Radio Frequency Burns in the Power System Workplace

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***Abstract*—Power system workers may be simultaneously in contact with a metallic object and exposed to power frequency electromagnetic fields or radio-frequency (RF) electromagnetic field from nearby sources such as AM broadcast antennas. Under these conditions, the person may experience either a shock or an intense heating of the tissue near the point of contact (i.e., an RF burn). Here, 50/60 Hz shocks and RF burns are compared and models developed to predict RF current at the point of contact with a metallic object and the resulting heating (and burning) of the tissue. Electric field levels at which RF burns can occur are often significantly less than the maximum permissible exposure in the most widely used RF safety standards. The conditions for which these burns occur are common and are discussed in detail.**

***Index Terms*—Occupational health and safety, power transmission line.**

I. Introduction

It is well known that electric currents induced in a grounded human body by direct exposure to 50/60 Hz electromagnetic fields typically found near electric power lines are well below levels that cause obvious (if any) health effects [1]. Of special note here is the fact that the level of induced currents in the body is limited (in part) by the physical size of the body and the fact that the currents are generally well dispersed throughout the body resulting in electric current densities (J) below neurostimulatory thresholds [2]. The situation is different, however, if (for example) a grounded worker is in contact with a large metallic structure such as a de-energized (and ungrounded) transmission line conductor that is exposed to 50/60 Hz electromagnetic fields from a parallel energized transmission line. In this case, inductive and capacitive coupling with the conductor can occur and, hence, cause currents to flow in the person in contact with the conductor. Obvious effects such as startle reaction or electrical shock can and do occur near the point of contact between the body and the de-energized metallic structure [1]. These effects occur for two reasons. First, the human body is "augmented" by contact with the metallic structure and this "augmented body" effectively becomes much larger than an isolated human body. The metallic structure acts like a receiving antenna that "gathers" a larger amount of energy from the electromagnetic fields than the body would gather by itself. Second, the area of contact between the body and the structure is usually quite small and hence the electric currents traveling from the structure to the body and then to ground are concentrated in a very small cross-sectional area of tissue. This means that the electric current density (and the associated electric field E since $J = \sigma E$, where σ is the body conductivity) can be quite large in that area. Since most biological effects are related to local electric field strength in the body, it is not surprising that electrical shocks occur near these points of contact. In this context, the IEEE "basic restriction" is the limit on the local electric field strength in the body because it is the threshold most closely associated with biological effects [3].

An analogous situation occurs for human exposure to radiofrequency (RF) electromagnetic fields (3 kHz–300 GHz). Electric currents are induced in humans who are exposed to RF electromagnetic fields as shown in Fig. 1(a). However, calculations reveal that, under most circumstances, currents induced by exposure to fields from RF transmitters (and the related local energy absorption rates) are below limits in relevant safety standards [4], [5]. Further, unless the exposure field is from a very small source very close to the body, the current will be spread out over the body, resulting in a relatively small electric current density (and hence small electric field) within the body [4]. However, RF burns can occur at points of contact between the human body and metallic structures that are exposed to RF electromagnetic fields from nearby sources [6], [7] as illustrated in Fig. 1(b). This happens because the body is now "part" of a larger object and the body is "augmented" in size. As a result, the current induced in the body may be significantly increased. As with the extremely low frequency (ELF) case described above, the connection between the body and the object often has a small area and the current injected into the body is concentrated near this point. This can result in a current density near the contact strong enough to raise the local temperature and cause surface or deep burns. It is these RF burns that are the subject of this paper and that are of concern to the power industry because high powered RF sources such as AM broadcast antennas are often located near power system facilities. Given that the temperature rise is what causes the burns, the "basic restriction" exposure limit is different in this

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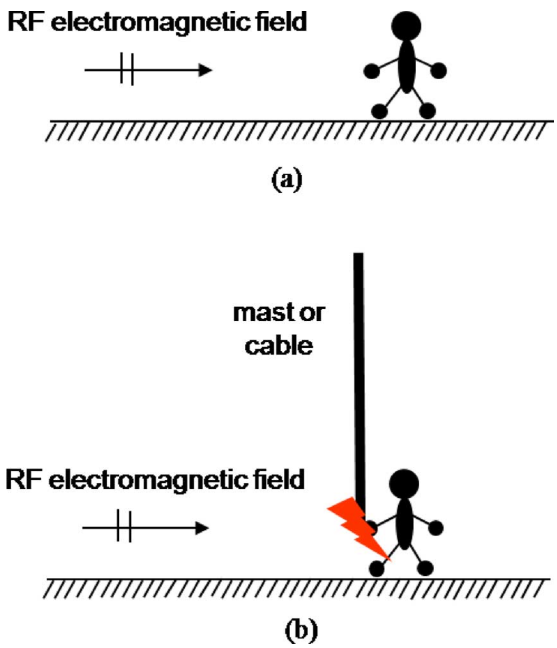

Fig. 1. (a) Person in an RF field with no obvious effect. (b) Person touching a mast or long cable in an RF field leading to an RF burn at the point of contact.

case from that for exposure to ELF fields. More specifically, the basic restriction is the specific absorption rate (SAR) defined as the energy absorption rate in tissue per unit mass. The SAR at a point within the body is defined as

$$\mathrm{SAR} = J^2/(\sigma\rho) = \sigma E^2/\rho \text{ watts/kg} \tag{1}$$

where J is the current density, E is the electric field, σ is the local electrical tissue conductivity and ρ is the tissue density. SI units are assumed.

