SUCKER-ROD PUMPING UNIT LIGHTNING PROTECTION

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I am not going to announce a new break through to end all POC failures. If you want to hear God laugh, tell him about your new 10-year plan or solution to end all lightning damage.

My goal today is to show some incremental steps we have taken to reduce costs and improve reliability. This is a preliminary report. This is not mature technology tested with a large number of devices through many storm seasons. Some background is needed for perspective.

Anthony J. Welker of Santa Fe Energy Resources covered many operational issues in his excellent 1998 SWP Short Course presentation. His paper will serve as the context or "big picture" for what I have to say about Pump-Off Controllers (POCs) and next generation product Rod Pump Controllers (RPCs) dealing with high-energy surges.

There have been some improvements in our ability to model high energy events. University of Missouri-Rolla has many programs listed in the back of this book that are available on the Internet. M. Ishii and his colleague Y. Baba more recently wrote "Advanced Computational Methods in Lightning Performance." This paper is an example of how the "Numerical Electromagnetics Code (NEC-2)" is progressing, and being applied. This important work allows people to model things like why a lightning strike hitting the CN Tower in Toronto appears to change along its path. At four microseconds the downward current wave is joined by a reflective wave from the ground. The resulting distortion in current deviated significantly from calculated results. (See full citation and figures at end of paper).

M. Ishii & Y Baba were able to model the phenomenon using thin wire, thick transmission wires, and actual measurements to see how well theory aligned with the real world. Those interested can find citations for their work and others at the end of my humble effort. One point in bringing this article to your attention is to say thank goodness we are not trying to run POCs on top of the CN Tower. They can count on getting lightning strokes on regular basis.

The current version of NEC4 is not available on the net. It's obtained from Lawrence Livermore National Labs and was funded by **US** Department of Defense. To get it you have to sign a license form and send in a fee. NEC4 is also under export control. Of particular interest to this group, NEC4 extends the NEC2 capabilities. NEC4 includes the capabilities of NEC2 and also can model wires that are buried or penetrate into the ground. NEC4 also includes a revised modeling algorithm that is stable for electrically small models and has a more accurate treatment for wire junctions and stepped-radius wires as well as a number of other new features.

Last August after a very dry summer, one of our Permian Basin clients experienced an unusually violent storm, after a very dry summer. Production was lost. Labor expenses added to equipment damage losses.

Severe lightning damage can sure strain a budget. This client surveyed the production area with a Global Position System (GPS) unit and contracted with a service to monitor their field. They did not have long to wait. A few weeks later another big storm hit. This time they were able to track the number of lighting strokes from cloud to ground (over 300 in a two hour period). The record of equipment damage reported as a result of the storm helped to understand some functions about their grounding and protection measures. I do not intend to go further into that story except to say I found the overlay maps of lighting, equipment, topography, and damage reported very interesting.

Building a good system for lightning protection starts with grounding appropriate for the situation. After that statement, the subject of grounding starts sounding more like a discussion of something other than science or technology. People talk about: beliefs, sacred cows, actions based on faith, unnatural acts and spectacular events. **All** these concepts have been raised in regards to grounding.

Before addressing some of our beliefs, I would like to refer back to Mr. Welker's paper for two points that he made very clearly.

P334 "Motors and control panels for pumping units are usually grounded to the wells they serve, however they are a frequently reported source of damage. This was somewhat surprising in view of the apparent rarity with which transformers were damaged. If motors are burning up because of power line surges, then either the line fuses and lighting arrestors are not doing their job, or they cannot react quickly enough. Another explanation for the apparent discrepancy may be because motors could be *caught* in the middle of a parallel grounding path lightning could seek if it strikes the pumping unit. Contrary to popular opinion, current doe **not** go to path of least resistance. It goes inversely proportional to the resistance, and if only 1% of a 100 KA strike to the horsehead went through the motor (and 99% went down the bridle), the motor would still receive about 1000 amps, or 4761% of the normal full-load current of a 15 HP motor." [2]

That helps explain why a POC connected to a sucker-rod-pump has to deal with electrical surges. It is in a ground path that is going to divert some of the energy that flows through the beam unit.

P337 **"The connection to the earth** is usually made with ground rods. Ground rods are typically 5/8" Cu of – foot lengths. The national Electric Code recommends that rods be buried at least **8** feet deep, however this does not necessarily insure good grounding in the dry, resistive soils of the Permian Basin. The ability of ground rods to dissipate energy rapidly to earth is very important, and the practical goal is to have less than 10 ohms of resistance from the ground rod into the earth. Yet this goal may be difficult or impossible to achieve in the Permian Basin due to the nature of our soils. If the current cannot dissipate easily to earth it will seek another conductor, and in doing so the current can dig a trench in the earth. In highly resistive soils, damaging currents can spread outward for an area hit for several hundred feet[3].

