Underground Cable Ampasity

Michael Beanland

Biography

Well thank you, everybody, for showing up and being here. I have several presentations, we're going to walk through several different aspects of the thermal aspects of underground cables and this'll be the first presentation. Michael Beanland, I've been an electrical engineer for 30 some odd years and am licensed in New Mexico now, I actually started work in the electric utility industry while I was in college doing summer work. In fact, some of my first work was with the Pacific Gas & Electric Department of Engineering Research in San Ramon when we are actually doing all kinds of interesting esoteric studies back in the 1970's. I'm based out of Vancouver, Washington and Tri-Axis Engineering is predominately a company providing services to electric utilities. We also do a lot of work for developers on everything from data centers, photo able take projects, wind projects, gas-fired generation and a lot of different things. My forte in the company as business studies is the analytic side. We also have a group that does design overhead underground transmission line designs all over the United States and then we have a group that does substation design, and in fact I'm involved in all those. I was just up in Port Angeles across the sound here getting ready to do a substation redesign last week. one of the many different projects I work on.

In fact, one of the nice things is I've lucked out being able to do a lot of things. I do everything from commercial building design, underground cable thermal analysis, airport lighting design, substation design, transmission design, interconnection studies and protective relay. I'm basically a controls guy with a lot of analysis capability. My graduate degree's is controls and in fact, I think it's humorous, as I like Jim's comment about nuclear issues. My professors in college tried to encourage us all to get into nuclear engineering and all of us in the graduate program looked at him and went, "No," and we all went different directions; like controls or microelectronics because we kind of read the writing on the wall where trying to get a job in that industry was ahead.

Neher-McGrath

My focus is starting off really giving some background about the history behind the way underground cables and ampasity calculation have been done and I thought I would bring a little show-and-tell. This is a nice brand-new piece of 35 KV underground electrical cable, this is a piece of almost new 35 KV underground cable that overheated. The comment that Gaylon was making about some of the wind projects buried in the soil, this is an exact example of that and a combination of having very poor thermal properties of luss soils, which are a windblown particulate matter, very poor thermal conductor, with the added negative side of the fact that it was all excavated soil, stacked by the side, wonderful chance to dry out, dumped back in the ground as backfill, not very well compacted because it was on the side of a very steep hill so they just basically threw it in. Then they added to that is in an area where the rainfall in Eastern Washington is maybe 10 inches a year. They actually have to wait two years to be able to get enough moisture in the soil to grow a crop, so it's in action every other year crop and then we also than had an extraordinary wind event surely after all of this came together where we had nonstop full tilt wind production for about a week and of all strange things we actually had a cable failure and it was for a totally unrelated reason but as they were troubleshooting that cable failure, they excavated and exposed some of the underground cable that we have installed and then we looked at it and said, "Uh, something isn't right." We went back and started debugging what happened and that was actually my introduction into cable thermodynamics. The interesting part is the cable is rated for 140°C. the jacket melts at 105°C, the cable is nominally rated for 90°C so you normally design the cable to run at 90°C, it can handle 140°C, but the jacket will melt at 105°C, it's a low-density polyethylene jacket. So that's where all of my involvement got started.

Traditionally, when somebody talks about doing underground cable ampasity calculations we go back to this seminal work from 1957 of Neher-McGrath. And Neher-McGrath presented a very detailed analytical paper to the IEEE that basically looked at and in fact, are we distributing CDs with all of the attachments? OK, so that should be in your handout. So if you really are interested in going back and looking at some of the calculations and the theory, it's very beautifully done it was a seminal work at that time. This is the standard by which all of the national letter code tables are prepared, all of the ICEA cable ampasity calculations are performed, this is the way everything has been done.

