Switching Overvoltage Measurements and Simulations—Part I: Field Test Overvoltage Measurements

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***Abstract*—This paper presents the work carried out by the IEEE Working Grou[on field-measured overvoltages and their analysis for validating power system component models to be used in switching transients studies. The work uses measurement data obtained from field tests performed by Bonneville Power Administration in June 1995 where switching overvoltages were measured on one of its 230 kV lines. This paper includes a description of the switching tests and the main results derived from field measurements. Details of the switching procedures that were followed to calibrate component models used to match field-recorded waveforms can be found in the Part II paper.**

***Index Terms*—Power system switching transients, switching transients, transmission system.**

I. Introduction

SWITCHING transients in power systems are caused by the operation of breakers and switches [1]–[11]. The switching operations can be classified into two categories: 1) energization, including reclosing, and 2) de-energization. The former category includes energization of lines, cables, transformers, reactors, or capacitor banks. The latter category includes current interruption under faulted or unfaulted conditions.

The results from the study of switching transients are useful to 1) determine overvoltage stresses on equipment; 2) select arrester characteristics; 3) calculate the transient recovery voltage across circuit-breaker contacts; 4) analyze the effectiveness of transient mitigating devices (e.g., preinsertion impedance, controlled closing); and 5) determine overvoltage factors for live-line maintenance.

Manuscript received September 15, 2013; revised December 20, 2013; accepted January 25, 2014. Paper no. TPWRD-01059-2013.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2014.2303575

The level of detail required in the model varies with the study. In addition, the results are highly sensitive to the value of certain parameters (e.g., the point on the voltage wave with which the transient is initiated and the trapped charge on the phases). Therefore, a number of simulations using the same system have to be made with the time of energization modified in each simulation either in a predictable manner (i.e., for determining the peak overvoltage) or statistically (for obtaining an overvoltage probability distribution) [1]–[6]. Thus, model validation must be performed using specified parameters (e.g., point on wave in which the transient is initiated, etc.).

Field measurements are the preferred method of validation of models for switching transients. This is due to the range of frequencies associated with most switching transients and the fact that the initiation of the transient can be predefined; that is, there is no randomness involved in the origin of the transient events. However, field measurement data obtained with accurate measuring equipment are relatively rare. Some field measurement data have been presented to date for validation of computer models. Reference [12] presents some cases with a good agreement between simulation results obtained with an Electromagnetic Transients Program (EMTP)-type program and either field measurements or transient network analyzer (TNA) results.

This paper summarizes some of the work carried out by the IEEE Working Group on Field Measured Overvoltages and Their Analysis. A primary goal of the working group is to quantify the capability of transient programs to accurately predict switching overvoltages, particularly on transmission lines which do not utilize mitigation measures to control switching surge overvoltages (e.g., 230 kV class systems). Validating transmission-level power component models and simulation methods requires accurate measurements of actual switching transients. The model validation work takes advantage of the switching surge tests performed by Bonneville Power Administration (BPA) in June 1995 on the Big Eddy–Chemawa 230 kV line. BPA carried out extensive single- and three-phase switching tests on this line, with and without trapped charge, from which a significant amount of information was recorded [13].

This Part I paper provides a description of the BPA field test, including the purpose, procedures, and measurements, along with a summary of the main results. The Part II paper details simulation work carried out to validate the models applied in this study.

II. Test Line and Instrumentation

A. Test Line

The Big Eddy–Chemawa 230 kV line is a typical, long, high-voltage (HV) line without switching surge overvoltage control, such as surge arresters, breakers with closing resistors or controlled closing. It is 187 km (116.4 mi) long and uses a single conductor per phase. Approximately one-third of the line is double-circuit construction and two thirds is single-circuit construction. Details of the line configuration and surrounding 230 kV system can be found in the Part II paper. There are no surge arresters on this line—only station entrance rod gaps at each end, which will spark over for overvoltages and create a fault. There are also no transformers or magnetic voltage transformers to drain away trapped charge.

The line is switched with two SF_6 circuit breakers of different manufacturers using single mechanisms and no closing resistors. When a fault occurs on the line, the breakers will trip and then high-speed reclose after an open time of approximately 500 ms (30 cycles). The high-speed reclose can result in substantial overvoltages on this line because of 1) the trapped charge on the unfaulted phases; 2) the near simultaneous closing of the three circuit-breaker poles; and 3) no overvoltage mitigation equipment.

At one end of the line is the Big Eddy 230 kV bus, a very strong source with a maximum three-phase short circuit current of 46 kA (at the time the measurements were taken) and numerous connected lines and equipment. In contrast, the Chemawa end of the line is a relatively weak source, with few lines and about 12 kA (at the time the measurements were taken) of short circuit current availability.

B. Background

Rod gaps are installed at the ends of a transmission line to protect substation equipment by sparking over during lightning-caused overvoltages. These rod gaps are expected to rarely operate during line switching, except under worst-case conditions. In November 1994, a rod gap sparkover occurred on the Big Eddy–Chemawa 230 kV line at the Big Eddy end during a high-speed reclose of the Chemawa breaker following a fault. The sparkover was unexpected and led to some minor equipment damage [13]. The main concern about the Big Eddy–Chemawa rod gap sparkover was that reclosing overvoltages, particularly with SF_6 breakers, might be higher than expected. As part of the investigation into this event, a field test was performed to measure overvoltage levels that can occur on long transmission lines during high-speed reclosing. The findings could affect transmission line and substation maintenance at BPA, such as clearance practices and minimum approach distances.

