedance abnormal contact between two points of different potentials. In this case, the short-circuit duty cycle is studied; that is, the maximum available short circuit fault during the first half cycle or interrupting current. Specifically, the study looks at the worst case scenario, which is a three phase ungrounded fault. This short circuit analysis is done in order to ensure its adverse effects do not undermine the validity of this research.

When selecting a cable and its corresponding rating and size, it is important to know the range of temperatures as well as current it is expected to carry. This study is aimed at deriving the fault current to be used to calculate cable ampacity and temperature values in order to ensure and confirm that the sizing is appropriate. The process using the ETAP® software is shown in the outline below:

(i) Perform the Short Circuit Calculation faulting the buses of the analyzed cables.

(ii) Run a Transient Temperature Calculation using the Fault Current obtained from the previous calculations.

(iii) Compare max temperature to manufacturer specified melting point of analyzed cable.

5.2 Short Circuit Calculation

Running the 3-Phase Device Duty (ANSI C37) short circuit calculations produced the following values:

Table 5.1 Short circuit calculation values

Device ID	Nominal kV	Initial Current (A)	Fault Current (kA)	X/R Ratio	Fault Runtime (s)
Bus1	13.8	209.2	54.21102	11.91934	0.3

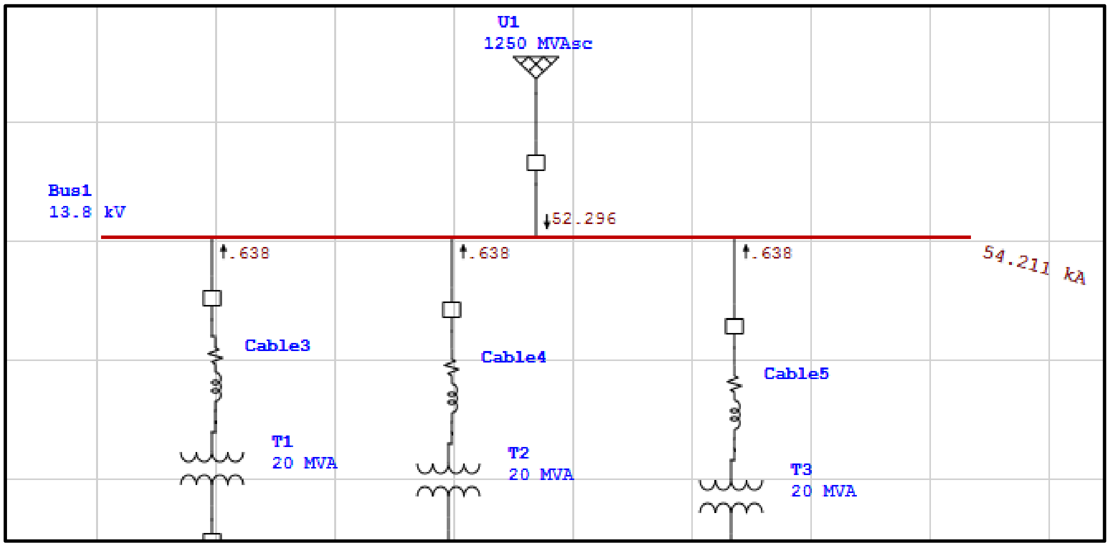


Figure 5.1 Short circuit calculation on network

5.3 Transient Temperature Calculation

5.3.1 Calculation Overview

As previously mentioned, this process involves the time-variant simulation of the thermal characteristics of the cables when the calculated fault current is passed through. The fault current being used as shown in Table 5.1 is 54,211 Amperes, and it will run for 0.3 seconds, i.e., between the inception time of 0.5 seconds and end time of 0.8 seconds before the circuit breaker trips and renders the flowing current to be approximately zero. It will also consider 1 – 3 cables in the conduit. It is important to note that the standard melting point for copper wires is 1,085°C, therefore, this value shall be used a reference point for which the maximum temperature of the cable during this peak fault current should be significantly below. The melting point of the insulation (XLPE) is 108°C, at a melt flow rate of 0.1 g/10min, thus, this analysis will assume the melting of the insulation occurs during the fault.