The driving force behind both 50/60 Hz electrical shocks and RF burns is the electric field and/or electric current density induced inside the body. One major difference between the two phenomena is that the physiological response to 50/60 Hz currents is not the same as that due to RF currents. This is apparent from a graph of perception and tolerance thresholds for sinusoidal electric currents such as can be found in [8], [9]. At frequencies below approximately 10 kHz, the nerves in the body are excited by the current resulting in electrical shock. As the frequency is increased, the nerves become less sensitive to these currents in a roughly linear fashion. At frequencies above approximately 100 kHz, the heat generated by the current flowing in the body can produce a physiological response (i.e., the sensation of heat). Electromagnetic energy is absorbed at a rate proportional to the square of the current density which, in turn, causes a local temperature rise in the body. As frequency increases, this thermal response becomes essentially independent of frequency. Another difference between ELF and RF dosimetry is the dissimilar current distribution in the body due to "skin effect," that causes electric current at higher frequencies to flow closer to the outer surface of the body rather than uniformly through the body's cross-section [10].

II. Historical Background

A good review of the important aspects of RF exposure to electromagnetic fields can be found on the website of the Occupational Health and Safety Administration (OSHA), United States Department of Labor [11]. These materials relate mostly to non-ionizing, non-contact, RF exposure that dramatically reduces in incident power density as a person moves away from the source of RF energy, such as a communications antenna. These "isolated humans" do not have physical contact with RF conducting devices. However, the subject of RF burns, as a result of contact with an object energized by an RF source such as a communications antenna (such as shown in Fig. 1(b)) is covered briefly in the OSHA guidelines. Two specific problems discussed in the OSHA document are worker contact with crane cables located near an AM broadcast antenna and worker contact with radio frequency antennas. As noted above, these cases are fundamentally different from the case for exposure of an isolated human body to RF electromagnetic fields and the exposure from contact that leads to burns is not as well understood.

Concern about occupational hazards from RF burns spawned a significant amount of research on the subject in the 1980's [6]. As mentioned above, the problems included human contact with metallic objects that are insulated from the ground and located near AM broadcast stations or high powered communication and radar antennas. In some of the early work, Ghandi and Chatterjee [7] used quasi-static theory identical to that used by power engineering researchers to study electrical shock hazard. They calculated the amount of RF current induced in a person by contact with an insulated metallic object such as a vehicle when exposed to an RF electromagnetic field. Since quasi-static theory assumes that all objects are small compared to a wavelength, the studies were limited to frequencies below approximately 3 MHz. It is interesting to note that the authors concluded, "...there may be situations where the thresholds of perception and let-go can be exceeded for fields considerably lower than the American National Standards Institute (ANSI) recommended guideline of 615 V/m." Additional work was done by Chatterjee, Wu, and Ghandi to determine a range of human body impedances useful for predicting RF burn thresholds at these frequencies [9]. For finger contact, they found impedances that ranged from roughly 1000 to 2000 ohms depending upon frequency and size of the person. At the same time, the Navy conducted work to study the safety of their personnel who were working on ships that had communication or radar antennas that radiated high powers. The Navy summarized this research by saying, "The specific level at which contact with RF voltage should be classified as an RF burn hazard is not distinct" [12]. Nevertheless, this work also led to a suggested limit on contact voltage in the IEEE standard for exposure to RF electromagnetic fields [4]. Specifically, the standard states that for frequencies between 100 kHz and 100 MHz, the maximum allowable open circuit voltage measured between any two points of contact with the body is 140 volts (rms).

Although open circuit voltage is an important measure of the probability for an RF burn and is relatively easy to measure, it is contact current through the body that can be directly related to RF burns. To calculate contact current from open circuit voltage, it is necessary to know both the human body impedance described above as well as the impedance of the system (later called the Thevenin impedance) that supplies the RF energy. This impedance depends upon the frequency and the specific geometry of the system that the person contacts.

Given that contact current is more closely related to RF burns than the open circuit voltage, standards have been written by the IEEE and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for human exposure to RF contact currents [4], [13]. It is useful to note that, at this time, the Federal Communication Commission (FCC) standard does not have a limit for contact current. For "touch" exposure to sinusoidal currents at frequencies between 100 kHz and 110 MHz, the ICNIRP guidelines specify a maximum contact current of 20 mA and 40 mA for general public and occupational exposures, respectively. The limits in the IEEE standard for the same situations are 16.7 mA and 50 mA, but an averaging time of 6 minutes is allowed. There are no standards for frequencies above 110 MHz.