Cable to Duct Thermal Resistance

Now the one thing is until you read the fine print in this paper you don't realize that a lot of this is based upon other work. In fact, I even have another paper that's also from the early 50's on this subject, where basically people were trying to understand and they were doing empirical studies. Before Neher and McGrath actually went through the analysis, there were basically studies trying to get an empirical feel for what the heat transfer was like, and as a result of this they looked at things and they looked at the different kinds of heat transfers that you deal with between the cable and a conduit and were trying to come up with some generic understanding of what was going on. One thing you have to keep in mind though, is these studies were performed in the early 1950's. The kinds of electrical cable that were done are different. The types of conduits that were done were different. The cable fills were different and there were a lot of factors here so they were basically looking at cable in metallic conduit. Well we don't usually put rigid galvanized steel conduit in the ground much anymore because of the expense. They were doing fiber duct. Fiber duct used to be very common but it was in air, well I'm sorry that doesn't apply. Fiber duct and concrete, that was an old predecessor to PVC. Transite, that's asbestos concrete pipe, it's not even legally allowed to be used anymore. Very, very common though and in older cities you'll still find a lot of transite. In fact, transite was used for water pipe and flew pipe because it was wonderful ingredient, very strong and very convenient to use. Transite duct in concrete and then also they were looking at some of the studies, looked at gas filled pressurized gas insulated piping. A lot of types of things that we don't see today. The solid dielectric cables that we have today were not in use, PVC pipe was not included in any of the analysis.

Equations

As a result of that, is some general recommendations were made, and these are some tables actually extracted from the Neher-McGrath paper, with some various constants for looking at the heat transfer between a cable and duct. If you think about it is, if you have a complicated system is you've got a cable, a duct, and you've got something around, the modeling for the solid material around is relatively straightforward but the modeling between the cable and the duct is very complicated because you're dealing with convection, conduction and radiation. None of which lend themselves very easily to analysis. So in the empirical studies, they came up with some interesting equations to kind of simplify what they did and to come up with recommendations for heat transfer.

Table VIII – Constants

Now the only thing you got to watch out for is if you go back and look at the early papers that Neher-McGrath was based on, it's all very approximate and in fact, the papers are very interesting because they will say things like, "Well we made an assumption, we made an approximation, we decided empirically to do this." So basically they did the best they could with the data that was available to try to get a handle on it. The one thing I noticed is if you look at the A constants in this, its 0.07, and for anybody that knows anything about significant digits that means it could be anything from 0.065 to 0.0749 or whatever. So there's a significant error involved in all of the various constants that were done and I don't believe I have them in my presentation, but if you look at some of the graphics that were used for generating some of these numbers you'll find that their data points were very scattered that the equations and the values they came up with, were just the best they could do given the empirical data that was very hard to analyze and work with. The one thing that is very interesting in all of this is that when you work through these equations the heat transfer between the cable and the ductwork is not a function of the diameter of the duct. This has a lot to do with the fact that most of the heat transfer between a cable and the ductwork is radiation and in that case you basically just have a body inside a body around it, in which case the diameter of the ductwork really doesn't matter. The other thing that is very important is if you look at the earlier studies, is that in many of these cases they might've been dealing with a 4 inch duct with a 3 or 3 $1/2$ inch diameter cable inside and that's the kind of cable fill we're talking about that is never used today, we have much more restricted cable fill practices for a lot of good reasons.

IEC 60287-1-1

So a lot of the modeling that was done was based upon the practices at the time which are really not representative of what we do today and were approximate. So when you get into looking at the classic calculations in Neher-McGrath and you look at the tables, you have to remember to always take them with a grain of salt because they're based on some calculations that are approximate and are based on a lot of assumptions, which may or may not be valid in your particular case, and that was the kind of thing that we found, when in those particular cables is the IEC cables that were used for calculating ampasity assume a row of 90 which is actually degrees C centimeters per watt. And in reality we don't find soil of that low of a thermal resistivity unless it's in an almost saturated condition. So you may find that in the case where you're dealing with a lot of moisture in the soil. In the kind of installations we were dealing with the soil was very dry, otherwise, I'm sorry, the cable ampasity calculations don't cut it at all.

That cable was installed with the owner's requests using those tables and then we found out that things didn't work so well. In addition since Neher-McGrath the IEC calculations have come along and they are fundamentally the same, they are basically an analytic model that tries to go through the expression for developing an equivalent thermal resistance between the conductor and the ambient through a process, and it also has a lot of estimations and approximations that are applied because one of the things engineers like is we don't want to have to do a scientific research paper in order to have an answer. We need the most economically answer quickly so we use approximations and analytic tools and graphs and charts.

(Audience comments) I'll talk about that more because in reality there is no net heat transferred down. All heat from underground cables has to dissipate through the surface. It may go underneath but eventually it does level out and it's still going to dissipate up through the surface eventually.