5.3.2 Results and Analysis

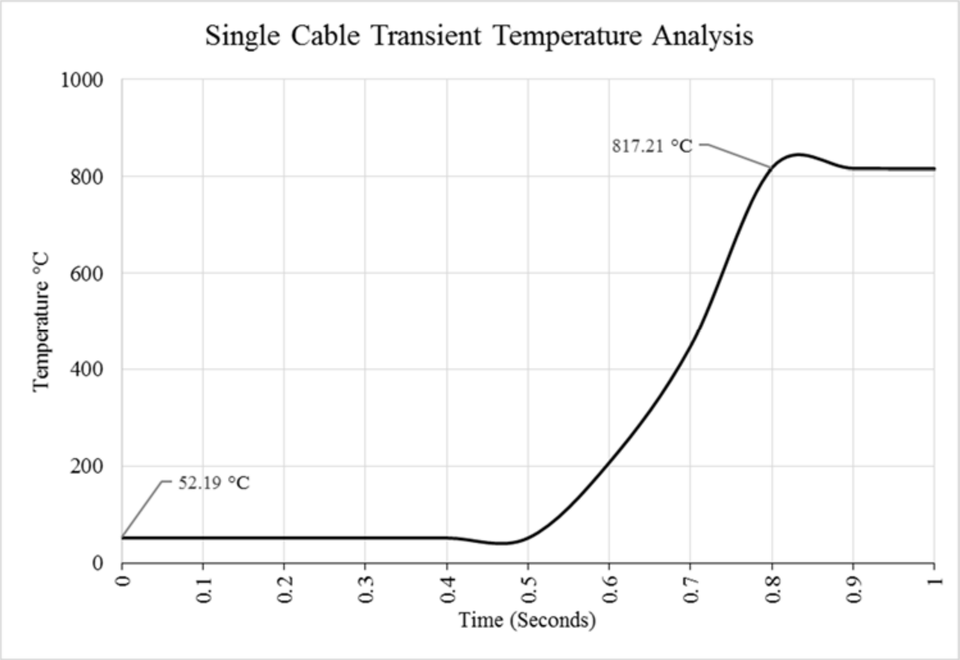


Figure 5.2 Single cable temperature fault analysis over one second

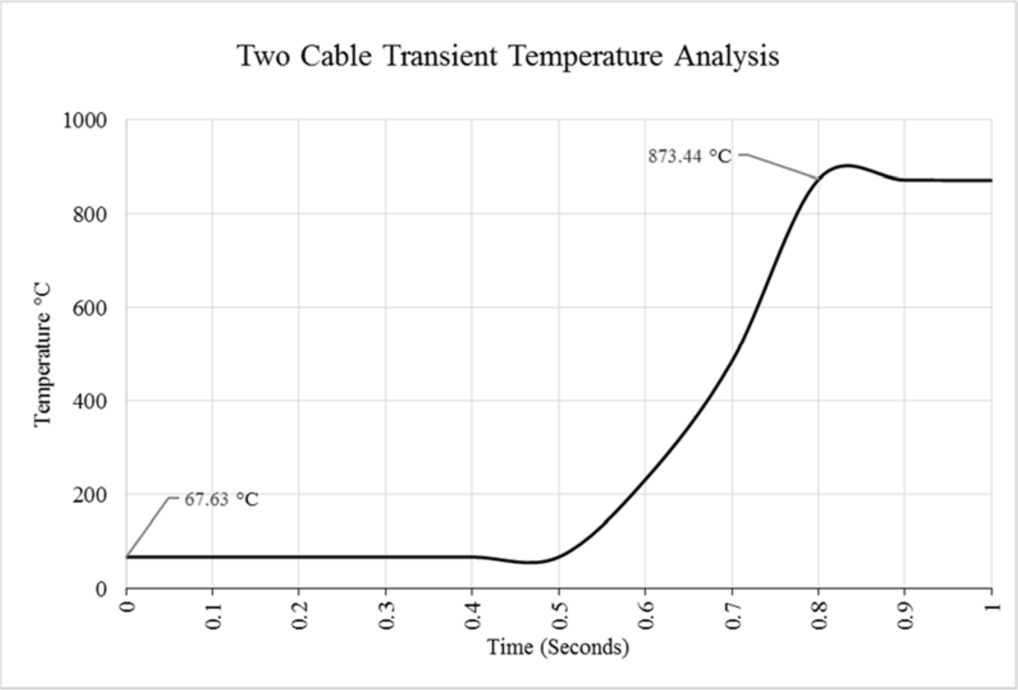


Figure 5.3 Double cable temperature fault analysis over one second

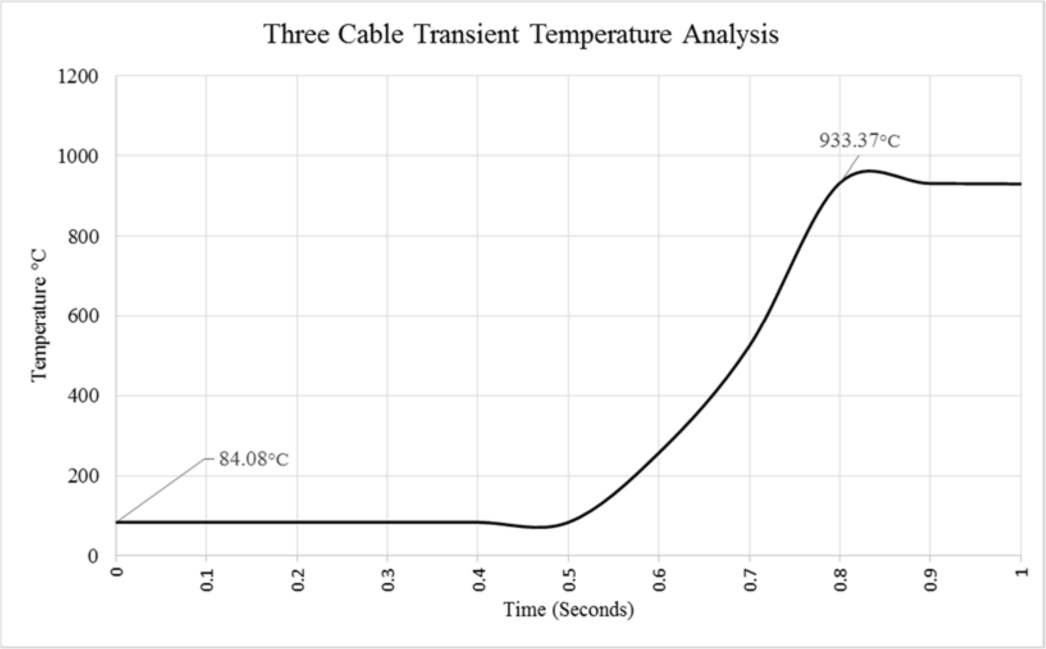


Figure 5.4 Triple cable temperature fault analysis over one second

This thermal analysis was performed over the period of one second. As shown in Figures 5.2 – 5.4, the fault current is introduced to the cable(s) at 0.5 seconds to 0.8 seconds before the circuit breaker is tripped, removing all incoming current flow to the cable(s). The graphical illustrations above show the rapid incline and steady decline of the cable(s) temperature during this event.

5.3.3 Summary

As seen in the plots concerned (Fig. 5.2 – 5.4), the cables' maximum temperatures never reach up to 50°C proximity to the melting point of the cables (1,085°C), which satisfies the test as to whether the cable size selected is suitable for both steady state normal operations, but during fault conditions as well. This further emphasizes the role of cable sizing, for at a smaller size, these thermal conditions would have been significantly higher, possibly surpassing the limit and resulting in a faulty cable which will then require capital, effort, and loss of reliability to rectify.

Chapter 6 Summary and Conclusions

6.1 Summary

This thesis was aimed at highlighting the limitations in the current system of cable sizing calculation through the study of two important values influenced by it, temperature and ampacity. The results gotten from the steady-state temperature calculations, and both ampacity calculation options were compared and shown to be significantly different from the standard values put out there for engineers to use as a reference thanks to factors such as the number of cables combined in a common conduit. The short circuit calculations further act as an indicator to certify that the calculations and processes performed leading to this conclusion were valid in all scenarios, and to ensure safety and reliability of the proposed construct.

6.2 Conclusions

The use of accurately calculated ampacity values is integral for ensuring the safety and reliability in underground power distribution. As the world trends towards more underground distribution due to limited overhead space and obstruction, this research will play an important part in providing designers and project engineers with additional variables to consider during the cable selection process; this thesis proves that these seemingly trivial assumptions and approximations result in a significant margin of error. Safety and reliability are some of the major reasons why underground raceways can be preferred when selecting methods of distribution, therefore, it is important to ensure all other factors that affect cable reliability are in good shape before venturing into the most expensive mode of power distribution.

