

Practical Approaches to Reducing Transient Overvoltages Factors for Live Work

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Abstract— The Occupational Safety and Health Administration (OSHA) on April 11, 2014, published new default transient overvoltage factors (T) for use in calculating the Minimum Approach Distance (MAD) for workers operating in the vicinity of energized transmission lines. These new default T values result in an appreciable increase in minimum approach distance at certain grid voltage levels that, in many cases, could render existing live-line work unviable. As a result, OSHA’s new default T has caused the electric utility industry to review live-work practices to ensure they are in compliance with OSHA.

Index Terms—Live-Line Work, Live Work, MAD, Minimum Approach Distance, T , T values, T factors, Transient Overvoltage, Transmission Line.

I. NOMENCLATURE

a	switching surge air saturation factor
C_1	60 Hz rod gap withstand (100 kV _{rms} /ft)
C_2	the tool factor
M	inadvertent movement factor
MAD	minimum approach distance
T	maximum anticipated per-unit transient overvoltage (TOV)
V_{L-G}	ac voltage line-to-ground (rms), in kilovolts

II. INTRODUCTION

LIVE work (work on energized circuits) is the preferred method of maintenance where system integrity, system reliability, and operating revenues are at a premium and where removal of the circuit from service is not an acceptable option.

The scope of this paper is limited to live work performed on lines and equipment operating at 72.5 kV or higher using insulating-tool (“hotstick”) and barehand methods.

Live work must be performed safely. Safety is achieved through thorough, specialized work practices and training of workers in those practices; the use of specifically designed, manufactured, and maintained tools, equipment, and devices; and adhering to minimum approach distances to energized parts in the insulating tool method and to grounded objects or objects at different potentials in the barehand method.

The minimum approach distance (MAD) is determined for each live work task to ensure that the probability of a sparkover between the worker and ground or energized parts is kept at an

extremely low level, with a probability of 0.0013 (3σ). MAD depends on the voltage of the line or equipment worked, the transient overvoltage factor that is expected in case of an unintended disturbance to the system, and additional factors that account for the presence of tools, defective insulators, non-standard atmospheric conditions, and other considerations. Per IEEE Std 516-2009 [1], MAD is computed as:

$$MAD = (C_1 + a) \cdot T \cdot V_{L-G} + M \quad (1)$$

The provenance of (1) and of the transient overvoltage factor T reaches back more than a half-century [2], [3], [4], [5]. The early studies reported in [2], [3], [4], and [5] led to the development of the first IEEE standard for live work, including determination of MAD, published in 1986 as Trial Use Guide [6]. That Trial Use Guide has since been revised and updated several times, and has over the years formed the basis for both the NESC and the relevant OSHA rules.

Recently, OSHA has focused on the specific values of the transient overvoltage factor T ; therefore, the purpose of this paper is to address the issue of T and provide practical approaches to reducing T for live work.

This paper will demonstrate practical values of T (and hence MAD) when certain practices and procedures are implemented during live work.

This paper is further limited to the case of phase-to-ground MAD. This paper does not discuss in detail methods that are commonly used to attenuate transient overvoltages (for example, metal oxide varistor (MOV) and portable protective air gap (PPAG)), which are effective methods of limiting transient overvoltages. In addition, it is assumed that maintenance work will not be performed during inclement weather; therefore, the T values associated with lightning are not included in this paper.

III. TRANSIENT OVERVOLTAGE FACTOR VALUES

The transient overvoltage factor is a parameter used in the calculation of MAD, as shown in (1). Utilities that have performed sufficient engineering studies and determined the T factors for their lines can use those factors in calculation of MAD. Utilities that do not have a detailed knowledge of the transient overvoltage factors for their lines may seek to use default T values from published standards.

The default values of T for Live Work Listed in IEEE Std. 516-2009 [1] offers values based on the “old” OSHA T values, or the “industry accepted values of T ”, shown in Table I, which is a copy of Table 4 on p. 39 of Ref. [1].