The upper frequency for the contact current limit (i.e., 110 MHz) was not selected using a scientifically based rationale. In fact, according to the ICNIRP guidelines, "the upper frequency for contact current is imposed by lack of data on higher frequencies rather than by the absence of effects." One example of an RF burn that can occur at frequencies above 110 MHz is found in [14] and it has been suggested in that paper that contact current limits be extended to higher frequencies. The study reported here, however, is limited to frequencies below about 20 MHz.

III. Organization

There are several important questions that are addressed in this paper.

- Is there a more basic rationale for RF contact current limits?
- What parameters (e.g., voltage, current) should be used to describe the potential for RF burns?
- What are the conditions for which RF burns can occur especially while the exposure field is below the maximum permissible exposure (MPE) limits specified in appropriate standards?
- Why is the probability of an RF burn during contact with a conducting object apparently reduced at higher frequencies and is there an upper frequency beyond which contact current limits should not or need not be set?

The results of the study are presented as follows. First, a clarification is made about which aspects of RF burns are studied and which are not. More specifically, although arcs are sometimes associated with RF burns, arcs will not be considered here. The reasons for this are discussed below. Following this, a model that can be used to calculate currents (that lead to RF burns) due to contact with parasitically excited conductors at frequencies higher than those allowed for quasi-static models will be introduced. This model is a person in contact with the bottom of an ungrounded vertical mast as shown in Fig. 1(b). It can be used to determine the limitations of quasi-static theory, to study why RF burns can occur despite the fact that (for the parasitic case) the energizing field is less than MPE limits and why RF burns appear to occur less frequently at higher frequencies. But, it is limited to the case for which direct interaction of the field with the body is ignored and a human can be represented by a single impedance (i.e., an upper frequency of about 20 MHz). Finally, a thermal model is developed that can be used to determine the amplitude of contact current responsible for a temperature rise rapid enough to cause an RF burn. This may be useful for identifying a different rationale (i.e., basic restriction) for the exposure limit on RF contact current.

IV. Arc Damage versuss Heating Damage

If a neutral conducting object is immersed in a 50/60 Hz electric field, it acquires a constant electrical potential with respect to ground approximately equal to the unperturbed space potential at its center. As it is moved close to a conductor held at "ground" potential, the electric field between the two conductors increases. Eventually, this electric field may be large enough (assuming that there is enough charge available) to cause an arc. This is similar to the electrostatic discharge that occurs between a fingertip and a doorknob. When enough charge has been transferred and the voltage between the two conductors is too small to sustain the arc, the arc is extinguished [1]. This initial "arc" (i.e., a "transient" current) is of very short duration. For the "electrostatic" case, the event ends after this transient. However, if contact is made with an object exposed to 50/60 Hz fields, a current continues to flow back and forth between the two conductors since the electric field surrounding them is constantly oscillating and the charge distribution required to keep them at ground potential changes. This current is the "steady state" current between the two conductors [1].

By analogy, there also may be an arc followed by a steady state current when a human in contact with or very close to the ground comes into contact with an ungrounded structure immersed in an RF electromagnetic field [15]. As the human's finger comes close to an ungrounded metallic object, there is an increasingly large electric field between the finger and the object as shown in Fig. 2(a). If this field is high enough and there is enough charge available, the air breaks down and one or more arcs can be created between the finger and the object before contact occurs as shown in Fig. 2(b). It is, in principle, possible that this arc could be perceived and/or cause damage to the finger. But, this incident is usually brief because (in most cases) the finger is moving towards the object relatively rapidly. Due to the brevity of the period during which the arc could occur as well as the difficulty in describing such an arc, direct damage from the arc will not be considered here except for one possible effect. It is possible that the arc could puncture the skin and (since the skin has high resistance) create a small area (of size equal to that of the arc area) of relatively low contact resistance between the metallic object and the body. This might reduce the total body impedance and restrict the current to a small region of the finger. The importance of such a small area is that it would create a very high current density very close to the current entry point. This high current density, in turn, creates a very high specific absorption rate (SAR) that can cause a rapid temperature rise (i.e., hot spot) in the finger as shown in Fig. 2(c).

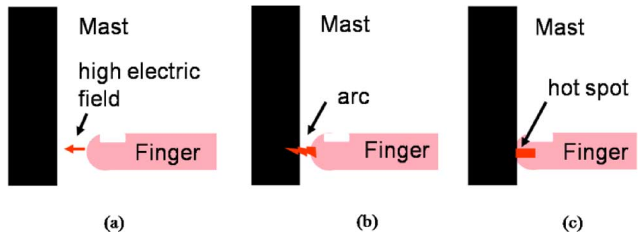

Fig. 2. Steps in contact. (a) Before arc. (b) At point of arc. (c) At contact.

