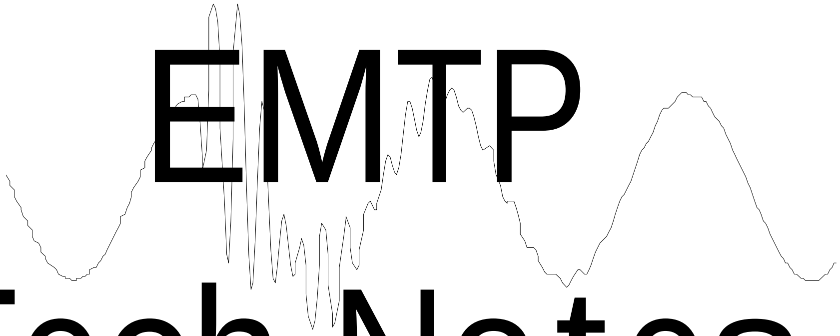

EMTP Tech Notes

for users of the Electromagnetic Transients Program

Issue # 94-1 **February 1994** **Editor: Thomas Grebe**

in this issue:

Letter from the Editor:

EMTP Tech Notes is the technical newsletter provided to members of the EMTP User's Group. The newsletter is a quarterly technical publication highlighting contributions from members of the User's Group. This newsletter is published using Microsoft Word for Windows 6.0. If you wish to contribute an article, please contact me (or Susie Brockman @ x41) for appropriate text and figure formats. Contributions in the following areas are welcome:

Technical articles
Modifications / enhancements to the code
Case studies / unique simulations
Research projects
EMTP data preparation / model development
Modules developed for distribution on the BBS
Letters to the editor / User's Group
Technical paper abstracts
Questions for members of the User's Group

I believe that the exchange of technical information is one of the most important functions of the EMTP User's Group and this newsletter, in conjunction with *Transients*, will help to serve the needs of the members. Thanks to the authors for helping to put this issue together. As always, I'm open for suggestions regarding this publication and the User's Group in general.

Thanks for your support

For more information concerning the newsletter or to submit a contribution please contact:

Thomas Grebe or Susie Brockman
EMTP User's Group
Electrotek Concepts, Inc.
10305 Dutchtown Road, Suite 103
Knoxville, Tennessee 37932
Phone: (615) 675-1500 x33
FAX: (615) 966-5497

Transformer Modeling

Transformer Winding Behavior Under Transient Conditions - EMTP Use at the University of Pittsburgh

At the University of Pittsburgh, Department of Electrical Engineering, the EMTP has been incorporated into a graduate level two-course sequence on electrical transients in power systems. The courses are based on the text of the same title by Allan Greenwood [1]. Grades are determined by a set of ten take-home assignments in each course which require the use of computer simulations to obtain solutions. The students may use either the EMTP or SPICE [2] to perform the transient studies.

An example of an assignment using the EMTP is the analysis of transformer winding behavior under steep-rise transient voltage stress. The winding is first modeled as a capacitance network, assuming no current penetatration into the winding inductances during the initial portion of the steep voltage rise. The capacitance network is shown in Figure 1. Hand calculations for the voltage at the front of the winding (the voltage across the first capacitor VC1) for an applied step voltage of 1.0 per unit are performed, and then verified by an EMTP simulation using a step voltage of 100 kV for Vapplied.

Figure 1 - Transformer Winding Lumped-C Equivalent

For the lumped-C equivalent network in Figure 1, capacitance values of CS = 1 C and CG = 5 C were chosen, and the voltage at any node along the winding in terms of Vapplied can be obtained. An equivalent of the lumped-C network at Bus B yields the following:

CEQ-F = 1 C + 5 C = 6 C
CEQ-E = (6 C // 1 C) + 5 C = (0.8571 + 5) C = 5.8571 C
CEQ-D = (CEQ-E // 1 C) + 5 C = (0.8542 + 5) C = 5.8542 C
CEQ-C = (CEQ-D // 1 C) + 5 C = (0.8541 + 5) C = 5.8541 C
CEQ-B = (CEQ-C // 1 C) + 5 C = (0.8541 + 5) C = 5.8541 C

This results in the equivalent circuit shown in Figure 2 for the front of the winding.