And in the IEC also, not only are you looking at the losses that are created in the underground cable or by the resistance of the cable, there are some small amount of dielectric losses which is just heating through the installation itself, more significant that that usually, is that any current that might flow on the neutral conductors or the sheath on the grounded conductor, that was actually the fatal killer for us on these cables. I actually did field measurements and we had 600 amps of current flow on the center conductors and 200 amps of current flow on the concentric neutral. It's $1/3$ concentric, so we actually had as much heat dissipation from the current in the concentric neutral, as we did from the phase in the current conductor. (Audience Comments.)

Available Software

OK, anybody doing cable ampasity? This is what we found; is that if you go to a manufacturer it is, there a lot of computer software companies that have basically taken Neher-McGrath and computerized it. I mean you can basically slap this in an Excel spreadsheet, if you wanted to. There are companies who do this. They have various fancy graphical interfaces and what have you to be able to look at all of the different cable configurations and other things of that nature. This was just a sample, you can go out and look there's a couple of software listing services that basically you can say, "Engineering Software, Cable Ampasity," and then it will give you a list of 40 or 50 different software packages that can do this. When I got involved in this, when we had this issue, I started researching cable ampasity software we were looking at all of these and most of the software packages were up in the 10,000+ dollar range. We actually had the cable manufacturer running some calculations for us because of the cost of the software. And of all things engineering economics, the reason I got involved in this and into a lot more detail and ended up doing finite element modeling, was simply the cost of the software, is buying some packaged software that I had to kind of assume on faith and this was the industry standard we could have gone that way and just come up with numbers, but I said, "Well wait a minute, there has got to be a different way to do this," and researched and came up with what I ended up doing.

Conductor Loss Calculations

We talked about this just basically, the heat loss in the conductor, things that have to be taken into consideration is conductor resistivity increases with temperature. So there is, in essence, a bit of a thermal runaway issue with that because as the cable gets hotter and hotter if you have a constant amount of current flowing through it more heat is dissipated because the resistance of the conductor increases so that effect has to be taken into consideration. The induced currents on the sheath in neutral and this is your question, this is what really happens...(Audience comments) I don't know if I have a chart that shows losses but there are some standardized equations and if I don't actually have them in the slideshow, actually they are just a couple pages down and I'll show those equations.

Whenever you have multiple conductors, so if here's my three-phase conductors and many of the standard historic practice, actually, in the ICE tables, have these spaced 9 inches. And they say, "Okay, here we go. Here's your cable to cable ampasity, cables are spaced 9 inches apart, and flat configuration X number of inches down below the grate, here's the thermal rating of the ampasity of those cables." The one thing they don't do a good job of reminding us of, is that which is kind of like in the small print, is that if you have a concentric neutral or sheath around that, that is electrically conductive, that the current flowing in this conductor and this conductor and this conductor, will induce a voltage on that conductor and if a circuit is made to allow current to flow, current will flow in that conductor. Current flowing in a conductor generates heat. So if you have a path, if you look at those samples and, in fact, there's a little piece out on each of those tables. If you look at the concentric neutral around that is, the presence of the conductors around that other conductor, they produce a magnetic field, the coupling on the magnetic field on each of those wires ends up inducing a voltage and if you give that voltage path for current flow you will get current flow. So it is actually not unbalanced, it is the fact that you have induced current on those concentric neutrals, if you give them a circuit to flow on. I will be going into that actually quite a bit more detail. Another part of that is dielectric losses and that is actually just the fact that you have an insulating material with an electric field on both sides of it and the changing of that electric fields involves some losses in that material. Those losses are normally extremely low and for most electrical engineering purposes we neglect those because the losses in the central conductor are so huge relative to that. You know the dielectric losses or infractions of percent so we normally don't pay too much attention to it.

Conductor Loss

Issues again about conductor loss; things that all have an impact, that have to be worked through. There's lots of good data about the conductivity of electrical conductors, but the fact of the matter is that when you have current flowing in a conductor you get a magnetic field. AC conductors in particular, that magnetic field then has an affect on where the current flows, where the electrons choose to flow in that conductor. And we have what's called "The Skin Effect," which means basically that the electrons prefer to flow on the outside of the conductor. That when a conductor gets very large the current density in the center of that conductor gets very low and that's "The Skin Effect." "The Skin Effect" because you have a varying current density across the size of your electrical conductor creates the AC resistance to actually be different from the DC resistance because of the changes in current density. Here, Jim, you were asking about the equations for thermal characteristics of different materials and the change in resistance is those are actually the two factors. For aluminum standard electrical aluminum 0.00395 per degree C and that's on a unit basis. Copper is there right below and then the actual equations that are typically used to calculating the resistance based upon a change in temperature are the two equations given down at the bottom.