C. Instrumentation

Fig. 1 provides a simplified one-line diagram of the line and test instrumentation used to conduct the field test.

1) Line Voltages: The most critical results of the field test were the line voltage measurements. Typical power system voltage measuring devices, such as CVTs and MVTs, do not provide the high-frequency or dc response needed to accurately measure reclosing voltages or properly verify transient simulations. On each phase at each end of the line, BPA installed special R-C-R voltage dividers with a flat frequency response from dc to 1 MHz.

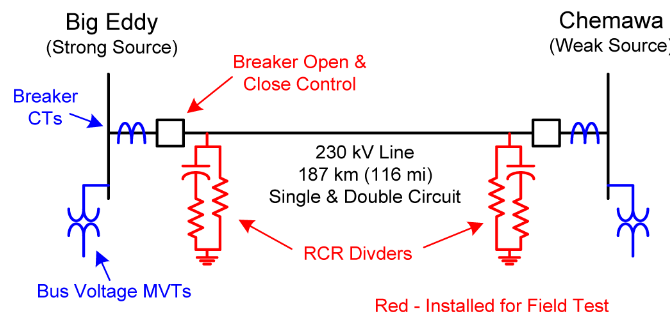

Fig. 1. One-line diagram of the test line and measurements of line voltages, bus voltages, and line currents.

2) Bus Voltages and Line Currents: For the bus voltage at each end of the line, the substation bus MVTs were used, since the transients associated with the bus voltages would not be substantial. The line currents were obtained by using the line-side circuit-breaker bushing current transformers (CTs). Thus, some reduced frequency response was introduced into the bus voltage and line current measurements through the use of standard high-voltage devices.

3) Data Acquisition: BPA recorded the data from each test in digital format with a 1 MHz sampling rate using fiber-optic data links to the voltage and current sensors.

III. Field Test Measurements

A. Line Switching Tests

The field tests carried out by BPA in 1995 included transformer switching and line switching. The line switching tests, which are discussed in this paper, can be classified into two groups as described below [13].

1) Single-Phase Line Switching: Single-phase energization of the line eliminates the additional transients and coupling that occur when other phases are energized. This provides a means of separating the direct transients from the coupled transients and reduces the number of variables when comparing measured and simulated waveforms. The main purpose of these tests was to acquire switching surge waveforms for validation of transient models used in line switching simulations. To perform the tests, a disconnect switch was blocked open on two phases and the circuit breaker was operated normally. These tests were performed by energizing the line from each end with and without trapped charge. To create the trapped charge, the breaker that was initially energizing the line was opened and reclosed in 500 ms (30 cycles).

2) Three-Phase Line Switching: The highest switching overvoltages occur while reclosing into a line with trapped charge. The three-phase switching tests were performed from each end of the line. Three-phase trip and reclose tests were performed since they approximate high-speed reclosing of a faulted line. The tests were performed to acquire waveforms for validation of transient models and to provide statistical data on actual overvoltages that could be expected during a high-speed reclosing