TABLE I

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IEEE STD 516-2009 VALUES OF T FOR LIVE WORK BASED ON THE "OLD" OSHA T VALUES (COPY OF TABLE 4 ON P. 39 OF REF. [1])

AC line-to-line voltage	T for live work
At and below 362 kV	3.0 p.u.
363 to 550 kV	2.4 p.u.
551 to 800 kV	2.0 p.u.

On April 11, 2014, OSHA published new standard maximum transient overvoltages for use in calculating minimum approach distances [7]. Table II presents the default T values that validated after April 1, 2015. (See 29 CFR 1910.269, Table R-9, and 29 CFR Part 1926, Subpart V, Table V-8.)

TABLE II
NEW OSHA VALUES OF T FOR LIVE WORK[7]

AC line-to-line voltage	T for live work
72.6 to 420 kV	3.5 p.u.
420.1 to 550 kV	3.0 p.u.
550.1 to 800 kV	2.5 p.u.

A. Published T Values Listed in IEEE and EPRI Reports

Transient overvoltages have been studied by the industry since the early 1920s. The results of these studies and tests have been published and referenced in various documents [8], [9], [10], and [11]. Therefore, values of T are nothing new to the industry. This section will examine some of these published T values in IEEE and EPRI publications [1], [2], [3], [4], [5], [6], [12] and [13].

The T values on a transmission line can vary depending on the line length, compensation, line termination, total short circuit power, inductive or complex source, etc. [14]. T values can be affected by the switching actions of a circuit breaker, such as energizing a line, opening a line, and by reclosing. Besides initial switching operations, overvoltage transients can result from the initiation of a fault on a transmission line. A brief explanation of common causes of transient overvoltages follows:

- *Fault Initiation* – The occurrence of a fault. For example, when a ground fault occurs on one of the phases of a line, a voltage surge that is equal and opposite to that existing on the faulted phase conductors gets suddenly applied. Consequently, a system of waves is sent out on the faulted conductor and also on adjacent conductors due to electromagnetic coupling. The worst case overvoltage occurs on one of the healthy phases, which can be a concern during live-line work.
- *Fault clearing* – The interruption of the faulted condition typically performed by a circuit breaker. Once the circuit breaker responds to the opening command from the protection system due to a fault on the line, the arc is extinguished and the fault itself is cleared. At this stage, the fault clearing voltage surge is generated that results in an overvoltage on the line.
- *Energization* – Connecting or reconnecting an element such as a transmission line, transformer, or capacitor

bank to a voltage source.

- *Energization into a Trapped Charge* – Connecting or reconnecting a voltage source to an element such as a transmission line, transformer, or capacitor bank with existing energy stored as voltage.
- *Restrike* – Restriking is a phenomenon that occurs during a switchgear opening operation when the contact opening is not successful resulting in a momentary re-energization of the line.

Table III is reproduced from an IEEE transaction on switching surges [11] and summarizes the highest overvoltage magnitudes likely to occur for each listed scenario, along with the overvoltage magnitudes achieved from typical methods used for limiting or controlling the switching surges. Likewise, the EPRI Transmission Line Reference Book [12] lists typical magnitudes for overvoltages obtained from analysis and measurements. These values are reproduced in Table IV. Published field testing and calculations were used to construct Tables III and IV.

Based on these well-established transient overvoltage factors in Tables III and IV, overvoltages greater than 3.0 are associated with such events as automatic reclosing, line energization, line switching, and capacitor switching.

The overvoltages that result from fault clearing (no reclosing) are below 2.0 p.u. The upper T values listed for fault initiation in Tables III and IV range from 1.7 pu to 2.1 pu. As explained in [11], the T values for fault initiation are typically less than 1.7, but simulations have shown values as high as 2.1.

The differences between testing and modeling results are important to note. Reference [15] highlights that simulation results over-estimate the transient overvoltages that occur on transmission lines, particularly when the actual and simulated circuit does not employ transient mitigation. Reference [15] also provides possible reasons why the predicted overvoltages are higher than observations in the field.

Tables III and IV both show that the magnitudes of overvoltages associated with energizing and reclosing result in much higher T values than that of fault clearing without reclosing and fault initiation.