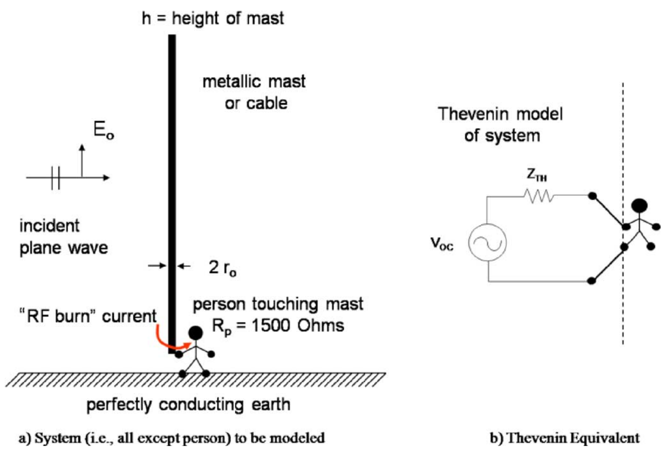

Fig. 3. Geometry of the ungrounded vertical mast problem and its equivalent circuit.

V. Contact With an Ungrounded Mast Exposed to RF Electromagnetic Fields

To understand this phenomenon, a simple model was constructed. More specifically, the problem defined in Fig. 3(a) was set up and solved. In this problem a person is standing on perfect earth (i.e., $\sigma = \infty$) and is in contact with the bottom of a tall vertical cylindrical metallic mast (or cable) of height h and radius r_o that is ungrounded. The mast/person combination is exposed to a vertically polarized, horizontally traveling plane wave of frequency f and amplitude E_o V/m. As long as the directly induced currents in the body can be ignored, the system (i.e., all but the person) can be replaced by a Thevenin equivalent circuit as shown in Fig. 3(b). The person, then, can be represented as a simple two terminal impedance between the hand and foot. In this case, the impedance will be assumed to be a resistor with a value of $R_p = 1500$ ohms since "finger" contact is assumed [16].

Simple analytic expressions for the open circuit voltage $(V_{\rm oc})$ and Thevenin impedance $(Z_{\rm th})$ shown in Fig. 3(b) have been developed previously [17], [18]. From these simple expressions, insight can be obtained into the behavior of the contact current in limiting cases and the effect of different problem parameters can be made clearer. For example, it is shown that, at quasi-static frequencies (i.e., low enough that the mast is much smaller than a wavelength, $\lambda = 2\pi/f$), the open circuit voltage is roughly constant with frequency and the Thevenin impedance is capacitive and quite large compared to the body impedance. For this case the voltage and impedance magnitude are approximately 12.5 volts and 10 kΩ, respectively, at 100 kHz for a 25 meter high 12.5 cm radius mast in a 1 V/m incident electric field. Since the Thevenin impedance is capacitive and dominates the impedance of the person, the contact current is small (i.e., 1.5 mA at 100 kHz) and a linear function of frequency. However, as the frequency is increased beyond the quasi-static limit the Thevenin impedance becomes small (e.g., hundreds of ohms) compared to the body resistance so that the contact current is now limited by the body resistance while the Thevenin voltage increases only slightly (i.e., 16 volts at 3 MHz). At this frequency, the contact current is approximately 11 mA. As illustrated in Fig. 4, the peak current occurs at the first resonance of the mast when its electrical height is approximately $\lambda/2$ where $\lambda(\text{wavelength}) = 300/f$ (MHz) meters. Unfortunately, the simple formulas from [17] cannot be used to calculate this peak current due to an artificial "notch" and the numerical results introduced below will have to suffice.[1]

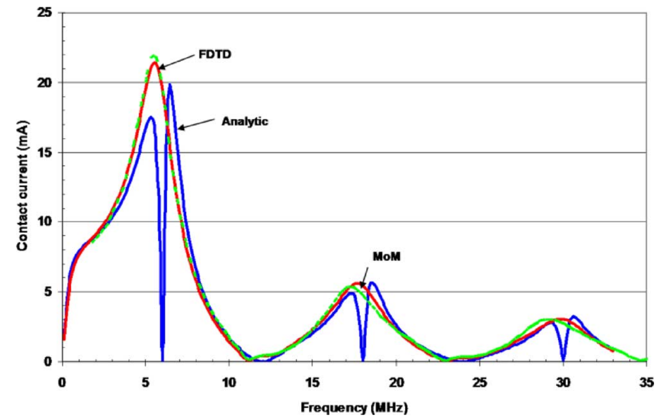

Fig. 4. Contact current injected into a person with $\rm R_p = 1500\ \Omega(E_o = 1$ V/m, $\rm h = 25$ m, $\rm r_o = 12.5$ cm).