(Audience comments) Well, overall the losses in a collection system in a large wind project conductor losses are probably 1%. It's not unusual in a very large project to have the whole transformation losses, so that basically includes an initial step up transformer, the underground high-voltage collection system, and the final step up transformer to the grid to be about 1% each. So it's not unusual to have about 1% losses in step up transformers at the individual units, another 1% in your collection system, and a final 1% of losses in your final step up to the transmission grid. Rule of thumb, and that's all.

One of the things that we do whenever we're designing such a thing is we do an economic conductor analysis and we look at the value of those losses. So if the value of the losses is very low, where you're willing to sacrifice, you're going to put less material in the ground because it's cheaper and as a result you're going to have increased losses but as long as economically that's acceptable to you, then that's fine. On the other hand, if you're dealing with the value of that power being very high then you want to reduce your losses so again you are going to look at the lifecycle economics. So that's actually where you get out of the engineering and into the economics side of the whole project.

Skin Effect

Here's an example of "Skin Effect." I did not create that, there is a note on there, but it basically shows that the current density varies in a large conductor and this happens that the skin is 6 inches, so this conductor is on the order of maybe 12 inches in diameter, and it's just to give you an example, it's not a realistic conductor, but it shows that there is a decrease in current density as you get towards the center of the conductor. And that's what's responsible for the increased AC resistance of a conductor and as a frequency goes up is the electrons prefer to flow on the outside, more and more of that conductor. To the point where when you get up in microwave frequencies, it is not unusual to use hollow conductors, which are called waveguides. And in fact, at those very high frequencies often what you will have is a tube with plated silver along the inside of that tube and the fact is that all of that energy that is flowing at those microwave frequencies is flowing on that silver plating. Because of the fact that at those kind of gigahertz frequencies the skin depth is so thin that there's no reason to have a solid block of anything in there because the electrons don't care, they don't use it. So, at 60 Hz it has a very small effect but at higher frequencies this has a greater effect. One of the things I have learned is this is a complicated issue when you deal with harmonics because in essence if you have a harmonic rich current it is that harmonic current that is going to have it's thinner skin depth and is going to tend to flow on the outside of the conductor. So, in essence the effective resistance of that conductor goes up for harmonic currents. There actually are some adjustments I've seen in some modeling software that tries to take that into consideration. Normally in a power system the harmonic content of the current is below 5% and we just let it go, we don't pay too much attention to it. On the other hand, if you were doing this work in a facility like a steel mill where you are dealing with an arc furnace and the arc furnace has a very high frequency component. Then the resistance of the conductors is going to be strongly affected by the frequency characteristics of the current that you're flowing.

So you may look at something and say "Oh, I'll put in 1000 kcmil of conductor because I know I have 1000 amps of current to flow and all of a sudden you're melting that conductor because of the fact that at the higher harmonics the electrons are all flowing on the outside of that conductor, increasing the heating. Heating is I^2R and it's I^2 by density so you can end up with a lot higher heating because the current is flowing on the outside.

Proximity Effect

Proximity effect also has an influence in current density and as a result the effective AC resistance. This is actually a little quick modeling idea just to provide a graphic image. Three conductors each carrying the same amount of current 120° C like in a standard three-phase system, however the magnetic fields of each conductor affects the other conductor and as a result the current density has a gradient across the conductor. In many cases that's not a big issue but it's something that at least has to be considered.

Induced Currents

This is where we get into the discussion of induced currents. That's the current that flows on the concentric neutral in the cable. These are just some classic equations for calculating what the induced voltage will be, and actually this is the mutual coupling x of m which then has to do with the amount of voltage that is induced on a conductor as a function of the current and the mutual coupling to that, the x of m and so when you calculate basically the mutual coupling to the concentric neutral and then you look at the current flowing in the adjacent conductors and you go through the calculation process to determine the voltage rise on that concentric neutral.