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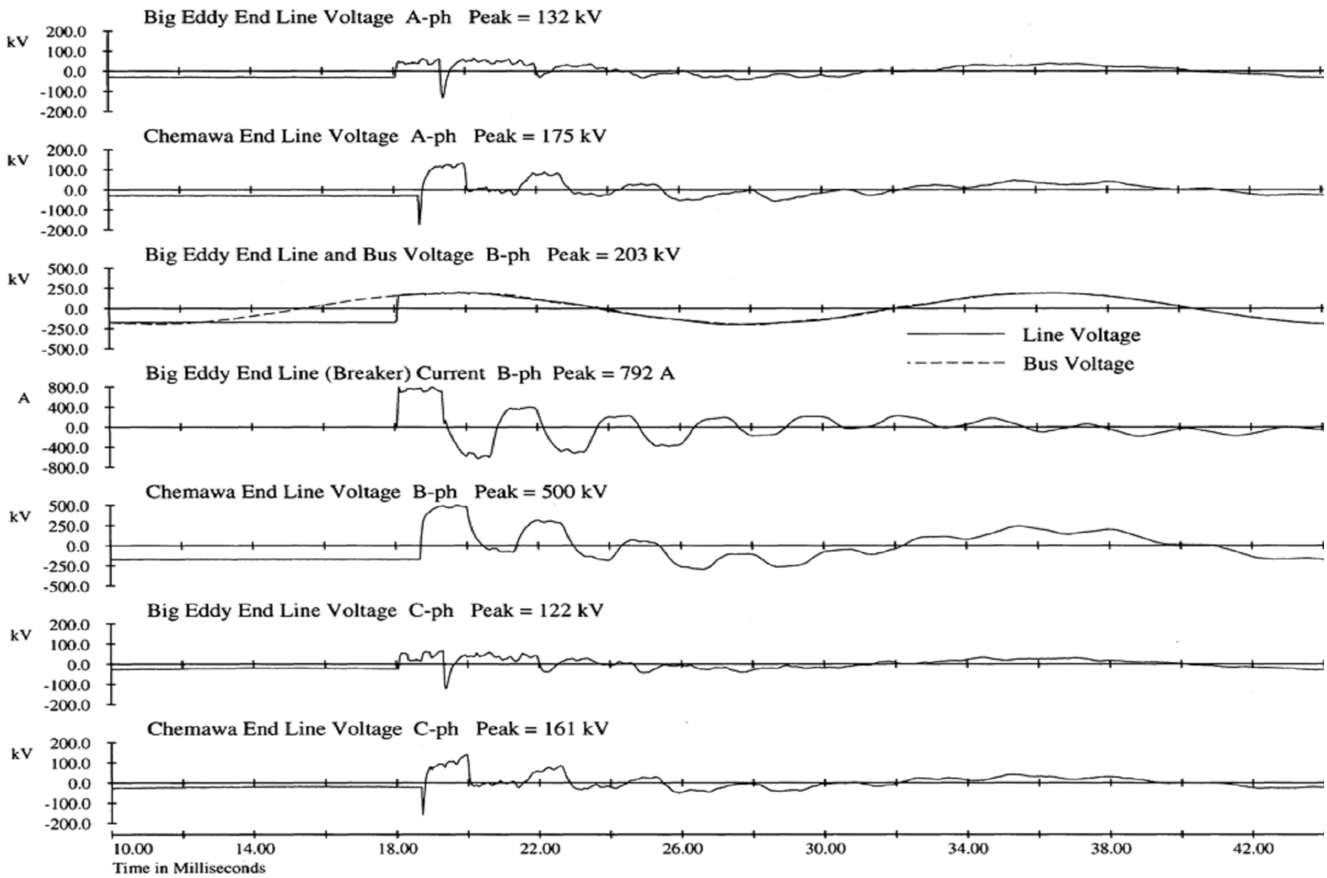

Fig. 2. Single-phase switching test from Big Eddy with trapped charge (Test 1–04).

event. Energizing the line from Big Eddy provided information about line switching from a strong source, while energizing from Chemawa provided information about line switching from a relatively weak source. A 60 Mvar, 230 kV shunt capacitor bank was in service at the Chemawa bus during the switching from the Chemawa end.

For each test, the circuit breaker initially energizing the line was opened for 500 ms (30 cycles) and then reclosed 3-phase. The opening was controlled to leave the same trapped charge on the line for each test. During the field test, the average time constant of trapped charge decay was measured and found to be approximately 1 min. The trapped charge voltage thus decreased about 1% during the 500 ms open time. This decay time constant for trapped charge is consistent with other BPA field test measurements made on other lines with these voltage dividers. The 3-phase reclosing test was repeated 20 times from each end, with the closing signal incremented by 18 electrical degrees for each test. Incrementing the electrical angle in this way provided a uniform distribution across a 60 Hz cycle. About five additional tests were performed from each end with the breaker timing focused around the closing times that generated the highest overvoltages.

B. Trapped Charge and Overvoltages

Fig. 2 shows a 40 ms window from a single-phase switching test with trapped charge. In this test, the Big Eddy breaker was tripped and reclosed in about 500 ms. Phases A and C of the line disconnect had been blocked open so only B-ph of the line was directly energized. The trapped charge voltage on B-ph of -176 kV is shown on the left side of the waveforms prior to the breaker close. The A and C phase voltage waveforms show a partial trapped charge (approximately 32 kV each) that had been induced from B-ph. The step voltage applied to B-ph was 341 kV (bus line) and the resulting overvoltage measured at Chemawa was 500 kV. The traveling waves on B-ph, interacting between the line and the system at Big Eddy, took approximately two cycles to dampen out. The waveforms show the relatively complicated voltages induced on A and C phases compared to the relatively simple waves on B phase.

Approximately 25 switching tests were performed from each line end, involving a three-phase reclose into a trapped charge. Nearly all tests conducted from a particular end of the line had the same trapped charge, within a few kilovolts. Table I provides a summary of the average trapped charge voltages and the highest overvoltages measured on each phase during the three-phase switching tests. The trapped charges were approximately 1.2 p.u. on the highest phase and 0.9 to 1.0 p.u. on the other two phases. The highest overvoltages ranged from 2.9 to 3.3 p.u.

While switching from Big Eddy (a relatively strong source), C-phase had the highest maximum and average overvoltages, even though A-phase had the highest level of trapped charge (see Table I). While switching from Chemawa (a relatively weak source), A-phase had the highest level of trapped charge

TABLE I
(a) Average Trapped Charge on Line. (b) Highest Measured Overvoltages

Switching End	A-ph	B-ph	C-ph
Big Eddy	-233.7 kV (1.18 pu)	-177.6 kV (0.90 pu)	179.4 kV (0.91 pu)
Chemawa	221.3 kV (1.18 pu)	185.5 kV (0.99 pu)	-182.3 kV (0.97 pu)

(a)

Switching End	A-ph	B-ph	C-ph
Big Eddy	567.0 kV (2.87 pu)	621.0 kV (3.14 pu)	-651.0 kV (3.30 pu)
Chemawa	587.0 kV (3.13 pu)	-569.8 kV (3.04 pu)	570.1 kV (3.04 pu)

(b)

Note: The value of 1.0 pu is referenced to the bus voltage at the switching location prior to reclosing.