The results obtained from this research are not comprehensive, and the ETAP software is not the absolute solution to this problem; however, it was able to highlight the importance of the factors discussed in this thesis, and shine a light on the inaccuracies ignored when deriving cable ampacities. It is ultimately up to the engineer to use all the resources at his/her disposal in order to ensure a reasonably accurate result, and possibly upsize after that to account for the unconsidered variables.

6.3 Future Work

The research done in this paper by no means covers all the aspects involved in this field. This research was only limited to underground duct bank raceways, though direct buried options are still very popular in the distribution field. There are also electromagnetic effects that were ignored in this analysis, which would provide a whole different dynamic when considering the effects of eddy currents on the cable thermal properties, both in steady state, and in the event of a fault.

Finally, important work can also be done in the use of multiple casings in a single conduit to limit thermal flow and undesirable electromagnetic effects. For example, each cable phase contained in a PVC conduit, then combined in an encasing steel conduit.

There are many variables and variation of methods to be considered when planning an underground power distribution system, and this research, and future work in the field will help to provide a framework and guideline for deducing an appropriate value for these variables, to ensure optimal safety and reliability.

APPENDIX A: Load Flow Report

Bus		Voltage		Generation		Load Flow				
ID	kV	%Mag	Ang.	MW	Mvar	ID	MW	Mvar	Amp	%PF
Bus 1	13.8	100.00	0.0	11.887	9.151	Bus 6	3.962	3.050	209.2	79.2
						Bus 8	3.962	3.050	209.2	79.2
						Bus 10	3.962	3.050	209.2	79.2

APPENDIX B: Short Circuit Report

Contribution		½ Cycle					1.5 to 4 Cycle				
From Bus ID	To Bus ID	%V From Bus	kA Real	kA Imag.	Imag/ Real	kA Symm. Mag.	%V From Bus	kA Real	kA Imag.	Imag/ Real	kA Symm. Mag.
Bus 1	Total	0.00	4.540	-54.024	11.9	54.214	0.00	4.475	-53.411	11.9	53.599
Bus 6	Bus 1	0.28	0.066	-0.636	9.7	0.639	0.19	0.044	-0.432	9.8	0.434
Bus 8	Bus 1	0.28	0.066	-0.636	9.7	0.639	0.19	0.044	-0.432	9.8	0.434
Bus 10	Bus 1	0.28	0.066	-0.636	9.7	0.639	0.19	0.044	-0.432	9.8	0.434
Utility	Bus 1	100.0	4.343	-52.116	12.0	52.296	100.0	4.343	-52.116	12.0	52.296

APPENDIX C: In-depth Cable Properties

Properties		Dimensions	
Conductor Construction	ConRnd	Diameter	0.46 inch
Inuslation	XLPE	Thickness	175 mil
		Max Stress	61.13 V/mil
Shield	Not Shielded		
Armor	None		
Sheath	Copper Sheath	Thickness	2.4 mil
Armor/Sheath Grounding	Open	Max Induced	0.02 V/ft
Jacket	PVC	Thickness	78.7 mil
Cable	SouthWire	Diameter	1.09 inch
DC Resistance		Rdc	64.3332 micro ohms
Cable Pulling		Weight	934 lbs/1000ft
		Max. Tension	11 lbs/lcmil

APPENDIX D: Steady State Temperature Analysis Results

No.	Cable ID	Energized Conductor Per Cable	Rdc @ Final Temp (µOhm/ft)	Dielectric Losses Watt/ft	Yc	Ys	Conductor Lsses Watt/ft	Current Amp	Temp °C
1	3-A	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
2	3-B	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
3	3-C	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
4	4-A	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
5	4-B	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
6	4-C	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
7	5-A	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
8	5-B	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08
9	5-C	1	78.98	0.007	0.003	0.001	3.475	209.20	84.08

Yc = Increment of AC/DC resistance ratio due to AC current skin and proximity effect
Ys = Increment of AC/DC resistace ratio due to losses of circulation and eddy current effect in shield, sheath and armor