Induced Voltage & Current

Here's also just an example of the same issue, this is out of an IEEE standard, and it shows the various calculations used for looking at the proximity, the induced currents depending on the geometric configuration of the cables. And it's really just looking at the geometry is if you have three cables equilaterally well they all kind of influence each other equally because all the cables are equidistant. Whereas, often what we find in electrical circuits is we'll find cases where because you're putting them in conduits is the cables are arranged physically differently. And the one thing to note on this is that the driving force is always the induced voltage on the shield and that is in volts per mile, volts per thousand feet, volts per foot; is anytime you have a conductor exposure varying magnetic field there will be an induced voltage, sorry that is electrical engineering basis of it. Whether or not there's any current flow on that depends on whether you provide a path. If you short those conductors out so that you created a circuit, yes, you will have current flow and then you get into the shield loss which has to do with the resistivity of the material and the amount of voltage present, the resulting current flow I^2R, watts per foot, watts per 1000 feet.

The thing is in American standard practices, this is part of the very interesting things we learned in the 35 KV wind collection system world, when you build an underground distribution system for supplying power to loads, because you're dealing with safety is the concentric neutrals are all bonded together and grounded everywhere. So you have all of these paths where all of the grounded conductors, the concentric neutrals, are all hooked together. Every time these go into a vault the grounded concentric neutrals are bonded together and a ground rod is driven. Every time there's a transformer the concentric neutrals are bonded together and a ground rod is driven. So you are providing that path for the circulating current. In transmission cables above 115 kV there's a different practice and you actually open shield your cables, you do not provide that path. Well, the problem is 35 KV cable looks like underground distribution cable and if you install it like underground distribution cable you'll get current flowing on the concentric neutral.

Induced Currents

These are the fundamental equations on how it's done. Here is the example, the sample I passed out. This was my rude awakening into the subject. This was what we had: 35 kV 1000kcmil cable, should have been rated for 600 amps, if I looked at a standard ampasity book, not a problem. However, we had 200 amps of current flowing on the concentric neutral, I actually went into the substation while this cable was in service, the concentric neutral was grounded everywhere so it wasn't going to be an issue. Grabbed my little Fluke Clamp Amp Meter and went to the pigtail where the copper wires came together, put my clamp on it and went, "Oh my gosh, what is this?" Our first assumption was where is this unbalance coming from? Why do we have all this unbalance? And it wasn't until we actually got into the calculations for the induced current that we really realized it had nothing to do with unbalanced ground fault current or anything like that, it was induced current, and that's what happened.

Actually, I was thinking as Gaylon was making his presentation. My first involvement in a lot of thermal issues was when I was in Palo Alto, California as a major electrical engineering manager. We had a 60 kV underground cable and we had to expose that cable and we were worried about the temperature capacity of it and we found out that it was buried in a really funky material called "limestone quarter to dust," which was a very interesting term that a lot of people haven't heard of but it is actually a standard specification for thermal backfill.

And the other thing that I recommend for anybody who's interested in the subject of thermal runaway, in particular, is in 1998 in Auckland, New Zealand there was a major catastrophe on the electrical system. Their underground cables had been in service 4 years, they were all, if I remember right, they were basically oil filled metal pipes with three-phase conductors inside. Everything worked wonderfully for years, Auckland had continued to grow, load when up. They had an extraordinarily dry year. What happened was the clay type soils around the underground cables dried out, and as the cables kept producing more and more heat, they dried out more and more of the cable. Until the cables were operating hotter and hotter and one of the things that happened was, it wasn't a thermal failure but as cables get hot they expand. Metals expand when they get warm. The cables basically, the copper cables inside the steel pipe pushed their way out of the pipe and ruptured the pipe and destroyed themselves. And It happened sequentially. They had a single cable fail well they went, " Oh okay, incidental, just happens. We'll just move all the load under the other underground cables." And another cable failed and all the cables were underground, they had a sequence of failures to the point where all of their underground cables failed because they kept, because nobody understood the whole issue of thermal runaway and the thermal issues involved in the underground cable design. They ended up fixing the whole issue by building overhead power lines down a railroad corridor because the entire central business district of Auckland, New Zealand was without power, for weeks. Basically, it was an economic catastrophe. There were heads that rolled massive changes in the political and economic structure for the utilities at that company. So I commend you, if you do a little searching out there there's really some excellent papers on the subject. So if you're interested in and knowing a little bit more about what can happen with the thermal aspects of underground cable I would highly commend doing a little bit of research on that.