Figure 2 - Front of Winding Equivalent Circuit

Analyzing this circuit using LaPlace Transforms yields:

VC1(s) = Vapplied(s) [(1/1s C) / (1/1s C + 1/s(5.8541) C)]

= [1 C / 1.17082 C] Vapplied(s)

VC1(s) = 0.8541 Vapplied(s) or 85.41 % of the applied voltage

To verify this result, an EMTP simulation of the transformer winding lumped-C equivalent network was developed. The applied voltage was represented by a step voltage of 100 kV, and CS = 0.1 uF, CG = 0.5 uF from Figure 1. Also, the voltage is applied through a 450 ohm resistor to provide some circuit damping and shunt resistances of 100 megaohms were place across all of the capacitors, as shown in the EMTP Input Data File 1. The simulation result for the voltage VC1 across the capacitor at the front of the winding is shown in Figure 3 and is 85.41 kV or 85.41 % of Vapplied, as previously calculated.

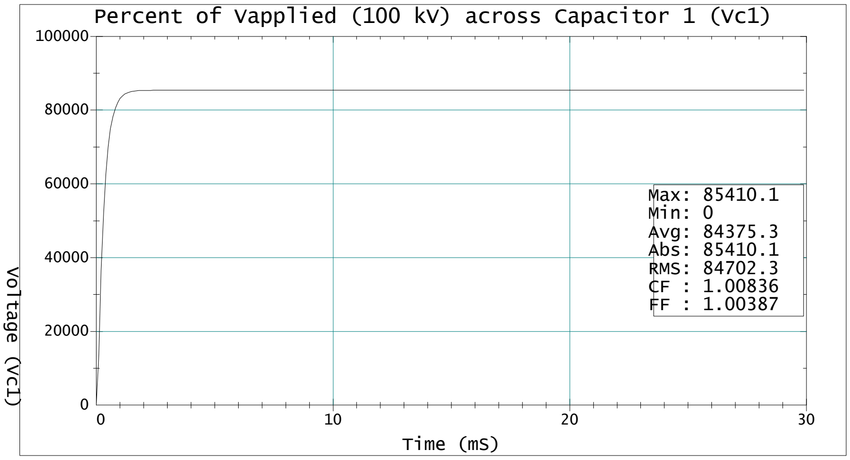

Figure 3 - Voltage Across Capacitor 1

With no current penetration into the winding inductance, it is possible to represent the winding as a lumped capacitance network and perform hand calculations to solve for network voltages and then verify the results with an EMTP simulation. When current penetration into the winding inductance is included, hand calculations can be very difficult to perform. The advantage of using the EMTP is then appreciated because voltages can be solved for as a function of time. Practically, the input voltage wave is not a pure step function, but has a very fast slope, and current penetration into the transformer winding inductance occurs.

To show the effects of including the winding inductance, the transformer winding was then represented with an inductance-capacitance (L-C) equivalent network, as shown in Figure 4.

Figure 4 - Transformer Winding L-C Equivalent

For this part of the analysis, the transformer winding was represented with 10 pi sections. An EMTP model was developed to determine the response of a step voltage of 1,000 kV applied to the front of the winding. Specifically, the voltage at each node along the winding is of interest. A transformer impedance value of X = 0.07 per unit on a 2,000 MVA, 362 kV base and a winding surge impedance of Z0 = 500 ohms were used to determine the pi section series inductance and capacitance, and the shunt capacitance values of the network. The winding parameters for the EMTP input data file are as follows:

ZBASE = (362)2 / (2000) = 65.522 ohms

XTOTAL = (0.07 p.u.) (65.522) = 4.58654 ohms

LTOTAL = (4.58654 ohms) / 377 = 12.17 mhenries

LPI-SECT = (12.17 mhenries) / 10 = 1.217 mhenries

Now: Z0 = [L / CG]1/2 CG = L / [Z0]2

CG = 1.217 x 10-3 / (500)2

CG = 4.87 x 10-3 uF and CG / 2 = 2.44 x 10-3 uF

And, using a ratio of CS = (1 / 10) CG :

CS = 0.487 x 10-3 uF

As shown in the EMTP Input Data File 2, a shunt resistance of 0.1 megaohms across each of the series L-C sections and each grounded capacitance section was used to provide some circuit damping and to eliminate numerical oscillations.

A step voltage of 1,000 kV was applied to the front of the winding of Figure 4, and the resultant voltages at each node were obtained from the EMTP simulation. Figure 5 shows the voltage at the front of the winding (Node 2), at the middle of the winding (Node 6), and at the end of the winding (Node 10).