APPENDIX E: Uniform Ampacity Analysis Results

No.	Cable ID	Energized Conductor Per Cable	Rdc @ Final Temp (µOhm/ft)	Dielectric Losses Watt/ft	Yc	Ys	Conductor Lsses Watt/ft	Current Amp	Temp °C
1	3-A	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
2	3-B	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
3	3-C	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
4	4-A	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
5	4-B	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
6	4-C	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
7	5-A	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
8	5-B	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00
9	5-C	1	80.45	0.007	0.003	0.001	3.825	217.48	90.00

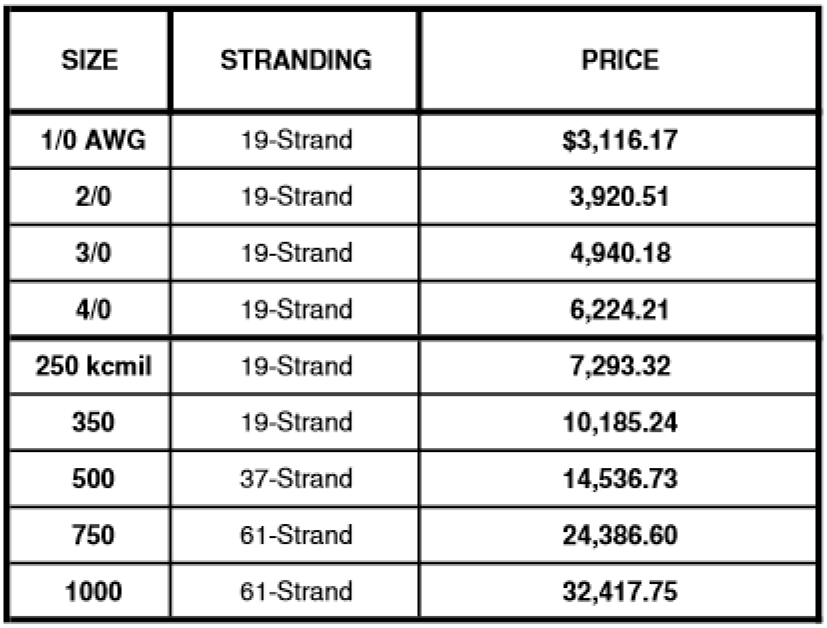
Yc = Increment of AC/DC resistance ratio due to AC current skin and proximity effect
Ys = Increment of AC/DC resistace ratio due to losses of circulation and eddy current effect in shield, sheath and armor

APPENDIX F: Uniform Temperature Analysis Results

No.	Cable ID	Energized Conductor Per Cable	Rdc @ Final Temp (µOhm/ft)	Dielectric Losses Watt/ft	Yc	Ys	Conductor Lsses Watt/ft	Current Amp	Temp °C
1	3-A	1	80.46	0.007	0.003	0.001	3.826	217.52	90.03
2	3-B	1	80.46	0.007	0.003	0.001	3.826	217.52	90.03
3	3-C	1	80.46	0.007	0.003	0.001	3.826	217.52	90.03
4	4-A	1	80.46	0.007	0.003	0.001	3.826	217.52	90.03
5	4-B	1	80.46	0.007	0.003	0.001	3.826	217.52	90.03
6	4-C	1	80.46	0.007	0.003	0.001	3.826	217.52	90.03
7	5-A	1	80.46	0.007	0.003	0.001	3.826	217.51	90.03
8	5-B	1	80.46	0.007	0.003	0.001	3.826	217.51	90.03
9	5-C	1	80.46	0.007	0.003	0.001	3.826	217.51	90.03

Yc = Increment of AC/DC resistance ratio due to AC current skin and proximity effect
Ys = Increment of AC/DC resistace ratio due to losses of circulation and eddy current effect in shield, sheath and armor

APPENDIX G: SouthWire Pricing Sheet for Copper Wire Sizes



SIZE	STRANDING	PRICE
1/0 AWG	19-Strand	**$3,116.17**
2/0	19-Strand	**3,920.51**
3/0	19-Strand	**4,940.18**
4/0	19-Strand	**6,224.21**
250 kcmil	19-Strand	**7,293.32**
350	19-Strand	**10,185.24**
500	37-Strand	**14,536.73**
750	61-Strand	**24,386.60**
1000	61-Strand	**32,417.75**

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