Throughout his paper Anthony Welker makes reference to the dry, resistive soils of the Permian Basin. The soil's inability to act as an efficient sink for lightning surges is another reason why equipment some distance from a prominent if unintentional lightning rod (pumping unit) has to deal with surges.

Automation Electronics has found following aspects important to consider before installing RPCs.

GROUNDING RECOMMENDATIONS FOR PUMP-OFF CONTROLLER

The major source for lightning induced component damage in the Load Cell input circuit on the POC is in the sacrificial components placed in the circuit to prevent damage to the circuit board traces. These components fail when a large differential voltage of sufficient energy exists between the Load Cell (Well Casing) and the POC Earth Ground (Electrical Service Ground).

To reduce the let-through voltage from one phase of surge protection to the next, and the ground differential between the Well Casing and Electrical Service Ground we make the following recommendations:

A ground rod of not less than eight feet in length must be placed at each location where surge protection devices are applied. A multiple strand #10 gauge wire with 3 separately insulated wires in single cable is suggested for use on the primary side of each three-phase step down transformer.

A 480-volt three-phase over voltage protector should be installed on each motor control panel with heavy emphasis placed on installation with a low impedance path to ground. This ground rod should also be tied to the #6 gauge protection grounds.

A single cable of multiple strand wire with 5 to 7 separately insulated wires is suggested for use in connecting the POC Star Ground stud to the POC ground rod. The wellhead should be directly connected to the POC ground rod with a low impedance conductor. **A** low cost solution is to use a multiple strand #10 gauge wire with 3 separately insulated wires in a single direct burial cable.

All ground conductors expected to dissipate lightning surge currents should be as short as possible. These conductors should be low impedance and be straight connections to the nearest ground rod. If bends are required, they should have a radius of eight inches or more, but not less than five inches.

One point I want to make here is the dual nature of lightning. It has both DC and AC characteristics that must be taken into consideration. If only resistance is considered large heavy copper conductors work just fine. But when the frequency of lightning is considered, stranded conductors work better because of the "skin effect" exhibited by all high frequency currents.

We believe that the stranded wire is important because that will allow a low impedance path for high frequency surges to discharge from the POC star ground to ground rod. Star grounds attempt to provide a dedicated ground path to the center of the star such that the currents in any path will not induce a voltage in any other path. That is easier said than done, especially at high frequencies. Please see "Proximity effect" for more information about skin effect and other citations on surface flow of current flow.

One final point from Anthony Welker's paper. He cites a calculation made by R.F. Ficchi, "Electrical Interference" to emphasize his advice to avoid making sharp bends of the down conductor. "It has been calculated that a 200 KA current passing through a right-angle bend will tend to straighten that bend with a torque of 5,500 ft.-lbs." That much torque can rip terminal board connections off a printed circuit board or tear an enclosure apart. And, it happens is a hurry!

Each sucker-Rod Pump Controller (RPC) that uses beam mounted transducers or polished rod load cells for load inputs is in an especially difficult position. On the line side of the RPC is a pump controller with NEC mandated ground. The RPC is connected through the pump panel to overhead power lines.

Load and position inputs are tied to the pumpjack. The pumping unit is not only the highest object in the area, (making it a prime target for electricity) but also has the best ground path through either the polished rod or casing. The RPC load cell circuit has to be able to measure a few microvolts to be effective. Protective devices that adversely affect load inputs cannot be used without defeating the purpose of the RPC to gather information for local control and remote data analysis.

In addition most units have a radio w/ antenna that can attract damaging surges. RPCs face surge threats from all different directions. Experience has taught the industry that radios will fail occasionally even with surge protection. We generally use N-Type bulkhead connectors for higher frequency radios. With proper grounding, impedance matched cabling, and good connections, antenna source failures are generally low.

POC failures from surges coming down high lines are also quite low. All it takes is money to avoid most failures on connections from POC to pump panel and out to service entrance.

A multi-layered or zone approach helps to limit the surge in stages. Large surges are progressively reduced over time through various layers of devices. There may be great arguments over exactly what values to use, but there is a general consensus that a zone defense works pretty well.

Dion Neri, Chief Design Engineer for MCG Electronics wrote a fine article "Surge Protection: Where and How Much?" for EC&M March 1997. For facility protection, his paper does an excellent job of sorting through a complex situation in a few pages. Pumping units do not have the luxury of living in a zone protected environment. They are exposed to more risks.