Switching from Big Eddy: 1.0 pu = 197.6 kV pk (242 kV rms L-L)
Switching from Chemawa: 1.0 pu = 187.4 kV pk (229.5 kV rms L-L)

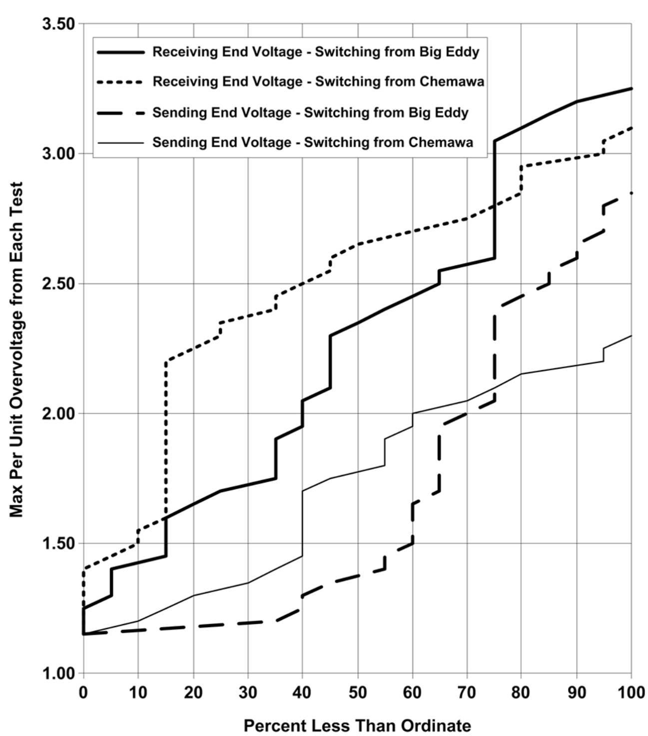

Fig. 3. Distribution of maximum overvoltages measured during the test for both receiving and sending ends.

and the highest maximum and average overvoltages. Switching from either end produced overvoltages exceeding 3.0 p.u., with the highest at 3.30 p.u. The upper 25% of overvoltages measured when switching from Big Eddy were higher than those when switching from Chemawa. This was expected since a stronger source, with more connected lines (and lower source surge impedance) will produce a larger voltage step onto a switched line. However, in the range of 15%–75% of overvoltages, this did not hold true and the levels were larger when switching from the Chemawa end, indicating additional variables at work.

Along with the receiving-end overvoltages, the sending end of the line also experienced overvoltages which were higher than expected. These occurred because of induced voltages from transients on other phases and because of the breakers having multiple prestrikes, which are discussed later. Fig. 3 provides a distribution of the maximum measured overvoltages for the sending and receiving ends of the line. This plot uses only the 20 reclosing tests from each end that were timed to be equally spaced across a cycle. Note from the graph that 25% of the tests when switching from Big Eddy are 3.0 p.u. or greater and 20% are above this level when switching from Chemawa. Chemawa switching also produced larger percentages of overvoltages in the range of 1.5 to 2.8 p.u.. Thus, overvoltage levels were similar despite the significant differences in the short circuit strength and complexity of the two buses. While switching from Big Eddy, the sending-end voltages above 2.0 p.u. (approximately 70th percentile and above) were substantially higher than when switching from Chemawa.

Three rod gap sparkovers occurred at the Chemawa end during the tests while reclosing the line from Big Eddy. One sparkover occurred on B phase with a voltage prior to the sparkover of 560 kV (2.83 p.u.). Rod gap sparkovers occurred on two phases in another test, where the voltage at which the gap flashed was 542 kV (2.74 p.u.) on A phase and 532 kV (2.69 p.u.) on B phase. Although significantly higher overvoltages were measured on these phases during other tests, the gaps did not spark over, which demonstrates the effects of surge polarity and the statistical nature of gap sparkover phenomena.

Fig. 4 shows the waveforms for all voltages and currents measured during one of the three-phase reclosing tests from Chemawa. This plot shows how the transients involved with the reclose operation dampen out in about one cycle. The sending-end line voltage and bus voltage are overlaid for each phase. The trapped charge can be seen as the constant dc level of the line voltage at the left side of the waveforms. The first breaker prestrike occurred on A-ph where the line trapped charge and the bus voltage were opposite polarity. The many complications and waveform distortions on each trace are from traveling-wave reflections, induced voltages from other phases, and multiple breaker prestrikes. The travel time that a switching surge takes to travel the length of the line can be seen to be about 0.6 ms. The "round trip" travel time for a current pulse to return to the sending end is about 1.26 ms. In this test, the A-ph voltage at the Big Eddy (receiving) end reached about 3.0 p.u. (−564 kV).

