Safety Science 51 (2013) 118–126

Contents lists available at SciVerse ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Safety risk management for electrical transmission and distribution line construction

Alex Albert *, Matthew R. Hallowell

Department of Civil, Environmental and Architectural Engineering, University of Colorado, 428 UCB, 1111 Engineering Drive, Boulder, CO 80303, USA

ARTICLE INFO

Article history:
Received 29 September 2011
Received in revised form 25 January 2012
Accepted 3 June 2012
Available online 21 July 2012

Keywords:
Occupational safety
Risk management
Injury prevention
Electrical transmission and distribution

ABSTRACT

Prior research has established that electrical contractors involved in the construction and maintenance of electrical transmission and distribution (T&D) lines are at extremely high risk of electrocution. The result of inadvertent contact with T&D lines often is death or severe injury that involves damage to internal organs, musculoskeletal disorders, neurological damages and severe burns. The Electrical Safety Foundation International has demonstrated that contact with overhead power lines has been the single largest cause of electrical fatalities over the last decade. To reduce this disproportionate injury rate, electrical contractors implement many strategies such as the use of rubber insulating equipment, and locking devices. Unfortunately, these strategies are often cost-prohibitive in certain construction and maintenance scenarios. Therefore, electrical contractors are faced with complex decisions that involve comparing the cost of injury prevention with the expected safety benefit. This paper presents research that objectively evaluated the risk associated with common T&D construction tasks and the effectiveness of specific injury prevention techniques. The research team then developed a decision support framework that provides electrical contractors with objective safety and cost feedback given specific project characteristics. The results indicate that many of the effective strategies implemented to reduce T&D electrical injuries are very costly (e.g., de-energizing lines). Consequently, under most conditions, the costs of injury prevention far outweigh the cost savings associated with the reduction of injury rates. The implication of these findings is that T&D electrical contractors must highly value the non-monetary benefits of injury prevention in order to improve safety in their sector.

1. Introduction

According to the US Energy Information Administration (2010), more than 4 billion mW h of electricity is generated annually in the United States to serve more than 300 million people. This electricity is transmitted for consumption through electrical transmission and distribution (T&D) lines. The nominal voltage in bulk transmission lines can be as high as 750 kV, which can cause instant death when contact is made (Short, 2004). Workers involved in the construction and maintenance of these electrical T&D lines are at extremely high risk of electrocution. In fact, according to the Electrical Safety Foundation International (2010), contact with overhead power lines accounted for an average of 43% of all electrocutions between 1992 and 2009. Other major causes of occupational electrocutions included contact with wiring, transformers, or other electrical components (27%) and contact with the electrical current of machines, tools, appliances, or light fixtures (17%).

Among all occupations, the Electrical Safety Foundation International (2010) found that construction contractors account for the highest rate of electrocutions. Within the construction trade, electricians accounted for about 17% of the electrocution fatalities; construction laborers accounted for 9%; and roofers, painters, carpenters, and maintenance workers incurred a total of 7%. Behind construction, T&D line workers have the second highest electrocution rate. The Bureau of Labor Statistics (2010a) estimated that among the 192 recorded electrocution fatalities in 2008, 53% involved T&D workers who contacted overhead power lines and the National Institute for Occupational Safety and Health (2009) documented that 80% of fatalities among linemen have occurred due to direct contact with T&D power lines. This injury rate caused the Bureau of Labor Statistics (2010a,b) to classify T&D line construction and maintenance as one of the most dangerous jobs in the American economy. Unfortunately, a thorough literature revealed no significant research into the proximal causes or methods of prevention for T&D fatalities.

The impacts of T&D electrical injuries are substantial. The result of inadvertent contact with T&D lines is often death or severe injury that involves damage to internal organs, musculoskeletal disorders, neurological damage, and severe burns (Lee et al., 2000). Such injuries cause long-term physical and emotional distress to workers and their families. In addition, these injuries and fatalities

* Corresponding author. Tel.: +1 970 227 3757; fax: +1 303 492 7317.
E-mail address: alex.albert@colorado.edu (A. Albert).

0925-7535/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ssci.2012.06.011

result in substantial economic expenses such as: higher insurance premiums, medical cost, compensations, lost productivity, administrative costs, and others (Everret and Frank, 1996; Ferret and Hughes, 2007; Oxenburgh and Marlow, 1996; Tang et al., 2004). According to Waehrer et al. (2007), the construction private sector accounted for $11.5 billion in fatal and non-fatal injuries in the year 2002. The electrical T&D sector contributed greatly to these statistics. In fact, the average cost of each electrical fatality was $4 million and the cost of each lost work time injury was $42,207. Despite the high injury and fatality rates and their severe financial and personal impacts, the electrical T&D industry continues to grow at an alarming rate.