What tools do we have today that help keep pumping units working? Active components can reduce surge magnitude for even better voltage regulation. Gas tubes, and passive components such as arrestors, capacitors and spark gaps are often selected for frontline equipment protection. MOVs, transorbs, and polyswitches now widely available have better ratings than before. These rugged components have demonstrated a resilience that is inspiring. They can take a great deal of abuse and maintain their ability to suppress surges.

Twenty years ago we did not have as many durable & sophisticated methods of dealing with high-energy surges. We could put in a fuse and have to replace them. If a circuit breaker was used every once in a while the electrical disturbance was going to be so great or so fast, that the breaker would fail. Sometimes the failures were quite spectacular. If you want to see graphic movies about breaker failures, contact a fuse manufacturer.

Today's devices run the gamut from passive spark gaps to active harmonic filters with nanosecond clamping devices capable of smoothing waveforms. Not all damage from surges comes from external energy sources. It seems as though every time someone offers a new solution for an existing problem, something else breaks.

POCs are generally installed in fields that have been producing for quite a while. The electrical department is not generally involved in automation. Electrical engineers may or may not be involved. The field may have changed considerably since an electrical engineer last inspected the electrical system. Changes may result from a new salesman.

Maybe today he is selling vacuum contactors. Vacuum contactors can interrupt electrical energy very quickly. Wonderful devices they can have duty cycles ratings of over 10,000,000 operations. Ten or even 100 times the ratings of comparable air break equipment. Why?

Because electrical arcs are not sustained in a vacuum. The vacuum contactor or breaker can chop a wave at any point in the sine wave cycle. The energy interrupted does not disappear, but it will go both ways from the vacuum contacts and may show up as unwanted source of problems.

Any air break device operating on AC power will extinguish the arc when it goes through zero in 3 to 5 cycles. During those cycles before the arc is interrupted, material at the contact tips arcs off the contact face. The shorter life of air break contacts is directly related to sustaining the arc while waiting for sine wave zero crossing to break the path.

If vacuum contactors are being used for motor starters, a combination of capacitors to limit the rate of voltage rise (dv/dt) and arrestors to limit peak voltage values can be purchased. Such protection is usually deemed cost effective only for medium voltage synchronous motors or other critical and expensive machinery. At 480 volts less elaborate methods are available.

How do you know you have a problem? What are the symptoms of surge damage? When the motor stops and is inspected in the shop. If the winding insulation fails at the first turn, it can be a sign of surge damage. Phase to ground failures indicate that the voltage potential was too high for the insulation of the motor. Phase to phase failures at the first winding may indicate that the wave front was too steep.

Deregulation of the power industry means that we will all face more questions about cost effective ways to use power. Utility engineers are not going to supply those answers as part of their long-term commitment to adequate supplies of good quality power. End users are going to have to determine what power quality they want to pay for.
Capacitor banks are increasing being used to support power factor. Supplying KVAR at user facilities can be more cost effective than sending the KVARs down the powerline. But, capacitor bank switching can cause failures of equipment due to high-energy surges. If something blows up that has been around for a hundred years, ask yourself "What has changed?"

We had one case in Wyoming where one place put in 14 medium voltage VFDs in service. Their neighbor several miles and 2 transformers away could tell if the VFDs were on. The noisy capacitor banks were telling them about harmonics. It was not just noisy . . . no one could stand to be in the building if the capacitor bank was on when the VFDs were working. Those harmonics were going down the power line right around the 31st harmonic of the fundamental 60 Hz frequency and found the 4160 Volt capacitor bank. IEEE at that time had not fully described the inter-harmonic phenomenon, but that did not stop the electrons from making the capacitors sing.

Energy saving Variable Frequency Drives (VFD) can cause problems. Harmonics can cause problems upstream and downstream from drives. Not only capacitors but also instruments and motors can suffer premature failures due to waveform distortion. At high frequencies capacitors look like a short circuit, and inductors look like an open circuit. Such is the impact of different frequencies on circuit behavior. Lightning is a challenge because it can act as both a DC and an AC energy source. From an equipment protection point of view, that is challenging.
Even with all of today's sophisticated protection, POCs load cell circuits pose special challenges because:

1. Polished rod load cells or beam mounted transducers produce microvolt signals. The low strength level means noise more easily interferes with obtaining good results.
2. Analog to Digital converters are not tolerant of noise or high energy. A 16-bit A/D converter is very fussy about the data that it receives.
3. The POC is between the government mandated National Electric Code ground and a pumping unit. Through the bridle is a long ground path of rod string ending at a pump that is probably in contact with water and oil. Fiberglass rods and different casing and tubing configurations can affect the ground path.

Not only is the pumping unit likely to attract unwanted attention from static discharges, but it is likely to send some of that energy through the load inputs and into to POC load cell circuit. That is a bad combination. What are the alternatives to sensitive strain gauges is such a poor location?