A plot of the current injected into a person with a body resistance of 1500 ohms and in contact with a 25 meter high 12.5 cm radius mast in a 1 V/m incident electric field is shown in Fig. 4. In addition to the "analytic" result from which the behavior discussed above can be observed, results are also shown that were obtained using two independent numerical methods: the finite-difference-time-domain (FDTD) method (see, e.g., [19]) and the method of moments (MoM) [20]. The FDTD simulations were performed on code that was written in-house while the MoM simulations used a version of the NEC software [21]. In each method the 1500 ohm resistance of the body was constructed with a simple physical model where, essentially, the body was modeled as a distributed resistance.

The three results agree well except for the anomalous notches in the analytic result that were discussed earlier. There are several things that should be noted about the numerical methods. First, they can be used to calculate the contact current near resonance when the simple analytical result fails. Second, they validate the simple approximate analytical result. Third, the general agreement between all results provides confidence that the numerical results are valid. Finally, numerical methods (especially the FDTD method) can be used in future work at higher

[1]The "notch" occurs because the current is assumed to have exactly sinusoidal variation along the wire and the input impedance is normalized to this current. At certain frequencies, the wire current is then exactly zero and the impedance predicted to be infinite.

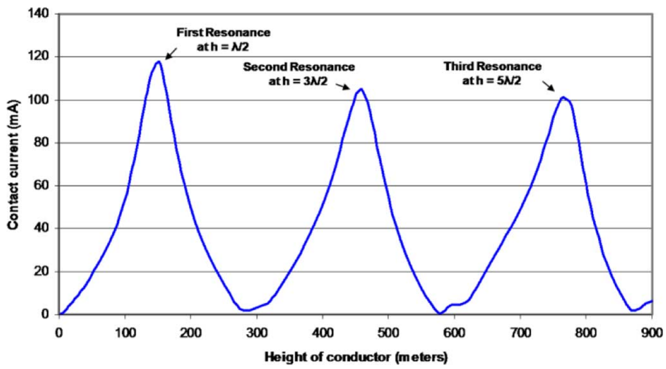

Fig. 5. Contact current at base of a vertical conductor (radius is 12.5 cm) of varying height exposed to an electric field strength of 1 V/m at 1 MHz. Body resistance is 1500 Ω. Resonances occur at one, three and five half wavelengths (i.e., 150 m, 450 m, and 750 m at 1 MHz).

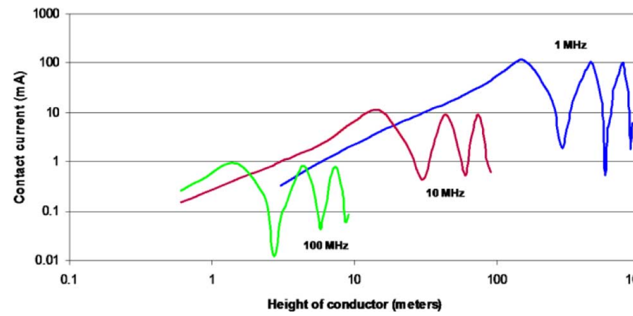

Fig. 6. Calculated contact current vs. height of conductor exposed to an electric field strength of 1 V/m for frequencies of 1, 10, and 100 MHz. Note the similar behavior of the oscillation in contact currents but, importantly, the diminished value of the peak currents at higher frequencies.

frequencies than the analytical method when the simple body impedance model is no longer valid.

Of perhaps most interest here, the largest contact current occurs at the first resonance of the mast which occurs when the height of the mast is approximately one half wavelength. At higher order resonances, only a smaller portion of the mast effectively gathers energy due to destructive interference effects between currents gathered from different portions of the mast. This results in an effectively shorter mast.

While it is important to note that the peak contact current occurs when the vertical conductor is approximately equal to a half-wavelength in height (i.e., the first resonance), the contact currents for lower frequencies than the first resonance must not be neglected. Consider, for example, the AM radio broadcast band (0.535 to 1.710 MHz), where the wavelengths are relatively long (i.e., 176 m to 560 m or half-wavelengths ranging from 88 m to 280 m) and most antennas radiate vertically polarized fields. For most practical situations near such an antenna, the taller the conductor, the more severe the open circuit voltage and available contact current. Fig. 5 illustrates this effect for a frequency of 1 MHz and a range of vertical conductor heights up to 914 m or about three wavelengths. It is apparent that the critical parameters related to the potential for RF burns increase rapidly with increasing height of the conductor up to 150 m, a significant height. This means that the hazard of RF burns increases for taller structures when in the environment of AM broadcast stations. For example, exposure to tall cranes is worse than exposure to shorter cranes.

VI. Why There Is a Diminishing Probability of RF Burns at Higher Frequencies

As mentioned above, the quasi-static open circuit voltage at the mast terminals is proportional to the height of the mast. But, there is a limit to this increase because at some point the height of the mast is no longer a small fraction of a wavelength and the open circuit voltage no longer increases linearly with mast height. As mentioned above, the voltage reaches its maximum when the mast is a half-wavelength in height.