Induced Currents - Finite Element Image of Magnetic Fields

Okay we were just talking about the induced current on concentric neutrals, this is an example of a model simply of the magnetic fields inside electrical cables and you would think and we all do is if you have three electrical conductors and each is carrying current 120°F out of phase so we know that the current cancels and so you say, "Well, the magnetic field cancels." Great, well that is true, if you're out far enough away from the three conductors that it looks like just one big conductor with no current flowing. Okay, because the magnetic fields cancel. But you have to be far enough away. When the conductors are in close proximity to each other you do not get magnetic field cancellation and the result is that if you have a shield around the, that's the conductor, that's concentric neutral, you are going to have a magnetic field on different conductors in that concentric neutral and therefore, you will get a voltage rise induced on those conductors. And if you give it a path you will have a place for current flow.

Mutual Coupling Analysis

My personal cheapness with buying software what was led me into finite element modeling and it has proven extremely valuable. I guess it's because my bent is being kind of an analytical guy, I wanted to be able to really get a better physical understanding. I hate plugging numbers into a software package and having it spit a number out and I don't understand that number is. I can say, okay, there's the number 642, great, I have no idea what that means but that's the number and we'll go from there. The beauty of finite element modeling is that it gives you a much better understanding of the processes involved and it helps with your understanding of what you're doing.

The particular software that I chose to use is a product called QuickField, there's a lot of different finite element modeling software available. I looked at several of them and there were some interesting ones that weren't supported or required in AutoCAD interface or other things of that nature. QuickField is a very simple package, it allows you to build rudimentary geometric objects, circles, boxes, lines, and assemble those into a model. And then the physics of that model, looking at the conductivity and the magnetic fields, are all embedded in the software. So by providing it the data and you build the physical model you can actually do some quite sophisticated modeling. When you build a physical model not only do you have to build a model of the conductors but obviously the conductor just doesn't sit there, it's got current flow, it's got conductivity between conductors and then those are parts of what you have to do to be able to look at some of this.

FEA Induced Currents

Here is an example of a very simple finite element model and this is the kind of thing that works very nicely; in this case I was looking at the magnetic fields between the conductors. I had three conductors in an approximant trefoil, as we call it, and the way we often installed conductors is if you think of them inside a conduit they're squeezed inside, I'm looking only at the magnetic elements of that or the current carrying elements. I, also, because I was curious I threw a ground conductor over here because a lot of times when we do underground electrical systems we throw a ground wire in the trench and it may be off to one side, maybe underneath, it may be someplace in there. The other part about this is that, obviously, the model is in the real world and the real world is huge and I'm not going to be able to model everything so I have to put a boundary around my project and I have to constrain my project in some way and define that. In this case, because all of the material in the soil is considered nonmagnetic and what I'm looking at is magnetic properties, I just basically build a model around it to constrain it so I can look at the magnetic field around the cables but I don't really care too much about what happens beyond that because the magnetic field might go out there but that's fine, so I constrain my model by building a boundary.

FEA Induced Currents - Electric Circuit

The other thing you have to do is provide the electrical conductivity for the model and this is an example of the electrical conductivity model that I built where I looked at the soil electrical conductivity, my concentric neutral electrical conductance, the ground wire that I put in and then the phase conductors and then I actually drove the phase conductors with current. So by defining all of those currents the software will allow me to put currents on specific conductors and allow currents to flow on other conductors and what I found worked out very nicely is where you have a system that has grounds in to the earth you may want to consider some kind of possible remote infinite earth return path. I got in the habit of throwing that in there, the reality of it is essentially because it's a higher resistance no current flows through it, but it actually helps stabilize the model and there's even a place for electrical conductivity in the soil, but if I don't put in electrical conductivity in it, it doesn't happen.

(Audience comments) There was no conductivity at all in the soil, and the reason we do that is the particular design cases that I was working with were, in essence, dry soil and when I'm only looking at the soil immediately around the conductor's and I think there is actually a value in there for the resistivity of conductivity is so low relative to the aluminum and the copper conductors and has negligible impact. (Audience comments) In these cases the current flow is really balanced and constrained to the conductors of the concentric neutral in the ground. It's not an issue, however, if you're doing fault current studies where you basically are allowing the current to flow into earth then you do have to look at that and I have done some of those. The challenge gets to be, it's actually very interesting to look at the soil resistivity but between two points in the current path. You can do that with finite element modeling. so you actually do use typically it's 100 Ohm cm I believe is the standard solar ground resistivity that we used.

FEA Induced Currents - Resulting Current Density

Here's the example: so that physical model coupled with that electrical model gives us this resulting information. And you notice this says "Current Density," and you look at these and go, "Well, gosh the current density's relatively moderate." The part that you can't see very well is the fact that there is this little thin ring here is the equivalent concentric neutral, that if you took the round conductors and flatten them out into a cylinder of equal area so that you would, in essence, have a good handle on what you've got. This is what you end with; this is what happens, is you actually end up with incredibly high current density flowing in your concentric neutral.