Research in the electrical T&D sector has predicted that recent technological advances will force utility companies to construct new lines, maintain existing lines, and upgrade their performance (Balducci et al., 2002). It has also been estimated that the demand for electricity will increase by more than 1 trillion kW h from the years 2003 to 2020 Further, studies by Chupka et al. (2008) have shown that, the electrical utilities will have to make an investment of $1.5–$2.0 trillion by the year 2030 to keep up with the pace in demand. These investments to enhance the T&D infrastructure will likely increase the volume and complexity of T&D electrical line work over the next 20 years (ESFI, 2010). Electrical utilities and contracting companies clearly need to consider injury prevention strategies that reduce the frequency and severity of injuries and their associated monetary and non-monetary costs. When addressing this issue, electrical contractors and utility companies are faced with complex decisions involving weighing the cost of injury prevention against the expected safety benefit.

The purpose of this study was to objectively evaluate the costs and benefits of safety management techniques in the electrical T&D sector of the US construction industry for commonly-encountered work scenarios. The associated objectives of this research study were to: (1) identify common work tasks performed around T&D lines and safety strategies used by utility companies to prevent injuries; (2) quantify the safety risk associated with each work task using a combination of opinion-based and empirical data; (3) quantify the percent risk reduced by the various injury prevention strategies; and (4) apply a risk-based contingent liability model developed by Hallowell (2011) to analyze the cost–benefit of the injury prevention strategies under specific work scenarios. The result is a stable, valid, and reliable decision support tool that provides critical safety and cost feedback that practitioners can use to make informed decisions that enhance both safety and financial performance.

2. Literature review

To provide context for this study and better understand the unique features of the electrical T&D sector, the writers reviewed literature on the topics of electrical T&D operation, the effect of high voltage electrical current on the human body, safety risk quantification, and safety risk mitigation. Though a thorough review revealed no research that had specifically quantified safety risks in the T&D sector or the impacts of commonly implemented injury prevention strategies, guidance from similar studies in other industry sectors were used as guidance. The results of this literature review are summarized briefly below.

2.1. Electricity transmission and distribution (T&D) operation

Traditionally, electricity is generated by the conversion of the stored energy in gas, oil, nuclear fuel or water position (Karady, 2006). Electricity may also be generated by utilizing energy derived from solar, wind, geothermal, chemical processes and even landfills (Wagner, 2007). The voltage at the point of generation is usually between 15 and 25 kV, which, unfortunately, is not ideal for transmission due to losses that may occur. In order to reduce power losses during transmission, a transformer is used to step up the voltage in the transmission line to 230–750 kV. Subsequently, the voltage is reduced at a substation preceding the subtransmission lines between 69 and 169 kV, which leads to the primary distribution line where the voltage is maintained between 4 and 35 kV (Short, 2004). Finally the distribution transformer reduces the voltage to 120 and 240 V, which is supplied to consumers through the secondary distribution lines.

2.2. Impacts of high voltage electrical current on the human body

The effect of contact of electricity with the human body is highly random and often manifests itself in a number of ways. Electrical injuries are usually induced primarily through hazards such as shock, arc and blast (Cardick et al., 2005). In the case of an electric shock, the degree of the injuries is typically a function of the intensity of current, current flow path, the duration of contact with the source, and the voltage magnitude (Lee and Dougherty, 2003). The nervous, musculoskeletal, cardiovascular and the pulmonary system can be adversely affected due to the flow of electricity (Spies and Trohman, 2006). Gordon and Cartelli (2009) recently categorized electrical injuries as:

- Immediate effects on the nervous system from shock currents, including life threatening effects on the heart, breathing, and brain;
- Stimulus of the muscles from current flowing through the body, including reflex action and being "frozen" to the circuit;
- Burns to the body from hot conductors caused by high currents flowing through metal conductors, does not necessarily involve a shock;
- Internal tissue damage from shock currents flowing through the body that ranges from mild cellular damage to major damage to organs and limbs; and
- External burns and other physical injury due to an arc, creating an arc flash (thermal energy) and/or an arc blast (including acoustic and kinetic energy).

As mentioned above, apart from complexities such as asphyxia (Shoemaker and Mack, 2009), arrhythmias, asytole, and myocardial injury (Spies and Trohman, 2006), fatalities or injuries may result even when there is no electrical current flow through the body (e.g., electrical ignition fire, blast, fall) (Cardick et al., 2005). Although very little can be done to reduce the severity of electrical contact (Soelen, 2007), much can be done to reduce workers exposure to electrical current and to reduce the frequency of injuries incurred.

2.3. Safety risk quantification

Quantifying occupational safety risks for the purpose of resource allocation is becoming increasingly popular in the academic and professional research communities. Risk is defined as, a measure of the probability of occurrence of an incident and the severity of the adverse consequence that results from an exposure to a hazard (ANSI, 2000; Lowrance, 1976; NFPA1500, 2002; NSC, 2009). These adverse effects (such as an injury) often result in cost overruns, schedule delays, and poor performance (Sun et al., 2008). In the past, researchers have undertaken diverse approaches to assess safety risk in construction and infrastructure projects. For example, Lee and Halpin (2003) utilized fuzzy mathematical techniques and expert inputs to assess factors influencing accident potential in the context of trenching operations, Gürcanli and Müngen (2009)