Fig. 5 illustrates the oscillatory nature of the contact current with peaks in the current at odd integer multiples of a half-wavelength.[2] It is relevant to note that while the contact current does go through peaks at greater heights, the maximum current is always greatest at the first half-wavelength and has decreasing peak values at greater heights. The most significant insight from this type of analysis is that very long, or tall, conductors exposed to higher frequency fields, such as VHF transmissions, do not present the same maximum contact current values. This is dramatically illustrated in Fig. 6 where the contact current is plotted vs. conductor height for 1, 10, and 100 MHz. These data show why long conductors exposed to VHF RF fields do not present the same degree of potential for an RF burn as similar length conductors at lower (medium wave) frequencies.

VII. Simple Expression for the Maximum Contact Current

Given the facts that the maximum contact current in Fig. 4 for a 1500 Ω person is approximately 20 mA at 6 MHz, that parametric studies show that the maximum contact current is proportional to the half-wavelength resonant length of the mast (i.e., inversely proportional to the first resonance frequency) and that the contact current is proportional to the incident electric field strength, the maximum possible contact current due to contact with a vertical mast (of a height that causes the maximum current at frequency f) can be written as

$$I_{\text{contact}}(\max) = (120E_o)/f(\text{MHz})\ \text{mA} \tag{2}$$

where E_o is in volts per meter and $f(\text{MHz})$ is the frequency of the first resonance in megahertz. Since the person's 1500 Ω resistance dominates the input impedance of the antenna, the maximum open circuit voltage is approximately

$$V_{\text{oc}}(\max) = (180E_o)/f(\text{MHz})\ \text{volts}. \tag{3}$$

This result is very interesting since it can be inferred that the open circuit voltage can be substantial even in a relatively weak incident electric field (i.e., in the 6 MHz case, the voltage is the electric field multiplied by 30). Very roughly, the maximum open circuit voltage at any given frequency is the electric field multiplied by a numerical value equal to a half-wavelength in

[2]Resonances do not occur at even multiples of a half-wavelength because the input impedance (and hence the Thevenin impedance) of the mast is very large for these cases and hence the contact current will be very small.

meters at that frequency. Of further interest is the fact that at 6 MHz, the incident electric field required to exceed the Navy and IEEE open circuit voltage of 140 volts to protect against RF burns is approximately 4.7 volts per meter, much smaller than the FCC MPE limit ($< 1\%$) for direct exposure to electric fields at this frequency (i.e., 307 V/m). In addition, the contact current for this situation is approximately 100 mA, a result that will be shown later to be large enough to cause an RF burn. It is interesting to note that this current is larger than the ICNIRP limits mentioned in Section II. This should be no surprise since the ICNIRP limits should indicate the threshold for an effect.

This approximation to the "maximum" contact current is fairly consistent with what is shown in Fig. 4. As the frequency goes up the maximum contact current available at higher order resonances is decreased because the electric field is "collected" from a smaller length of mast because the contributions from different parts of the mast destructively interfere with each other due to phase shifts as they travel along the mast.

Given (2) and the fact that the contact current at higher order resonances is smaller than (2), it is clear that as the frequency is increased the largest possible contact current (i.e., that which occurs when a human touches a half-wavelength mast) is reduced. It follows that the electric field exposure required to cause an RF burn at the point of contact is increased as well. At some frequency the FCC MPE limit is large enough that it may be protective against RF burns as well as against exposure of isolated bodies. Hence, at higher frequencies than this, it may not be necessary to limit contact current from passively excited wires separately.

If the human impedance is assumed to be 1500 Ω and 100 mA is taken as the threshold for an RF Burn, then the electric field at which RF burns may occur is

$$E_o(\text{threshold for RF Burns}) = 0.83\ f(\text{MHz})\ \text{V/m}. \quad (4)$$

The FCC MPE limits (occupational) for electric field exposure are

$$\begin{array}{ll} 614\ \text{V/m} & 0.3-3.0\ \text{MHz} \\ 1842/f(\text{MHz})\ \text{V/m} & 3.0-30\ \text{MHz} \\ 61.4\ \text{V/m} & 30-300\ \text{MHz.} \end{array}$$

Given these limits, the frequency above which the MPE limit would become protective of RF burns (from touching ungrounded vertical masts that are parasitic antennas), with the assumption that the only criteria for a burn is a contact current of 100 mA, is approximately 75 MHz. Note that this does not cover the case for touching directly energized antennas or address the issue of potential RF burn hazard from electrical arcs that may carry less than 100 mA of current.

VIII. Model for Predicting Minimum Contact Current Needed to Cause an RF Burn

In Fig. 7, the details of the contact between a mast (or cable) and a finger are shown. It is assumed that there is a steady state current traveling from the tower (or mast) to the finger and that this current is the one that has been calculated using the previously developed models. The purpose of this section is to approximate the current density in the finger and the associated temperature rise that could lead to a burn.