FEA Induced Currents - 13% of phase currents

This was a particular model that I was using in this case with 400 amps on the phase currents, the induced currents ended up being 13% in a triangle. I was told I only have five more minutes so I'll try and hurry this up. I think I am getting pretty close to the end here.

FEA Induced Currents - Flat Cables

Now, that was triangular. Here are some cables flat that were installed like they were at the Stateline Wind Project and, again, using this kind of 9 inches on center. What happens in this case is the magnetic fields don't cancel as well and as a result the modeling indicated that the concentric neutral currents would be about 35% of the phase current and my field measurements came out to be 33%. So it gave me a very warm and fuzzy feeling that the modeling was an accurate tool for modeling a real world situation because I knew I had 600 amps flowing on the conductors and measured 200 amps on the neutral and the modeling said I should have had about the same amount. It's kind of like when you use software and build a model and it gives you results that you can validate; you can sit there and say "Okay, I believe these numbers now", and then when you go on to do something new that you don't have real-world tests from, you can now have a lot higher degree of confidence.

FEA Benefits

Why do you use finite element modeling? It's because of the fact that you can have as many conductors and as complicated electrical system as you want; they can be in any physical configuration, not just the standard IEEE's, they can be spaced any way you want, you can have them in 3,6,9,12. You can have them in different spacing's in any arrangement. You can play with the phase arrangement not just ABC, but you can put ABB, ACC. You can throw them in ground wires, which is something that the standard calculations don't give you. What kind of induced current might I have on that ground conductor, depending on where it is installed and also you can look at the effects of any magnetic materials if you happen to have conduits or pipelines.

Nine Conductors with Grounds

Here's an example of a finite element model with ground conductors located tight in the bundle. Again, there's the electrical model. It's the same thing just three times as many. It's relatively simple and straightforward to do some very complicated modeling.

Control of Induced current

We were talking about induce currents. I still have a lot to go here. Will it cause you grief if I go a little over? When you have a current flowing on the concentric neutrals or shield, as I said, as there's induced voltage and if you give it a path you run into a problem because you have current flow. There is a technique, which is called open shields cross bonding and trefoil. Each one of those does it a little different. When you open a shield you basically do not connect your conductors together is if I have three phase conductors and I have concentric neutrals. So pretend these are the cylinders in concentric neutrals, and if I ground these three on one end and leave the others just sitting there, I have no path for current flow. So I will not suffer the heartbreak of the heat induced by the current flowing on the concentric neutral which is what open shield does. The problem with that is at the point where the shield is open you can get elevated voltages and depending on what that is and especially during fault events where currents are very high because the voltage is proportional to the current, you have to take special steps which you get into what are called shield voltage limiters which are basically surge arresters.

Another technique that is used. If I break my cable up into segments and then actually connect my concentric neutrals and in a crossover fashion at various points, it's called cross bonding and I will be talking about that in a little more detail, I can basically cancel the voltage on my shield because I can take one third of the length and then one third of the length and one third of the length and I can connect those on A phase, B Phase, C Phase, connect the shields or the neutrals together on those. Now all of a sudden what I have is the induced voltage on one, the other one is 120° out of phase, the final one is 120° out of phase, the net result between end to end is negligible. So you can actually then reduce the amount of current flow. However, both open shield and cross bonding takes work, extra equipment, and special design. What we found is usually most economic is if you just put the conductors in a tight trefoil, the amount of induced current is low enough that you can live with it and you're concentric neutral doesn't pose a problem.

Review

So quick review. We talked about the history of Neher-McGrath history. I do commend you go back and look at the old papers, it's very instructive if you're interested in understanding why we use the numbers we use and where those numbers came from. Take a look at the IEC method, this is actually in the documents I provided. It's interesting to look at but it's fundamentally the same practice, It looks at a net thermal characteristic. There are a variety of software implementations of Neher-McGrath and IEC available, if you want those, go for it. However, in my opinion there's a better way. Something that gives you a lot more flexibility and that's finite element modeling. It's very straightforward, it gives you a much better understanding, it's also one of the things we'll talk about later, it's excellent for mitigation when you're dealing with, how do you fix a problem that you know you're going to have. When you have very poor thermal soils what are you going to do about it? Okay, well finite element modeling is very good for really understanding how to go about doing that.