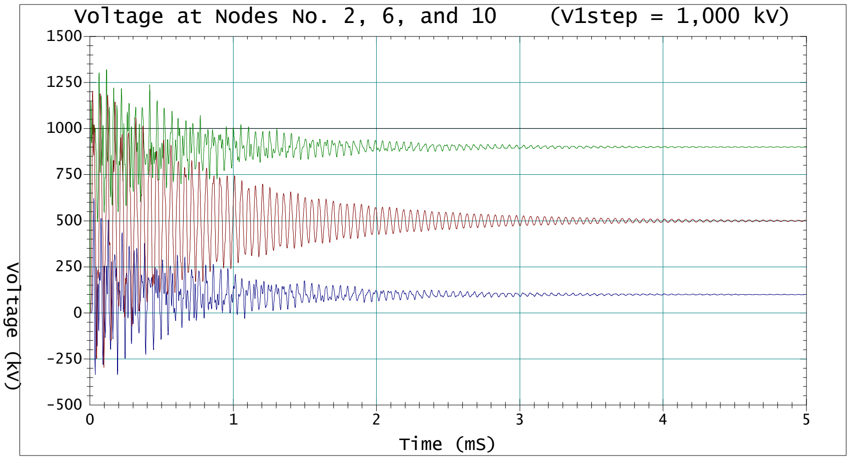

Figure 5 - Transformer Winding Voltage Distributuion

Figure 6 shows the voltage response over the first 250 microseconds for the L-C equivalent winding representation at Nodes 2, 6, and 10. Figure 7 shows this same response for all of the Nodes 1 through 11.

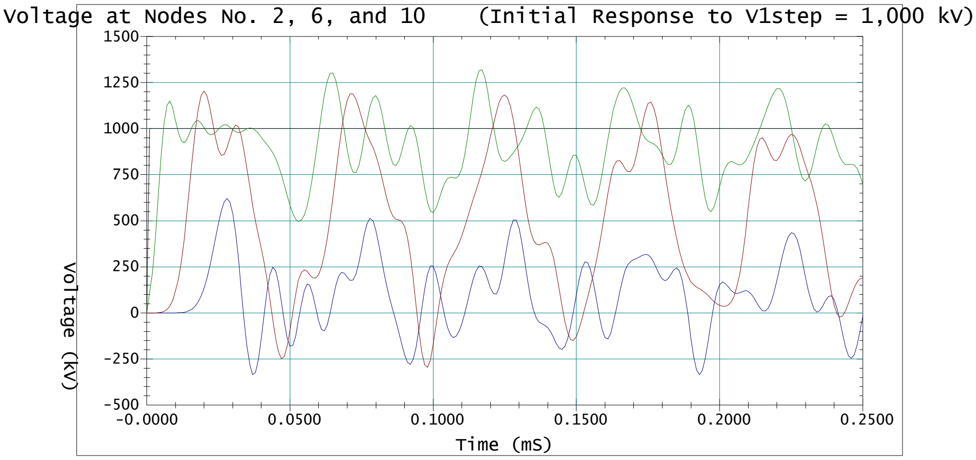

Figure 6 - Initial Winding Voltage Distribution

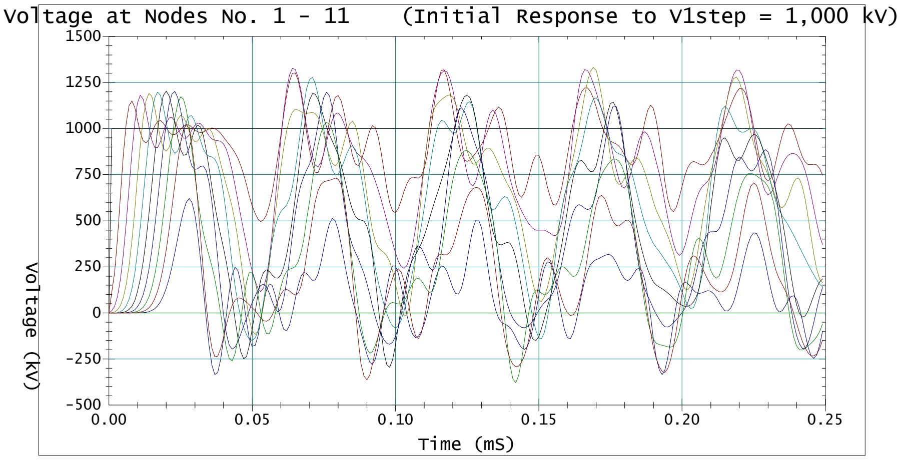

Figure 7 - Initial Winding Distribution (Nodes 1 - 11)