C. Multiple Prestrikes

The measurements taken during the three-phase reclosing tests revealed an unexpected phenomenon—that breaker closing operations into trapped charge can result in multiple prestrikes [6], [14], [15]. The majority of breaker closings resulted in only a single prestrike; however, in a few tests, up to four prestrikes occurred on one phase during a single closing operation. During breaker prestrike, a current wave (initiated by arcing across contacts) travels down the line to the receiving (open) end where it is reflected. As the reflected wave travels

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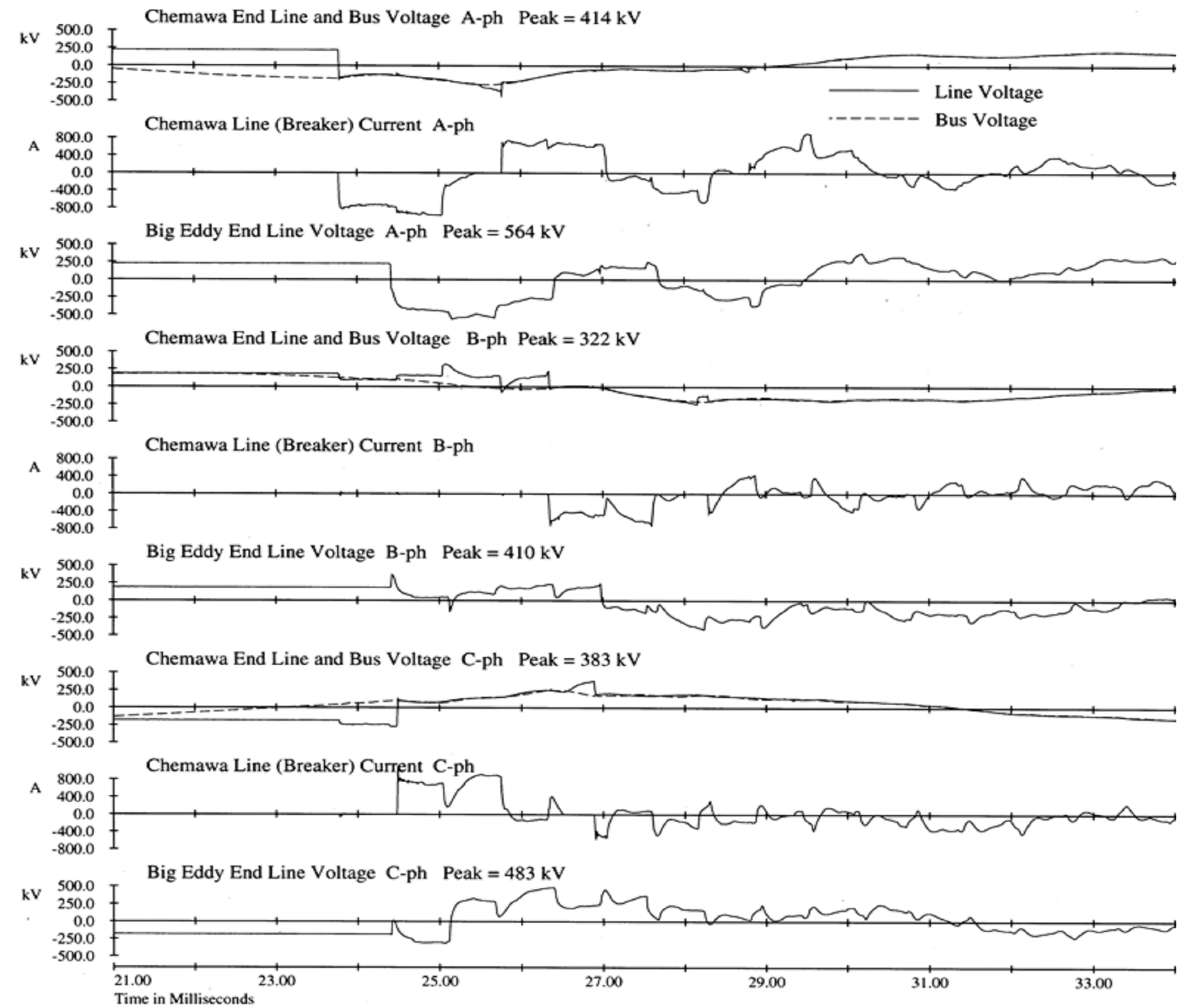


Fig. 4. Three-phase high-speed reclose test while switching from the Chemawa end of the line (Test 5–71).

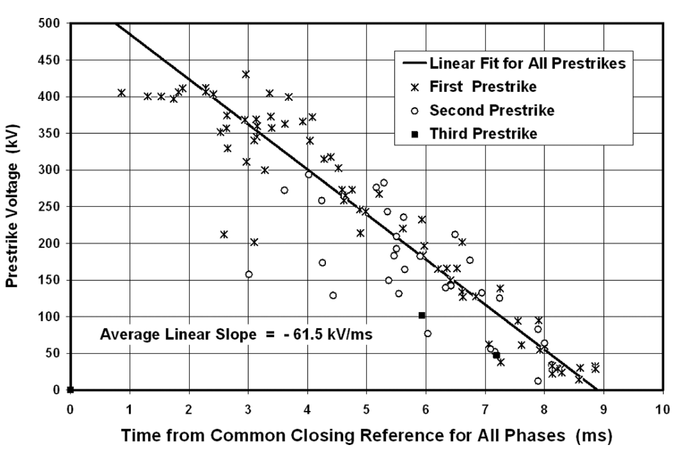


Fig. 5. Chemawa breaker prestrike data for all phases.

back toward the sending end of the line, it reduces the current to near zero along the line. When the reflected current wave reaches the sending end, it creates a current zero and allows the prestrike arc between the breaker contacts to extinguish, isolating the line voltage from the bus voltage. The line voltage may then increase due to travelling waves that continue to be reflected from the receiving end and induced voltages. The voltage across the breaker then builds up until another prestrike occurs. The next prestrike occurs at a lower breaker cross voltage because the breaker contacts are then closer.