We talked about the heat loss, what the sources of heat loss are. AC resistance versus DC, induced currents, and then the induced currents and then what you can do with the induced currents, if you want to. That summarizes my first presentation. At this point we are headed to a coffee break.

Questions and Comments

Question 1- Gaylon Campbell: "Why did they use the flat versus the trefoil configuration when they installed those originally, is there some reason for doing what they did?"

Yes. This is straight out of the IEEE and if you go to ICEA cable ampasity calculation, they provide you with the cable ampasity for that flat arrangement and there's a standard spacing on all of these cables. So what the owners said is, "Oh, well what's an easy way to put these cables in the ground. I'm going to dig a trench and stick the cables in according to that configuration or roughly 9 inches apart; I know what the ampasity is going to be, it's very simple to install and build and that's what we're going to do." And it was based upon the fact that nobody had looked at the modeling, nobody had looked at the thermal characteristics of the soil. The thought of actually testing the thermal resistivity of the ground had never occurred to anybody, prior to this time. You went to the standard tables and they were based upon a row of 90, okay. Does anybody know where that number came from, no. Does anybody know if that number applies, no. Are we going to use that number because that's what the standard has been for hundred of years, yes! And that's where it came from.

Question 2 - "What kind of education is there for not using these standard values?"

It's a training process. The education is the fact that when you have a multimillion-dollar cable replacement program on a brand-new project, the developers of those projects become aware. This project was a Florida Power & Light Project. We put in cross bonding and replaced a lot of cable. Every project since then has evolved because the owners of the project realized how important that was. We, as engineers, have consulted on a lot of other projects. We've brought that up to the attention of the developers that you have to look at the thermal resistivity of the soil as part of the design. It has now become standard practice, we finally got general contractors, it's part of engineering design that people understand one of the things they have to do is do thermal resistivity tests for my project, I have to do that. Before that nobody thought about it.

(Audience comments) My cynical part of me says that, traditionally, the utility engineer was the one who worried about the design and utility engineers are historically very conservative and overbuilt everything and so as result, a problem never occurred. It really wasn't until we got to be building basically EPC jobs where every penny mattered, that you put the smallest wire in the ground the cheapest way you could because you were trying to get the maximum profit out of the job. A utility has a whole different economic model and they'll say, "Well I need to build this for 20 years so I need to look at the load forecast for 20 years and if I assume a 5% load growth or 2% or whatever it is, I'm going to need this huge cable." What happens is it's a nonissue. But now we're building everything tighter and tighter and in this case the engineering wasn't done to prevent it from coming around and biting us. It was basically underbuilt. We put less and less materials in the ground and in products today in order to take advantage and we try to take advantage of the structural characteristics of those materials or the thermal characteristics of the conductive characteristics, in order to reduce the cost. I remember years ago Hewlett-Packard, when they were building plastic boxes for PC's, their tool test equipment, they were injection molded and basically the cost of that box was dollars per pound. So somebody said, "What if we foam the plastic before we inject it, will it be okay? What will happen?" Well, they found out that they could foam the plastic and inject it in the mold. The outside of the plastic was solid and hard, the core of the plastic was hollow with bubbles. They reduced the material count of the required to make the exact same product. If anyone ever deals with plumbing. ABS pipes. Used to be ABS was pure plastic, okay. You go to the store now and buy ABS pipe and it's foamed. Look at a cross section of it and the inside is all foamed. Same structural characteristics, same hydrolic characteristics, less material. And this is exactly the same thing we're dealing with here, is we wanted to put as little material in it as we can because you want to make the maximum profit you can and that's what happened here.

(Audience comments) Not if the conductors were laid in seperated. The general practice of today is you put the cables in a tight trefoil and you usually put tape shield in because it saves money and you throw copper weld for your ground wire because it's a lot cheaper than solid copper wire, and so your tape shield now is reduced in size, it has reduced capabilities, it has higher resistance so there's going to be less current flowing on it. You do bond it so you accept that, but also the fact is there's relatively little current flow on it because the conductors are in a tight configuration. (Audience comments). To the concentric neutral or to the ground? We did some ground rod testing and I don't remember what the numbers were. When you're talking about 1000 kcmil aluminum conductor and a 25 Ohm ground rod, there is very little current flow through the ground rod anyway.

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