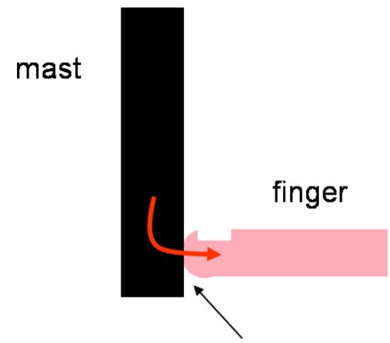

Fig. 7. Contact between a finger and an energized mast.

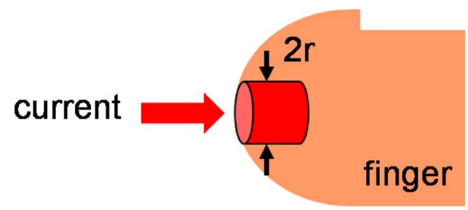

Fig. 8. Simplified model for current flow and temperature rise in the finger.

It is assumed that the contact area between mast and finger is circular as illustrated in Fig. 8 and that the radius of this contact area is r. Then, the current density in the finger at the point of contact is

$$J = I/(\pi r^2)\ \text{A/m}^2. \quad (6)$$

The power absorbed per unit volume is then

$$P = J^2/\sigma\ \text{W/m}^3 \quad (7)$$

where σ is the conductivity of the tissue (assumed here to be $\sigma = 0.6$ S/m) [22]. The local SAR (power absorbed per unit mass) can be computed from (1) where ρ, the density of flesh is assumed to be 1000 kg/m^3 [18].

If it is assumed that the radius of the contact point is 0.25 cm and the current into the contact point is 10 mA, then the local SAR is 432 W/kg, more than 43 times the local basic restriction for controlled environments used in the IEEE standard of 10 W/kg averaged over 10 g of tissue [4]. If the radius of the contact point is half of this value (i.e., 0.125 cm), then the local SAR is 6917 W/kg. This radius is equivalent to that for the RF burn shown in Fig. 9.

The final step in determining whether a burn can occur is to assume adiabatic heating and to then calculate the temperature rise at the contact point as a function of time. This temperature rise can be written as

$$dT = \text{SAR}/c\ ^\circ\text{C/sec} \quad (8)$$

where SAR is in Watts/kg and c (the specific heat) is approximately 3500 joules/(kg - °C) assuming that the body is mostly water [18]. For the example given above (i.e., SAR $=$ 6719 W/kg) $dT = 1.9$°C/sec, probably too small to cause a burn. The reason is that the temperature rise needed to cause a burn in a short time is approximately 55°C [4]. During the 9 seconds

Fig. 9. Typical RF burn on the finger. The radius of the burn is approximately 0.125 cm.

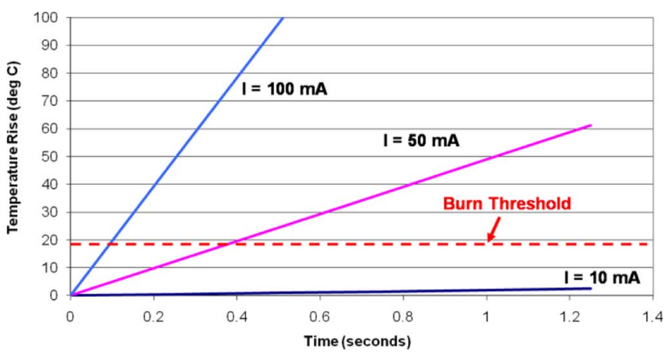

Fig. 10. Local adiabatic temperature rise in a finger with a contact area of 5 mm^2 due to RF contact current.

required to "heat" the tissue from 37°C (approximate body temperature) to 55°C, cooling mechanisms would generally be activated. If, however, the RF burn current is 100 mA, the temperature rise would be 190°C/sec and it would take only 0.09 seconds to raise the temperature from body temperature (assumed to be about 37°C) to 55°C. A graphical presentation of these data is shown in Fig. 10.

IX. Conclusion

Analytical and numerical electromagnetic models that are useful for predicting RF burns at higher frequencies than previously possible have been developed. The specific case considered is for humans touching vertical conductive masts that are exposed to electromagnetic fields from nearby sources. The model is augmented by a theory that relates the contact current to temperature rise near the point of contact. The models can be used to determine the threshold conditions for which an RF burn could occur.