Figures 6 and 7 show how the initial distribution of the winding surge becomes a complicated system of oscillations within the winding, making hand calculations very difficult. Figure 5 shows how these oscillations settle at final steady-state values. The initial voltage at each node swings as high above the final steady-state value as below, as can be seen in Figure 5. The final steady-state value at Node 2 is 899.81 kV or 89.98 % of the applied step voltage. Note that the percentage of the applied voltage decreases along the length of the winding, as expected. The voltage at Node 6 is 501.21 kV or 50.12 % of Vapplied, and the voltage at Node 10 is 106.92 kV or 10.69 % of Vapplied. The transformer winding L-C equivalent network behaves much like a transmission line to an applied voltage with a short at the end of the line. This is what would be expected since the winding was modeled with pi sections, as is often done in transmission line modeling.

The use of the EMTP in the graduate courses introduces the student to circuit simulation techniques and, at the same time, adds a sense of realism to the problem assignments. If the circuit can be modeled, it can usually be solved. The answers contribute to the students' understanding of the problem since a significant degree of simulation complexity can be required, and the times and magnitudes are indicative of real life situations. Modeling constraints are easily factored into the simulations by stressing the physical restrictions imposed by switching operations and making sure the simulations do not violate physical principles. The EMTP is an excellent tool for teaching electrical transients in power systems.