People have tried to avoid measuring weight and inferred loads from a variety of electrical measurements. Schemes to use motor load current, motor power factor, speed of motor and crank arm, and other indirect measures are tempting techniques. The more indirect the method, the better the chance that you arc measuring some effect other than what you expect to measure. That is especially true for sensitive measurements that rely on equipment conditions that may change over time.

For instance engineers have known for a long time that power factor is more sensitive to load changes than measuring motor current. It is also subject to factors that are difficult to control.

Burnout ovens that run too hot will change the iron saturation point. Changes in core loss measurements can indicate condition of stator laminations. Few motor repair shops will perform such testing without customers specifying that that task. How many field maintenance people really understand how bad iron can affect motor performance?

The most direct way of measuring rod string load is to use a polished rod load cell. They can be highly accurate and allow very good information about what is happening in the reservoir. Polished rod cells also live in a dangerous place. They are on a likely ground path for surge currents, and even more likely to be in the way during a workover.

Beam mounted transducers measure the deflection of the beam instead of a direct reading of the rod string load. Their measurements are inherently less precise and give only a relative measure of load. If the calibration is good and no other factors are introduced, beam mounted load cells can do an adequate job of measuring load changes. They have fewer assumptions made about their readings than methods using motor speed, power factor, or loading measurements. They are still living on the biggest lightning attraction in West Texas.

The challenge for POC load input circuits is to be able to discriminate the very low magnitude load signals in a very robust and noisy environment that occasionally packs a real wallop. Our existing designs have been fairly successful at protecting the traces on the motherboard. But a failure of devices on the motherboard means disconnecting all the inputs and sending the board in for repairs.

To address this concern we have come up with a simple design we hope is durable and self-destructs at only the appropriate time. The transient over voltage protection module consists of two boards. The terminal board mounts on the motherboard with industrial Velcro. The plug-in module contains the active surge suppression elements.

The ZAP-Stix surface mount components are designed to keep data integrity of A&E RPC intact. The **18** Volt bi-directional voltage clamp with controlled current interruption limits load current to 150 ma per circuit. Terminal board size is 1.2" x 1.5", with the plug-in measuring 1.125" x 1.0".

If the ZAP-Stix takes a big hit, it will fail and be thrown-away. Heat sensitive tape will indicate that the unit has exceeded its thermal limits by changing colors. We hope more field experience shows that that the ZAP-Stix fails before either the strain gauge or POC, and no more often than absolutely necessary

In order to insert the new component in the circuit, we had to open up the clamping on the existing load cell circuit. That change was made so the ZAP-Stix would have a good chance of being able to protect the motherboard, without causing nuisance outages. Only field trials can prove we have hit the balance required for optimum results. We have a few POCs in service withe new surge suppressors. We are working to get more units in service before the lightning season hits.

After a full storm season with a significant population of devices in the field we will know more. We hope to report successful results. We may have more data to present on unintended consequences. Thank you.

CITATIONS:

1. LIGHTNING-ITS EFFECTSAND SOME SIMPLE SAFEGUARDS IN REGARDS TO OILFIELD OPERATIONS by Anthony J. Welker. Southwestern Petroleum Short Course 1998 especially pages 334 & 337.

2. "Advanced Computational Methods in Lightning Performance" is an example of how the Numerical Electromagnetics Code (NEC-2) is progressing by:
M. Ishii, Senior Member, IEEE **of** the Institute of Industrial Science, University of Tokyo, Tokyo 106-8558, Japan and *Y*. Baba, Member, IEEE Department of Electrical Engineering Doshisha University Kyoto 620-0321, Japan

3. Peter E. Vicmeister, The Lightning Book, Doubleday and Company, 1961.

R.F. Ficchi, "Electrical Interference", Hayden, New York, 1964

Dion Neri, Chief Design Engineer for MCG Electronics wrote a fine article "Surge Protection: Where and How Much?" for EC&M March 1997.

Lightning & CN Tower http://www.cntower.ca/faqs/l3_faq_coolstuff_lightning.htm

- Since 1978, observations and measurements of lightning activity have been carried out at the CN Tower.
- Lightning strikes Toronto an average of 2.5 times per square kilometer per year; lightning strikes the CN Tower many tens of times in a lightning season, an average of 30 times.
- Between 1978 and 1994, the CN Tower was hit by lightning 460 times.
- In Toronto, lightning takes place usually from April to October. However it occurs mostly in July and August.
- During the lightning season, lightning flashes may occur in Toronto at any time of the day, although the likelihood of those occurring at night is about two times greater then those taking place during the day. Lightning is at a minimum from 7-9am.
- The higher the structure the longer the lightning stays. The lightning that hits the CN Tower, on average, remains 60% longer then that hitting the Empire State Building in New York City. And three and a half times longer then that hitting in the open country.
- Videotapes of the CN Tower show that about 10% of lightning flashes last a long time – at least 1000ms or one second. It is significant that these same flashes also contain at least four strokes per flash – an abnormally high number of flashes.
- Every surface which can possibly attract lightning is attached to three copper strips running down the CN Tower, connected to forty-two *22'* grounding rods buried *20'* below the surface.