The models developed in this study indicate that:

- local SAR, tissue specific heat, exposure time and tissue burn temperature can be used to form a basic rationale for predicting the threshold for RF burns;
- it is important to know the RF open circuit voltage, and the system impedance at the point of contact and the body impedance in order to predict the RF contact current and to describe the potential for RF burns;
- for a human impedance of 1500 Ω and a 100 mA threshold for an RF burn, the threshold electric field at which an RF burn occurs from contact with a vertical mast at its first resonance (i.e., the worst case that occurs at $150/f(\mathrm{MHz})$ meters) is approximately $E_o = 0.83\ f(\mathrm{MHz})$ V/m;
- at frequencies below approximately 75 MHz, RF burns can occur at electromagnetic field levels less than the maximum permissible exposure in the most widely used RF safety standards;
- the electric field required to cause an RF burn is larger than $0.83\ f(\mathrm{MHz})$ V/m if the frequency is above or below the first resonance of the vertical mast;
- at frequencies below the first resonance, the likelihood of an RF burn is greater for contact with tall metallic objects than for short metallic objects;
- for a given electric field exposure level, the probability of an RF burn decreases with frequency at a rate of approximately $1/f(\mathrm{MHz})$;
- at frequencies higher than the first resonance, contact with taller metallic objects does not result in a greater probability of RF burns than contact with shorter metallic objects.

Note that the model used in this paper is valid only when the direct interaction of the electromagnetic field with the body can be neglected. This limits the work to frequencies below approximately 20 MHz when the body is a "small fraction of a wavelength" in maximum dimension.

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References

[1] *EPRI, EPRI AC Transmission Line Reference Book—200 kV and Above*, 3rd ed. Palo Alto, CA: EPRI, 2005, ch. 7.
[2] W. H. Bailey and J. A. Nyenhuis, "Thresholds for 60-Hz magnetic field stimulation of peripheral nerves in human subjects," *Bioelectromagnetics*, vol. 26, pp. 462–468, 2005.
[3] *IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz*, IEEE Std. C95.6—2002.
[4] *IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields 3 kHz to 300 GHz*, IEEE Std. C95.1–2005.
[5] "Radio frequency safety." 2010. [Online]. Available: http://www.fcc.gov/oet/rfsafety/
[6] S. J. Rogers, J. C. Mitchell, Ed., "Radiofrequency burn hazards in the MF/HF band," in *Proc. Workshop on the Protection of Personnel Against RFEM*, 1981, pp. 76–89, USAFSAM Aeromedical Review 3–81.
[7] O. P. Gandhi and I. Chatterjee, "Radio-frequency hazards in the VLF to MF band," *Proc. IEEE*, vol. PROC-70, no. 12, pp. 1462–1464, Dec. 1982.
[8] J. P. Reilly, *Applied Bioelectricity*. New York: Springer, 1998.
[9] I. Chatterjee, D. Wu, and O. P. Gandhi, "Human body impedance and threshold currents for perception and pain for contact hazard analysis in the VLF-MF band," *IEEE Trans. Biomed. Eng.*, vol. BME-33, no. 5, pp. 486–494, May 1986.
[10] W. H. Hayt, Jr. and J. A. Buck, *Engineering Electromagnetics*. New York: McGraw-Hill, 2001, pp. 369–376.
[11] "Radio frequency and microwave radiation." 2010. [Online]. Available: http://www.osha.gov/SLTC/radiofrequencyradiation/healtheffects.html
[12] Electromagnetic radiation hazards (hazards to personnel, fuel and other flammable material). 2003. [Online]. Available: http://www.cpp.usmc.mil/mcas/docs/NAVSEA%20OP%203565%20Vol.%201.pdf

[13] Int. Comm. Non-Ionizing Radiation Protection (ICNIRP), "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)," *Health Phys.*, vol. 74, no. 4, pp. 494–522, 1998. [Online]. Available: http://www.icnirp.de

[14] B. Hocking and R. Westerman, "Radiofrequency electrocution (196 MHz)," *Occup. Med.*, vol. 49, no. 7, pp. 459–461, 1999.

[15] MIL-STD-1399-408A (Notice 1), Military standard, interface standard for shipboard systems section 408 electromagntic radiation hazards to personnel and fuels. 1973. [Online]. Available: http://www.everyspec.com/MIL-STD/MIL-STD+%281300+-+1399%29/MIL-STD-1399-408A_NOTICE-1_ 13207/

[16] Y. Kamimura, K. Komori, M. Shoji, Y. Yamada, S. Watanabe, and Y. Yamanaka, "Human body impedance for contact current measurements in japan," *Inst. Electron., Inf. Commun. Eng.*, vol. E88-B, no. 8, pp. 3263–3267, Aug. 2005.

[17] E. C. Jordan, *Electromagnetic Fields and Radiating Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1950.

[18] "RF burns in the workplace," EPRI, Palo Alto, CA, Rep. no. 1015627, Nov. 2008, EPRI.

[19] A. Taflove and S. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3rd ed. Boston, MA: Artech House, 2005.

[20] R. F. Harrington, *Field Computation by Moment Methods*. New York: Wiley, 1993.

[21] R. W. Lewallen, EZNEC+. ver. 5.0.36. [Online]. Available: http://www.eznec.com

[22] C. Gabriel and S. Gabriel, "Compilation of the dielectric properties of body tissues at RF and microwave frequencies." Internet document. 1997. [Online]. Available: http://niremf.ifac.cnr.it/docs/DIELECTRIC/home.html

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