EMTP Input Data File 1 - Lumped-C Equivalent Network

```
C ******************************************************************************
C *                                                                            *
C *                                                                            *
C *             EE-3778 -  ELECTRICAL POWER SYSTEM TRANSIENTS II               *
C *                                                                            *
C *              Transformer Winding Capacitance Representation                *
C *                                                                            *
C *                                                                            *
C ******************************************************************************
C
BEGIN NEW DATA CASE
C
C ****************** Miscellaneous Data ****************************************
C
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
C
  10.E-5  30.E-3
C
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
C
    1000       1       1       1       1       1       1       2       0       0
C
C ********************** Circuit Data ******************************************
C
C Branch data
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
C
  BUSS  BUSA                450.
C
  BUSA                                   .50
C
  BUSA  BUSB                             .10                                   2
C
  BUSA  BUSB               10.E9
C
  BUSB                                   .50
C
  BUSB  BUSC                             .10
C
  BUSB  BUSC               10.E9
C
  BUSC                                   .50
C
  BUSC  BUSD                             .10
C
  BUSC  BUSD               10.E9
C
  BUSD                                   .50
C
```

```
  BUSD  BUSE                             .10
C
  BUSD  BUSE               10.E9
C
  BUSE                                   .50
C
  BUSE  BUSF                             .10
C
  BUSE  BUSF               10.E9
C
  BUSF                                   .50
C
  BUSF  BUSG                             .10
C
  BUSF  BUSG               10.E9
C
BLANK Card Ending Branch Data Component
C
C ****************** Switch to Simulate Circuit Breaker ************************
C
C *** Switch for Ground Simulation ***
C
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
C
  BUSG              -1.0       3.0
C
BLANK Card Ending Switch Data Component
C
C **************************** Source Data *************************************
C
C      V Step Input = 100 kV
C
C ------------------------------------------------------------------------------
C
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
C
11BUSS   1   100000.
C
BLANK Card Ending Source Data Component
C
C ******************Output Specifications***************************************
C
  BUSS
  BUSA
  BUSB
C
BLANK Card Ending Node Voltage Output Requests
BLANK Card Ending Plot Specifications Component
BLANK Card Ending EMTP Input
C
********************************************************************************
EMTP Input Data File  2  -  L-C Equivalent Network
```

```
C ******************************************************************************
C *                                                                            *
C *                                                                            *
C *               EE-3778 - ELECTRICAL POWER SYSTEM TRANSIENTS II              *
C *                                                                            *
C *              Transformer Winding L-C Equivalent Representation             *
C *                                                                            *
C *                                                                            *
C ******************************************************************************
C
BEGIN NEW DATA CASE
C
C ****************** Miscellaneous Data ****************************************
C
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
C
  10.E-7   5.E-3
C
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
C
    1000       1       1       1       1       1       1       2       0       0
C
C ********************** Circuit Data ******************************************
C
C Branch data
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
C
  BUS1                                .00244
  BUS1  BUS2                          .00049
  BUS1  BUS2                     1.217
  BUS1  BUS2               10.E4
  BUS1                     10.E4
C
  BUS2                                .00487
  BUS2  BUS3                          .00049
  BUS2  BUS3                     1.217
  BUS2  BUS3               10.E4
  BUS2                     10.E4
C
  BUS3                                .00487
  BUS3  BUS4                          .00049
  BUS3  BUS4                     1.217
  BUS3  BUS4               10.E4
  BUS3                     10.E4
C
  BUS4                                .00487
  BUS4  BUS5                          .00049
  BUS4  BUS5                     1.217
  BUS4  BUS5               10.E4
  BUS4                     10.E4
C
  BUS5                                .00487
  BUS5  BUS6                          .00049
```

```
  BUS5  BUS6                     1.217
  BUS5  BUS6               10.E4
  BUS5                     10.E4
C
  BUS6                                .00487
  BUS6  BUS7                          .00049
  BUS6  BUS7                     1.217
  BUS6  BUS7               10.E4
  BUS6                     10.E4
C
  BUS7                                .00487
  BUS7  BUS8                          .00049
  BUS7  BUS8                     1.217
  BUS7  BUS8               10.E4
  BUS7                     10.E4•
C
  BUS8                                .00487
  BUS8  BUS9                          .00049
  BUS8  BUS9                     1.217
  BUS8  BUS9               10.E4
  BUS9                     10.E4
C
  BUS9                                .00487
  BUS9  BUS10                         .00049
  BUS9  BUS10                    1.217
  BUS9  BUS10              10.E4
  BUS9                     10.E4
C
  BUS10                               .00487
  BUS10 BUS11                         .00049
  BUS10 BUS11                    1.217
  BUS10 BUS11              10.E4
  BUS10                    10.E4
C
  BUS11                               .00244
  BUS11                    10.E4
C
BLANK Card Ending Branch Data Component
C
C ****************** Switch to Simulate Circuit Breaker ************************
C
C *** Switch for Ground Simulation ***
C
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
C
  BUS11             -1.0       3.0
C
BLANK Card Ending Switch Data Component
C
C **************************** Source Data *************************************
C
C      V Step Input = 1000 kV
C
```

```
C ------------------------------------------------------------------------------
C
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
C
11BUS1   1  1000000.
C
BLANK Card Ending Source Data Component
C
C ******************Output Specifications***************************************
C
  BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9  BUS10 BUS11
C
BLANK Card Ending Node Voltage Output Requests
BLANK Card Ending Plot Specifications Component
BLANK Card Ending EMTP Input
C
********************************************************************************
```

References

[1] Allan Greenwood, Electrical Transients in Power Systems, John Wiley & Sons, Inc., 1992.

[2] Paul Tuinenga, SPICE: A Guide to Circuit Simulation and Analysis Using PSPICE, Prentice Hall, 1992.

Gregory F. Reed
Dr. R. G. Colclaser
University of Pittsburgh
Pittsburgh, PA 15261

Insulation Coordination Study for an EHV Station

Introduction

In the beginning of 1992, a new 500 kV station called Mt.Olive was commissioned in the ENTERGY System. This station was built by tapping the existing El Dorado-Hartburg 500 kV line. Exhibit 1 illustrates the transmission facilities associated with the Mt. Olive project. The Mt.Olive-El Dorado line is 50 miles long and the Mt.Olive-Hartburg line is 180 miles long. There are 140 MVAR of line reactors at Hartburg and Eldorado terminals of the 500 kV line. Also, the breakers at Hartburg and El Dorado stations are equipped with 400 ohm closing resistors. The surge arresters at Eldorado and Hartburg stations were initially Silicon Carbide (SIC) surge arresters.

Due to termination of rather long 500 kV transmission lines at the Mt. Olive Station, especially the Hartburg line, there was a concern about high voltages occurring at Mt. Olive, Hartburg and El Dorado stations during line switching. These overvoltages are of interest in station design studies and if not controlled can cause insulation failures on transmission lines and equipment failure at the substations.