NEC—2 information: Lau BURKE@,FLAME.LLNL.GOV Lawrence Livermore National Labs

Lightning Explorer National Lightning Detection Network®(NLDN) http://www.lightningstorm.com/ls2/gpg/lex1/mapdisplay_free.jsp?jrunsessionid=1013042596119344748

Lightning ObserverSM Lightning Observer, an online lightning map and notification service, tracks recent thunderstorm movement and lightning activity across the continental U.S. with zooming to regional maps and a 60-mile Personal Map of your area. Optional e-mail notification to your pager, cell phone, or computer when lightning enters and then clears your personal area map. Map refreshes every I5 minutes. Lightning data source is the U.S. National Lightning Detection Network@. Available in the U.S. More...

Lightning AdvisorSM Lightning Advisor, an online lightning map, tracks real-time thunderstorm movement and lightning activity across the continental U.S. Zooms to a specific location based on longitude and latitude. Updated every minute. Access to the last six months of lightning data available from the U.S. National Lightning Detection Network@ archives. Available in the U.S. More...

Lightning Notification® Lightning Notification, an online lightning warning service, sends e-mail messages to your computer, pager, or cell phone when lightning is within 8, 15, or 30 miles of your personal location. Notification services are available in three levels. The first level, Lightning Watch®, provides notifications and all clears for 8, 15, and 30 miles. Lightning Warning™ provides notifications and all clears at 8 and 15 miles. Lightning Alarm® zeros in on your location with 8-mile notifications and all clears only. Lightning data source is the U.S. National Lightning Detection Network®. Available in the U.S. More...

STRIKEnetSM Register Now STRIKEnet, an online lightning verification report, objectively and accurately reports individual cloud-to-ground lightning strikes at a specific location on the date of loss. Insurance claims adjusters, fire and arson investigators, legal professionals, news reporters, and others use STRIKEnet anytime at their desktops to verify the presence or absence of lightning. A STRIKEnet report summarizes the numbers of strikes detected in 5- to 15-mile radius surrounding a given location and time period. Report options are a street-detail lightning location map, a detailed text printout of the relevant lightning strikes, and a confidence ellipse map to illustrate lightning strike location accuracy. Lightning data source is the U.S. National Lightning Detection Network@. Available in the U.S. More...

- **Lightning Observer** offers a graphical display of storm development and movement based on lightning activity. Recommended for trend analysis and limited weather forecast support.
- **Lightning Advisor** provides up-to-the-minute information on local, regional, and national thunderstorm activity. Recommended for locating, identifying, and tracking storms and threatening weather.

subscribers of lightning activity within a chosen area via email. Recommended for public safety notices and for determining the initiation of contingency plans.

University of Missouri-Rolla: Computational Electromagnetic Modeling Codes Available on the Internet

ASAP - Antenna Scatterers Analysis Program A (Free!) General Purpose User-Oriented Computer Program for Analysis of Thin-Wire Structures in the Presence of Finite Ground An alternative to the Numerical Electromagnetics Code (NEC) for analyzing insulated or bare thin wire antenna structures owr a lossy or perfect ground plane based an the moment methcd Available onthe web at http://home.att.net/~ray.l.cross/asap/index.html

EMAP EMAP is a family of three-dimensional electromagnetic modeling mdes developed at the University of Missouri-Rolla Each code has different capabilities, but they all have a common easy to understand input file format EMAP2 is a scalar FEM code, EMAP3 is a vector FEM code, and EMAPS is a vector FEM/MoM code They are available via the web athttp //www emclab umr edu/emap html

Fasthenry, Fastcap, and Fastlap Fasthenry, Fastcap, and Fastlap are static moment method codes designed to calculate the resistance, capacitance, and inductance of 3D geometries They are available at rle-vlsi.mit.edu A Windows port of Fasthenry and Fastcap can be found on a web page maintained by Enrico Di Lorenzo at http://www.fastfieldsolvers.com/

(Geo-) Radar - FDTD This is a fully 3D-FDTD simulation code It uses Generalized Wrfectly Matched Layers to damp outgoing waves The configuration is highly configurable by a commented configuration file, but be sure to have 128MB+ memory available Authored by Carsten Aulbert aulbert@aei-potsdam mpg de Golm, Germany Available an the web at http //www welcomes-you com/radarfdtd/