The multiple prestrike phenomenon can be seen on each phase in Fig. 4, where the overlaid line and bus voltages deviate from each other after the breaker current has been established. At these points, the breaker current remains at zero until another prestrike occurs. As shown in Fig. 4, the multiple prestrikes add even more transients and distortion to already complicated waveforms.

The recorded waveforms of voltages and currents were analyzed and prestrike data were tabulated; namely, the voltage

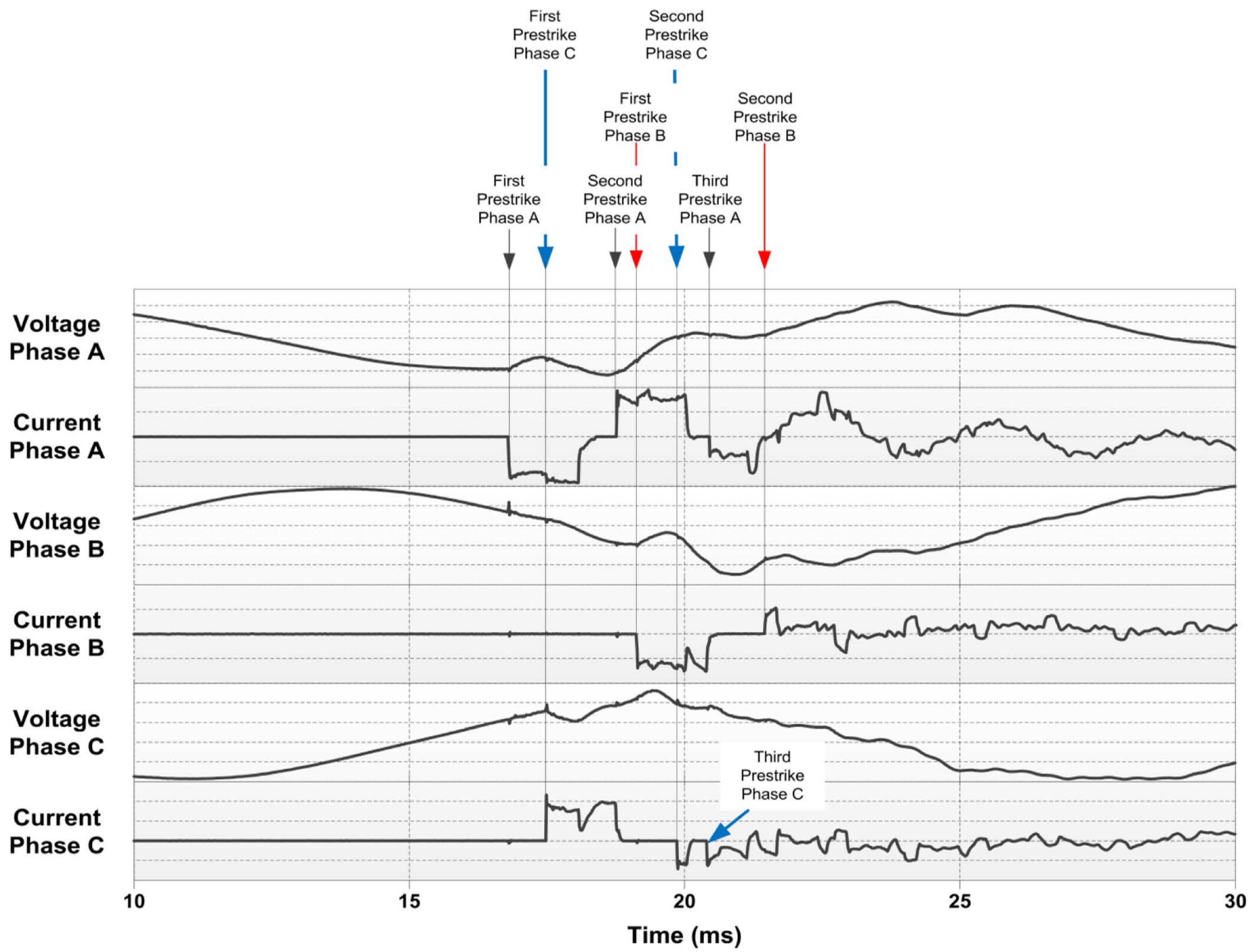


Fig. 6. Identification of prestrikes on the Chemawa breaker during a three-phase reclosing operation.