There are several factors that have to be addressed as a part of insulation coordination design for a 500 kV station. However, in this article the discussion is limited to the following issues:

- Surge arrester requirements at substation.
- Closing resistor requirements for circuit breakers.

Problem Discussion

The switching, or transient overvoltages results from breaker operation during normal and fault conditions. The magnitude of overvoltages caused by switching transients are important because they determine the required air clearance and insulator string lengths on transmission lines and surge arrester requirements at the stations. The most frequently considered switching transient on transmission lines are those generated by reclosing into a line with a trapped charge.

To evaluate the results of switching simulations a design criteria based on line insulation levels, overvoltage capabilities of equipment and arrester characteristics is needed. Primarily there are two concerns in evaluating transient overvoltages resulting from switching operations on the lines.

a. Basic Switching Surge Level (BSL) and b. Surge arrester duty. For safe operation, the maximum transient voltage should be less then the BSL of the station or equipment at the station, whichever is limiting, by a safety margin of 15 percent. Also, during overvoltages which result in arrester operation, the energy dissipation through the arrester should not exceed 85 percent of the maximum dissipation capability of the arrester.

The insulation design criteria used for the Mt. Olive project is shown in Table 1. Based on line design it was determined that the BSL for the 500 kV lines and the stations is 1333 kV. As the 500/230 kV transformer at the Mt. Olive Station is rated for only 1225 BSL, the Mt. Olive Station was limited by this insulation level. Considering a 15 percent safety margin, the maximum switching surge withstanding level for the 500 kV lines, as well as Hartburg and El Dorado stations was determined to be 2.78 pu, and for the Mt. Olive Station to be 2.55 pu. For safe operation , the maximum transient voltages are expected to be less than above values.

The switching overvoltages can be controlled by using a) Shunt Reactor, b) Closing Resistor, and c) Surge Arrester.

EMTP Model

To determine expected overvoltages due to switching, analytical studies were performed using the Electromagnetic Transients Program (EMTP). The system represented in the EMTP study is shown in Exhibit 2.

Equivalent sources were modeled at El Dorado 500 kV, Hartburg 500 kV and Mt. Olive 115 kV buses along with their source impedances. The distributed parameter line model was used to represent the 500 kV lines between Mt. Olive-El Dorado and Mt. Olive-Hartburg. A 560 MVA, 500/230 kV transformer and a 336 MVA, 230/115 kV transformer were modeled at Mt. Olive Station. Line reactors and closing resistors were represented at Hartburg and El Dorado terminals. No reactors or closing resistors were modeled at the Mt. Olive terminal. Also, Metal-Oxide (MOV) surge arresters were modeled at Mt. Olive and Silicon Carbide (SIC) arresters were modeled at Hartburg and El Dorado terminals.

The results of the statistical simulations of line reclosing under a trapped charge, which is considered to be a worst case scenario, are discussed in this article. The transient overvoltages on the network are dependent upon the point on the voltage waveform where switching occurs. In order to capture the maximum switching surge voltage that might occur during line switching, statistical closing by varying the point of closing on the voltage waveform was used. Under, statistical switching, one hundred random energizations were simulated. Circuit breaker closing times and pole closing were randomly varied for each of the 100 breaker reclosing operations. To model reclosing under trapped charge , initial conditions on the line were represented by steady state voltages on all the three phases

The statistical output in EMTP is given in terms of mean and standard deviation of the peak voltages at various nodes on the line. Using mean and standard deviation and assuming standard distribution , the expected value of the peak voltage with ninety eight percent probability of occurrence was calculated for each phase of the line. The largest of these phase values is referred to as maximum peak expected voltage in this study.

Results

The results of this study are summarized in Table 2. In this table the maximum peak expected voltage at the station of interest are shown in per unit (pu). Also the status of line reactors at Hartburg and El Dorado Stations under different simulations are indicated.

Switching of Hartburg- Mt. Olive Line

From Case 1a in Table 2, it can be observed that when the Hartburg-Mt. Olive line is reclosed at Hartburg end, the peak voltage at Mt. Olive end is found to be 1.45 pu. As this voltage is well below the maximum permissible switching surge voltage level of 2.55 pu for Mt. Olive Station, no problems are anticipated at the Mt. Olive end, when the line is switched from the Hartburg end.