FEMM - Finite Element Method Magnetics A set of programs running under win95/98/nt for the finite element solution of planar/axisymmetric problems in magnetostatics and low frequency magnetics Includes a graphical preprocessor, a solver, and a graphical postprocessor A free beta best version is currently available Authored by David Meeker, Ph D Available an the web at http //members aol com/GMagnetics/download htm

Mie Scattering Code (MIEV) A publicly available code that computes many of the quantities involved in electromagnetic scattering from a homogeneous sphere The code canbe found at the following sites climate gsfc nasa gov in subdirectory */pub/wiscombe* or at sunsite unc edu in */pub/academic/physics/Electro-mag/miev tar*

MOMIC MOMIC is a user-oriented method-of-moments PC program suitable for analyzing the electromagnetic behavior of arbitrarily shaped wire antennas and scatterers, modeled by piecewise linear segments, in free space Capabilities of MOMIC include evaluations of the currents induced/excited on the wires, impedance/admittance parameters, near fields, and far-zone radiation and scattering patterns With MOMIC one can analyze various antennas and scatterers composed of electrically thin straight and curved wires, and wire-grid models of conducting surfaces The target platform for MOMIC executable is an 80486 *(or Pentium) running under* MS DOS in 32-bit protected mode

MOMIC is available on the web at: main site: http //victrix iele polsl gliwice pl/~akarw/momic/ in Poland mirror site: http //emlib jpl nasa gov/EMLIB/MOMIC/ in USA The code is available from both these sites at no charge for non-commercial use

MultiSTRIP MultiSTRIP is a moment-method program that analyzes microstrip antennas on multiple dielectric layers.

NEC2 - the Numerical Electromagnetics Modeling code is a widely used 3D code based on the method of moments. It was developed at Lawrence Livermore National Laboratory more than 10 years ago and has been compiled and run on many different computer systems. NEC2 is particularly effective for analyzing wire-grid models, but also has some surface patch modeling capability. NEC2 is available from Ray Anderson's "Unofficial NEC Archives" at http://www.qsl.net/wb6tpu/swindex.html. Online documentation can be obtained from the "Unofficial NEC Home Page" at http://www.nittany-scientific.com/nec/

Penn State FDTD Code This is a public domain FDTD code developed by R. Luebbers and K. Kunz that is described in their book *The Finite Difference Time Domain Method for Electromagnetics* CRC Press. It is available from ftp.emclab.umr.edu in the directory /pub/aces/psufdtd.

Students' QuickField Students' QuickField(TM), formerly known as ELCUT, is a 2D finite element simulation package solving plane and axisymmetric problems of electrostatics, nonlinear DC magnetics, AC magnetics, current flow, nonlinear heat transfer, stress analysis and coupled problems on any PC.

Sonnet Light A light version of Sonnet Software's planar-MOM electromagnetic simulation software.

SUPERFISH SUPERFISH is one of several codes available from the Los Alamos Accelator Code Group. SUPERFISH evaluates the eigenfrequencies and fields for arbitrarily shaped two-dimensional waveguides in Cartesian coordinates and three-dimensional axially symmetric RF cavities in cylindrical coordinates. The package contains codes to generate the mesh, to plot the fields and to evaluate auxiliary quantities of interest in the design of drift-tube linacs. For example, transit-time factors, power losses, and the effect of perturbations are calculated.

ToyPlane (2D), Toy (3D) and Pulse (full-functional 3D); TLM and FDTD codes. The ToyPlane and ToyAirport codes are 2D test and example codes for time-domain local-operator methods. The Toy and ToyBox codes are 3D test and example codes for time-domain local-operator methods. The Pulse codes are fully functional general 3D codes based on time-domain local-operator methods.

Proximity Effect

H i g h - s p e e d   D i g i t a l   D e s i g n

On-Line Newsletter

Dr. Howard Johnson, Vo1.4 Issue 1

*________________________**________(QUESTION)________*

STRIP LINE PROXIMITY EFFECTSheng Bin writes:

Is there a model of "Proximity Effect" in strip lines or microstrips that is caused by the current generated forces of adjacent conductors? I would guess it could cause frequency dependent attenuation.

Thank you.

________(DR. JOHNSON REPLIES)________

Thanks for your interest in High-speed Digital Design.

You are correct that the proximity effect does play a role in determining the patterns of current flow (and therefore the attenuation and characteristic impedance) of microstrip and stripline transmission lines.