TABLE III

SUMMARY OF TYPICAL SWITCHING SURGE MAGNITUDE RANGES AND THE REDUCTION REALIZED BY CONTROL TECHNIQUES (REF. [11], TABLE II, P. 3)

Type of Event	Maximum phase-to-ground surge without control	Control Method	Maximum phase-to-ground surge with control
Energizing (no trapped charge)	2.4 to 2.8	Closing Resistors	1.5 to 2.2
Three-Phase Reclosing	3.5 to 4.0	Removal of trapped charge Closing resistor	2.4 to 2.8 1.5 to 2.2
Fault-initiation Single-line-to-Ground Fault and Double-line-to-Ground Fault	1.5 to 1.7 1.5 to 2.0	N/A	
Fault-clearing	1.4 to 1.8	Opening Resistors	1.3 to 1.5
Phase-to-phase switching surges Energizing Reclosing	 3.0 to 4.0 4.0 to 5.0	Closing Resistors Closing Resistors	 2.0 to 3.8 2.0 to 3.8

TABLE IV

TYPICAL MAGNITUDES FOR OVERVOLTAGES (REF. [12], TABLE 9.3.12, P. 435)

Cause	Maximum per unit Overvoltage
Energize 320-km (200-mile) line, no closing resistors	3.5
Energize 320-km (200-mile) line with one-step closing resistor	2.1
Energize 320-km (200-mile) line with multistep closing resistor	1.5
Reclose on full trapped charge, 320-km (200-mile) line, one-step closing resistor	2.2
Fault initiation (unfaulted phase)	2.1
Fault initiation (adjacent circuit)	1.5
Fault clearing	1.7 to 1.9
Energize line and transformer (crest of envelope)	1.2 to 1.8
Energize capacitor bank	2.0
First restrike on capacitor bank	3.0
Line-to-ground fault (temporary overvoltage – well-grounded system)	1.3 to 1.4

Line-to-ground fault (temporary overvoltage – ungrounded system)	1.73 or greater
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Examples of transient mitigation are presented in both Tables III and IV; however, the tables do not relate these mitigated T values to line voltage. Studies show that T values decrease as line voltage increases. Reference [13] explains this relationship as follows:

As transmission-line voltages are increased, and switching surges play a more limiting role in line design, there are more economic incentives to reduce their maximum values using sophisticated surge control techniques.

This relationship is illustrated in Table V, which is reproduced from Table 3.2-2 on p. 3-14 in [13]. This relationship is reflected in both the IEEE Std. 516-2009 [1] and the new OSHA default T values.

In conclusion, transient overvoltages have been examined and well documented. The T values associated with energizing and reclosing result in much higher T values than that of fault clearing without reclosing and fault initiation.

TABLE V

PRACTICAL VALUES OF STATISTICAL MAXIMUM PHASE-TO-GROUND SWITCHING SURGE AMPLITUDES VERSUS SYSTEM VOLTAGE (REF. [13], TABLE 3.2-2, P. 3-14)

Max System Voltage (kV)	230	362	550	800	1200
Statistical Maximum (2%) (p.u.)	2.0 – 2.5	1.75 – 2.25	1.75 – 2.0	1.75 – 2.0	1.5 – 2.0

B. Comparison of IEEE Std. 516-2009 Default T values to New OSHA Default T Values

For a comparison between the default values in IEEE-Std. 516-2009 [1] and the new OSHA values [7] listed in Tables I and II, respectively, EPRI developed a number of test network models to investigate the impact of system parameters on transient overvoltages in [14]. These models represent generic transmission lines. EMTP-RV was used to calculate T values varying voltage level (345kV, 500kV, and 765kV), line length (from 25 to 300 miles), fault condition (initiation, clearance, type, location), tower construction, number of subconductors, usage of closing resistors, and operating conditions (line energization, reclosing, and capacitor switching).