However, when the line is reclosed from the Mt. Olive end with line reactors in-service at the Hartburg end(Case 1b), the peak voltage at Hartburg end is found to be 2.69 pu. With line reactors out at Hartburg(Case 1c), this voltage can reach 3.16 pu, which is above the maximum permissible value of 2.78 pu. Also, in both the case the energy dissipation through the SIC arrester at the Hartburg Station was found to exceed its capability limit of 357 kilo joules. The plot of peak voltages at Hartburg end are shown in Exhibit 3.

Two options were considered for controlling the switching surge overvoltages. Option 1 was to replace SIC arresters at Hartburg with Metal Oxide(MOV) arresters, and Option 2 was to use closing resistors in the breakers at the Mt. Olive Station. Option 1 was evaluated first as it was more economical. The SIC arrester at Hartburg end was replaced with MOV arrester and reclosing simulations were repeated from the Mt. Olive end. As observed in Case 1d and 1e, the peak voltage at Hartburg with MOV arrester was found to be 1.61 pu with line reactor in-service , and 1.63 pu with line reactor out-of-service. Although in Case 1d, the energy dissipation through the MOV arrester was found to be within the maximum capability limit, in Case 1e it was found to exceed the limit of 1909 kilo joules. As Option 1 was found to be very effective in controlling peak overvoltages at Hartburg end, Option 2 was not pursued further. However in order to protect the MOV arresters and equipment at Hartburg Station when the line reactors were not available an operating procedure was established to close the Mt. Olive-Hartburg line. According to this procedure , the operator at the ENTERGY Control Center is required to check the status of the line reactors at Hartburg prior to closing the line. If these line reactors are not available, the operator is instructed not to close the line from the Mt. Olive end.

Switching of El Dorado-Mt. Olive Line

When El Dorado-Mt. Olive line is reclosed from the El Dorado end, the maximum expected peak voltage at Mt. Olive 500kV bus is observed to be 1.26 pu (Case 2a). This is well below the permissible value of 2.55 pu at Mt. Olive Station. The reasons for observing this low switching surge voltage at Mr. Olive end are: shorter line length, closing resistor in El Dorado breakers and Metal Oxide arresters at Mt. Olive.

When the above line is reclosed from the Mt. Olive end, the maximum expected peak voltage at El Dorado end with line reactors in-service is observed to be 2.07 pu (Case 2b). This voltage can go as high as 2.58 pu, if El Dorado line reactors are out-of-service (Case 21-c). The energy dissipation through SIC arresters at El Dorado was found to be within the maximum capability limits in the above case.

Because the transient voltages at the Mt. Olive Station were within acceptable levels for line switching from both El Dorado and Hartburg ends, no reactors were proposed at the Mt. Olive Station.

Conclusions

Based on the study results, the following conclusions were derived:

1. No switching problems are observed on the El Dorado-Mt. Olive 500 kV line. Shorter line length and strong source at El Dorado are the reasons for not observing switching problems on this line.

2. When reclosing the Mt. Olive-Hartburg 500 kV line from the Mt. Olive end, switching surge voltages were found to exceed the line design level under certain conditions and energy dissipation through the Silicon Carbide surge arrester was found to exceed its capability. Use of Metal Oxide surge arresters at Hartburg end was found to be an effective means for controlling the switching surge overvoltages.

3. An operating procedure is required for closing the Mt. Olive-Hartburg line from the Mt. Olive end, even with Metal Oxide surge arresters at the Hartburg end.

4. No closing resistors are required for the Mt. Olive breakers as the Metal Olive Surge resisters provide acceptable surge reduction.

5. No shunt reactors are required at Mt. Olive Station to control switching surges, as both Hartburg and El Dorado breakers have closing resistors for controlling transient overvoltages.

Recommendations

Based on the analytical studies, the following recommendations were made for the Mt. Olive Project.

1. Replace the existing Silicon Carbide surge arresters on the 500 kV line terminating at Hartburg Station with Metal Oxide surge arresters.

2. Follow an Operating Procedure when closing the Mt. Olive-Hartburg line from the Mt. Olive end.

3. Closing resistors are not required at Mt. Olive Station.

4. Shunt reactor is not required at Mt. Olive Station.

The use of Metal Oxide surge arrester instead of closing resistor in Mt. Olive breakers resulted in a cost savings of approximately $150,000 to the ENTERGY System. Additional savings are also expected because of reduced maintenance cost of using arresters instead of closing resistors.

Sharma Kolluri
Entergy Services Inc.
New Orleans, Louisiana

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