The proximity effect for PCB traces takes hold at rather low frequencies on the order of a few Megahertz. Below that frequency the magnetic forces due to changing currents in the traces are too small to influence the patterns of current flow. At low frequencies current in a PCB follows the path of least RESISTANCE. The path of least resistance for current flowing in a PCB trace fills the volume of the trace, flowing uniformly throughout the conductor. The path of least resistance for that same current as it returns to its source through the power and/or ground planes spreads out in a wide, flat sheet, tending to occupy as much of the surface area of the planes as possible on its way back to the source. That's the least RESISTANCE path.

Above a few Megahertz, the magnetic forces become VERY significant, and the current flow patterns change. Above a few Megahertz the INDUCTANCE of the traces and planes becomes vastly more important than their resistance, and current flows in the least INDUCTANCE pathway. We can state the general principle of least-inductive current flow in a number of equivalent ways:

1. Current at high frequencies distributes itself to neutralize all internal magnetic forces, which would otherwise shift the patterns of current flow.

2. In more technical terms, the component of the magnetic field normal to a (good) conductor is (nearly) zero. (If the normal component is non-zero, eddy currents build up within the conductor to neutralize the normal component of the field).

3. In terms of minimum-potential energy, current at high frequencies distributes itself in that pattern which minimizes the total stored magnetic field energy.

4. In terms of inductance, current at high frequencies distributes itself in that pattern which minimizes the total inductance of the loop formed by the outgoing and returning current.

5. The current in two round, parallel wires is not distributed uniformly around the conductors. The magnetic fields from each wire affect the current flow in the other, resulting in a slightly non-uniform current distribution, which in turn increases the apparent resistance of the conductors. In parallel round wires we call this the proximity effect.

All of the above viewpoints are correct, and they are all equivalent.

Above that frequency where magnetic effects take hold, the patterns of current flow attain the minimum-inductance configuration and do not vary further with frequency (except for the skin effect, mentioned below).

For example, in a typical 70-ohm microstrip configuration you will see at high frequencies the current distributed fairly uniformly around the circumference of a signal-carrying PCB trace, with slightly more current flowing on the side nearest the reference plane, and slightly less on the back side. The increase in resistance due to this effect (above and beyond simple consideration of the skin depth and trace circumference assuming a uniform current distribution) is on the order of about 30 percent, a percentage that remains fixed as a function of frequency.

On the reference plane beneath the trace, you will see another a similar effect. At high frequencies the RETURNING SIGNAL CURRENT FLOWING IN THE REFERENCE PLANE flows most heavily right underneath the trace, with wide tails of residual current falling off rapidly to each side as you move perpendicularly away from the signal-carrying trace. The exact distribution of current in the planes depends on the trace geometry, but not on the operating frequency (assuming your operating frequency is high enough to have attained the minimum-inductance flow pattern). Because the returning signal current at high-frequencies flows in a finite area of the reference plane the effective resistance of the reference plane must be non-zero. The total resistive circuit losses due to the high-frequency pattern of current flow in the reference plane totals approximately 30 percent of the PCB skin-effect trace resistance, a percentage that remains fixed as a function of frequency.

Modern 2-dimensional electromagnetic field solver software automatically takes the proximity effect into account.

A more serious source of high-frequency attenuation, in the range from 10 MHz up to 1 GHz, is the skin effect. The skin effect forces current to flow only in a thin layer around the circumference of the conductors (or the surfaces of reference planes). The thickness of the current penetration layer (the skin depth) changes appreciably with frequency, creating noticeable changes in the attenuation of long traces.

So when does all this attenuation stuff matter? In PCB traces shorter than 12", at frequencies of up to 1 GHz, you can generally ignore all trace losses. They just aren't significant enough *to* worry about. For longer traces, or at higher speeds, the skin effect becomes very significant. At frequencies above 2 GHz (for typical PCB trace geometries) the skin effect is superceded in importance by the effect of dielectric absorption.

Best Regards,
Dr. Howard Johnson

Comments welcome! hsdd@signalintegrity.com

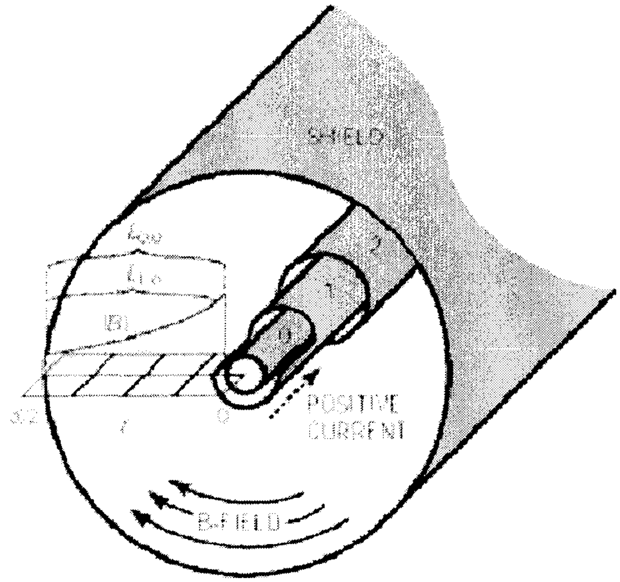
Modeling Skin Effect

(Originally published in EDN Magazine, April 2001)