The objective of the EPRI report, as stated in [14], was to investigate the critical parameters that influenced T for a given circuit, and determine the maximum T taking into account various scenarios that could possibly exist. The results of these studies were used to identify network conditions and characteristics where the default T values in [1] may be acceptable for calculating minimum approach distances. Additionally, the results of these studies were used to determine conditions where either site-specific studies should be performed or the new OSHA standard values should be used [7]. Based on [14], operational provisions had the dominant impact on the maximum transient voltages. The operational conditions having the most negative impact on the T values (i.e., conditions

resulting in high T) were circuit switching, reclosing, capacitor switching, and performing maintenance work during lightning. These conditions cause T values to exceed those listed in Table I.

The only circuit considered in [14] for which T values exceeded those in Table I was the 765 kV line over 200 miles under controlled operating conditions.

C. Consideration of Restrike

Unlike switching operations, reclosing, and prohibiting work during inclement weather, restrike cannot be ruled out operationally. It is well understood that restrike can result in very high T factors. As stated in [1], if restriking of the switching device is included, then the resulting overvoltages are essentially the same as those of reclosing into a trapped charge. The only difference is the probability of occurrence. Based on this understanding, if restrike is considered, the majority of cases will exceed the old and the new OSHA default values. If devices other than circuit breakers are utilized to protect or switch the line while live work is being performed restrike should be assumed to be very probable.

Assuming that, by design, a circuit breaker is capable of passing the required standardized tests, proper breaker application and maintenance will minimize the probability of restrike occurrence. Reference [14] concluded that it is impossible to determine a standard probability level related to restrike performance of a circuit breaker in-service. As such, restrike probability can only be minimized.

Based on the findings in [14], there are three primary factors affecting the probability of breaker restrike as follows:

- Breaker design,
- Breaker application, and
- Breaker maintenance.

Therefore, in order to neglect the probability of restrike, properly applied circuit breakers should be carefully inspected and maintained based on manufacturer's recommendations, industry standards, operational history, and testing history.

IV. CONCLUSIONS ON PRACTICAL APPROACHES TO CONTROL TRANSIENT OVERVOLTAGES

As shown in Table III and IV, the maximum transient overvoltage that can reach the work site is associated with switching operations on the line on which work is being performed. This statement is based on the recent EPRI report [14] and well-established T values provided in literature [8], [9], [10], [11] and [13].

If the automatic reclosing of circuit breakers is disabled for the duration of live work so that the line will not be reenergized after being opened for any reason and switching restrictions are established so that circuit breakers on lines on which live work is being performed are not permitted to be operated, then the maximum switching surge overvoltage is limited to the larger of the fault-clearing transient (1.4 to 1.9) or the greatest possible fault-initiation transient (1.5 to 2.1). The T values associated with fault clearing and fault initiation are much lower than those

associated with switching surges, and are in accordance with the default T values in Table I.

Therefore, if a utility plans to use the Table I default values without a detailed engineering analysis of T values and related conditions, it should implement all of the following requirements to facilitate safe live work:

- No live line work during lightning (minimizes lightning transient probability).
- Disable reclosing at all transmission voltages (eliminates closing into trapped charge).
- No line switching while live line work at MAD is being performed (eliminates switching surge probability).
- Capacitor switching disabled during line maintenance.
- Minimize probability of breaker restrike through proper selection and maintenance of circuit breakers.
- Avoid line work on 765-kV lines to 322 km (200 miles).

Overvoltages resulting from switching operations and lightning can be eliminated operationally. Overvoltages resulting from circuit breaker restrike can be minimized through proper circuit breaker selection and maintenance. As stated in [1], if restriking of the switching device is included, the resulting overvoltages are essentially the same as those of reclosing into a trapped charge. Proper selection and maintenance of circuit breakers should be a part of normal operating philosophy of every utility, whether or not live work is practiced.

V. SUMMARY

The new OSHA values address the entire range of system operating conditions. These values are pertinent unless you demonstrate through engineering analysis that T values can be reduced or you adhere to strict operational restrictions. Therefore, to use lower values of T (without a detailed engineering analysis of T values and related conditions), such as in IEEE Std. 516-2009, certain requirements and operating procedures must be adhered to during live work to ensure that safe MADs are in place. Circuit breakers must be carefully applied and maintained.

VI. ACKNOWLEDGMENTS

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