TABLE II
BREAKER DIELECTRIC SLOPES DURING CLOSING OPERATIONS

Substation	Dielectric Slope (kV/ms)			
	A-phase	B-phase	C-phase	Average
Big Eddy	-54.7	-54.0	-49.4	-52.7
Chemawa	-59.7	-63.6	-61.1	-61.5

as well as the time the prestrike occurred (relative to the initial closing time). From the tabulated data, the prestrike voltages versus relative prestrike times were plotted. As an example, Fig. 5 shows the plot of the Chemawa breaker prestrike data for all phases derived from reclosing operations [13]. Linear regression was used to determine the approximate voltage versus time characteristic for each phase of both breakers. Table II lists the slopes derived from that analysis.

The Big Eddy breaker was independent pole construction (i.e., constructed with each phase in its own tank), and the maximum closing time difference between the phases (or pole span) was approximately 3.7 ms. This pole span was determined by taking the difference in time that the prestrike characteristic of each phase crosses zero voltage (i.e., the point where the breaker contacts are connected metal to metal). The Chemawa breaker was constructed with all three phases in a single tank, and the maximum pole span was 0.24 ms, which would indicate that all three phases close nearly simultaneously [13]. For both breakers, the time differences of the prestrikes among the phases vary considerably, however, because of the differences in breaker cross voltage during closing, particularly with trapped charge.

Fig. 6 identifies the many prestrikes that occurred on the Chemawa breaker during the reclose test of Fig. 4. Note that the number of prestrikes for this test is different for each phase and results in up to three on A phase [13].

IV. Modeling Data for Tested 230 kV Line

The Big Eddy–Chemawa line can be divided into four main sections with about 1/3 of the line as a double circuit and the remainder as single circuit. Fig. 7 provides the basic line conductor and configuration data necessary for line modeling. Fig. 8 provides the parameters for simplified partial source equivalents for each line end.

V. Laboratory Tests of Line Entrance Gaps

As part of the investigation into the original rod gap flashover, switching surge and corona onset tests were performed at the

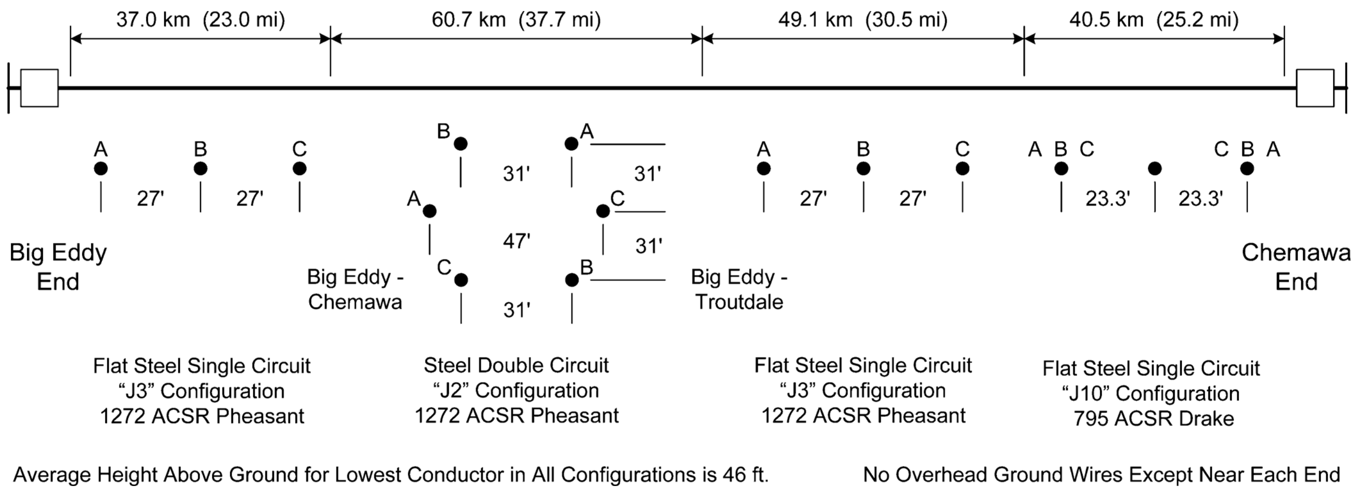
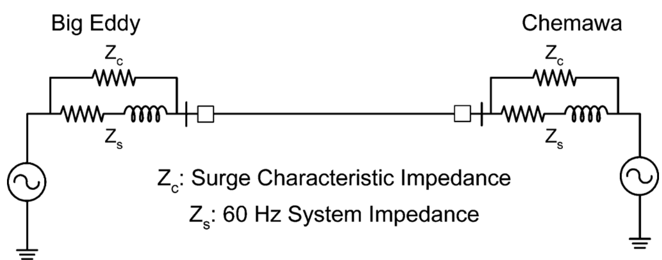


Fig. 7. Conductor cross sections for Big Eddy–Chemawa line.



Parameter	Big Eddy	Chemawa
Z_s (ohms)	$Z_1 = 0.12 + j3.1$ $Z_0 = 0.06 + j2.0$	$Z_1 = 1.6 + j12.6$ $Z_0 = 1.3 + j16.0$
Z_c (ohms)	$Z_1 = 64$ $Z_0 = 122$ (6 lines)	$Z_1 = 192$ $Z_0 = 367$ (2 lines)

Fig. 8. Equivalent source parameters for each line end.