Why does high-frequency current flow only on the outer surface of a printed-circuit trace?—Dipak *Patel*

Magnetic fields cause the behavior you describe. The technical name for this property is the skin *effect*. It happens in all conductors. If you really like mathematics, the following section **will** help you to better understand *why* the skin effect happens. If not, this might be a good time to step out for a cup of tea.

I'll start the discussion with a perfect coaxial cable. Figure 1 divides the center conductor of this cable into a series of three concentric rings with radii r_0, r_1, and r_2. **A** lumped-element model of this simple circuit demonstrates that high-frequency signal current flows only on ring 2.



The total magnetic flux within the shaded equals L_{10}.

At dc, the longitudinal-voltage drop per inch across each conductor n equals the current, I_n, times its resistance per inch. You can express this relation in matrix terms by defining a square matrix, R, with elements

$$R_{nn} = \frac{\rho}{\pi\left(r_n^2 - r_{n-1}^2\right)}$$

along the diagonal and 0 elsewhere. Then, write $V=RI$, where V is a vector representing the longitudinal voltage per inch across the ends of each conductor, I is a vector representing the currents, and P is the resistivity of the center conductor in units of ohm inches.

At high frequencies, the magnetic interactions between conductors become significant. Figure 1 illustrates the pattern of magnetic fields between the center conductor and shield. The magnetic lines of force (B-field) form concentric circles around the conductive rings. The drawing plots the field intensity, $|B|$, versus radial position, r, assuming a positive signal current of 1A flowing in ring 0 with the return current flowing in the shield. The field strength is zero within the interior of ring 0 and zero outside the shield and varies with $1/r$ (Ampere's law) in between. The exact field intensity for a current of 1A on conductor m is

$$B_m = \left(\frac{\mu}{2\pi}\right)\left(\frac{1}{r}\right)$$

for $r_m < r < d/2$, where μ is the magnetic permeability of the dielectric material (usually $3.192'10^{-8}$ webers/amp-in.). You calculate the mutual inductance per inch between conductors n and m (for $n>m$) using Faraday's law as the integral of the **magnetic-field strength**, B_m, taken over the range from conductor n (at radial position r_n) and the shield (at radial position $d/2$). Integrating $1/r$ yields $\ln(r)$ and the following matrix equation for mutual inductance:

$$L_{n,m} = \left(\frac{\mu}{2\pi}\right)\ln\left(\frac{d}{2r_n}\right).$$

To find values for $n<m$, use symmetry: $L_{n,m}=L_{m,n}$.

The Laplace system equation for the whole coaxial circuit sums both resistive and inductive terms as $V=(R+sL)I$. The following is the inductance matrix for an RG-58/U coaxial cable:

$$L = \begin{bmatrix} 112.1 & 8.6 & 6.5 \\ 8.6 & 8.6 & 6.5 \\ 6.5 & 6.5 & 6.5 \end{bmatrix} \text{nH/in.}$$

Now comes the main point of this article: The terms in the right-hand column of L are all the same. Why? Because ring 2 concentrates *all its flux* into the space between ring 2 and the shield. Therefore, all other rings couple 100% to this flux. The constancy of the right-hand column greatly simplifies the solution to the system equation. To solve this equation, you must find a pattern of currents I such that $(R+sL)I$ generates the same longitudinal voltage across every ring. You need the same voltage across every ring because the rings are all connected together at their ends. If you operate at a frequency so high that the R term becomes insignificant compared with sL, the solution is simple. Just fill in the last element of I, leaving all others zero. This solution peels off only the right-hand column of L, properly generating the same voltage for every ring. This is one of the few matrix problems you can solve by inspection.

The simple solution says that at high frequencies, the signal current flows only on the outer ring, as governed by matrix L. At dc, the current distributes itself more evenly, according to matrix R. At middle frequencies, you get a mixture of both effects. That's the nature of the skin effect.

Continuous conductors behave in a similar manner, as if they were made from a continuum of infinitely thin rings. At higher and higher frequencies, the current squeezes more and more tightly against the surface of the conductor, progressively decreasing the useful current-carrying cross section of the conductor and raising its effective resistance.
You can view all of the mathematical details in a completely worked 40-ring example at **http://sinnalintenrity.com/articles/misc/skineffect.htm**.