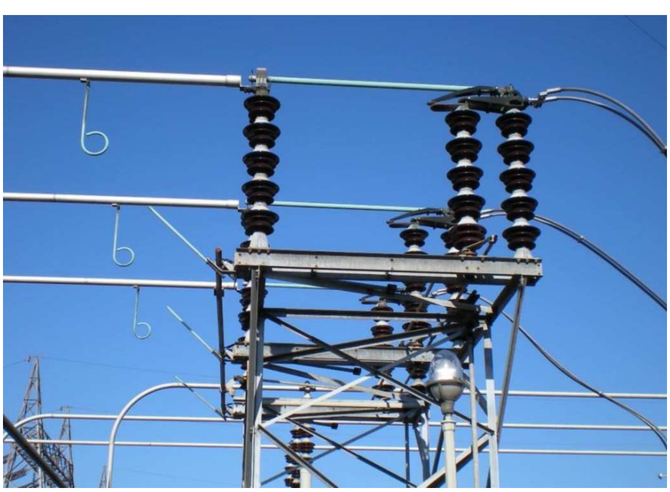


Fig. 9. BPA 230-kV line entrance gaps.

BPA Laboratories on a standard BPA 230 kV transmission line entrance gaps. The tested rod gap was similar to those on the Big Eddy–Chemawa line and set to the BPA standard 101.6 cm (40 in). Fig. 9 provides a photo of typical BPA 230 kV "shepherd's hook" rod gaps.

TABLE III
LINE ENTRANCE GAP SWITCHING IMPULSE TEST RESULTS VOLTAGES IN PU WHERE 1 p.u. = 197 kV PK [16]

Switching Surge Voltage Polarity	**Positive**	**Negative**
Measured 50% Flashover Range	3.3-3.6	3.3-3.6
Average 50% Flashover	3.4	3.4
Lowest Flashover Measured	2.9	3.1
Lowest Flashover (Corrected*)	3.1	3.2
Highest Flashover Measured	3.9	3.4
Highest Flashover (Corrected*)	3.9	3.5
Calculated 100% Withstand	2.9	3.2
Calculated 100% Flashover	4.0	3.6
Measured Standard Deviation (%)	5.6	2.0

* Corrected to standard atmospheric conditions.

Table III provides the results of the switching surge portion of the testing, including both measured flashover voltages and also values corrected to standard atmospheric conditions. Other weather conditions could lower or raise these numbers. As Table III shows, flashover voltages varied more for positive polarity surges than for negative. The rod gap critical flashover voltage was found to increase with higher relative humidity but not be sensitive to the waveform time-to-crest, which was varied between 100 and 1000 μ.

Notice that the minimum flashover voltage in per unit is 3.1 for positive and 3.2 for negative polarity overvoltages, and that these values were exceeded during field tests (Table I).

VI. SUMMARY AND CONCLUSION

A series of single-phase and three-phase line switching tests were performed on a 116-mi, 230 kV line. These tests were conducted to both obtain switching surge data for transient simulation model validation and to measure the approximate magnitudes of overvoltages that result from high-speed, three-phase reclosing with a trapped charge on the line. The complexity and short circuit strength of the sources at each end of the line varied considerably, which offered a unique opportunity to evaluate the effects that such complexities have on the resulting switching transients. The circuit breakers at each end of the line were also different in their electrical characteristics during closing.

The critical line voltage measurements for this test included high-quality voltage dividers to provide accurate readings and a 1 MHz sampling rate to provide good frequency response allowing for direct comparison with simulation results. The bus voltage and line current measurements used existing substation MVTs and CTs, which did not provide quite as good of frequency response but was adequate for the application.

The high-speed, three-phase reclosure tests were performed by tripping a breaker that was charging the line and reclosing it 500 ms later into the trapped charge, similar to a high-speed reclose after a fault. The trapped charge levels were approximately 1.2 p.u. on the highest phase and slightly less than 1.0 p.u. on the other phases. For each test the breaker was controlled to trip at the same electrical angle, leaving approximately the same trapped charge for each test. The breaker was also controlled to receive a close signal at times that were uniformly spaced across a 60 Hz cycle.

About 25 three-phase reclosing tests were performed from each line end. At each line end approximately 20% of the tests resulted in an overvoltage of 3 p.u. or greater. The maximum overvoltage measured was 3.3 p.u. while switching from the strong source end. The tests confirmed that overvoltages at the receiving end of a line reach magnitudes that can result in rod-gap sparkovers, which actually occurred on two of the tests.

The tests also captured the interesting phenomena of multiple prestrikes by a breaker closing into a trapped charge. This is caused by the prestrike arc extinguishing, and results in the voltage at the sending end of a line reaching values that are higher than were previously expected. Multiple prestrikes also add additional complexity to the switching surge waveforms.

The subject line switching tests provided measurements that can be used to accurately model transmission system components for use in transient simulations when analyzing switching surges, and data that can be used for modeling breaker prestrikes. Typical characteristics of the dielectric strength across the breaker contacts, together with multiple prestrike models can now also be developed and used for statistical switching surge studies. Improved modeling techniques based on the measurement data provided herein is the subject of Part II of this paper.

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