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ANALYSIS OF THREE-PHASE POWER-SUPPLY SYSTEMS USING COMPUTER-AIDED DESIGN PROGRAMS *

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Summary

A major concern of every designer of large, three-phase power-supply systems is the protection of system components from overvoltage transients. At present, three computer-aided circuit design programs are available in the Magnetic Fusion Energy (MFE) National Computer Center that can be used to analyze three-phase power systems: MINI SCEPTRE, SPICE I, and SPICE II. These programs have been used at Lawrence Livermore Laboratory (LLL) to analyze the operation of a 200-kV dc, 20-A acceleration power supply for the High Voltage Test Stand. Various overvoltage conditions are simulated and the effectiveness of system protective devices is observed. The simulated overvoltage conditions include such things as circuit breaker openings, pulsed loading, and commutation voltage surges in the rectifiers. These examples are used to illustrate the use of the computer-aided, circuit-design programs discussed in this paper.

Introduction

Computer-aided, circuit-design programs have been available for a number of years. Until recently however, the emphasis for their use was placed on the design of transistor and integrated circuitry. At LLL, three circuit-design programs available from the MFE National Computer Center - MINI SCEPTRE, SPICE I, and SPICE II - have been adapted for use in analyzing large, three-phase, power-supply systems. They have been effective in evaluating the performance of the acceleration power supply designed for the High Voltage Test Stand.

In several instances, we lacked computer models of some of the components of the power-supply system. Therefore, it was necessary to develop suitable models for these components using the existing features of the programs. In this paper, we discuss some of these models and also present some of the simulated operations along with examples of the results. As part of the conclusion, we discuss plans for further development of these programs.

System Modeling

The model elements presented in this section were used to represent components in the acceleration power supply of the High Voltage Test Stand. A one-line diagram of the power-supply system is shown in Fig. 1.

All three programs discussed in this paper use nearly the same input format to describe the circuit elements; that is, each element is described by a unique name, with numbered nodes identifying its connection points in the circuit and the value of the element. The MINI SCEPTRE program is more versatile than the other two in that an element value can be described in one of five ways: as a constant, table, defined parameter, equation, or mathematical expression.

We ignored the distributive nature of some of the system components, such as feeder lines and transformers. Instead, with no apparent effect on the overall system operation, they were represented in the circuit model as lumped elements.

A circuit breaker can be modeled as a current-controlled switch. Of the three programs being discussed, only MINI SCEPTRE is capable of simulating this device, and it does so with a resistance element that has a value described by a FORTRAN function subprogram. An example of this subprogram is shown in Fig. 2. The arguments for the subprogram are time (T) and current through the resistor (C). The value of the resistor is initially set at a very small value to simulate closed contacts of the circuit breaker. At a selected time, the subprogram begins monitoring the current level through the resistor. When the current is within the actual chopping current level of the circuit breaker, the value of the resistor is switched to a high value that simulates open contacts. We have tried other models of circuit breakers (diodes and transistors) in the other two programs with no dependable results to date.

Transformers were modeled in two different ways: as the "T" equivalent model and as a pair of inductors with mutual inductance. These two models are shown in Fig. 3. SPICE I does not have the capability to handle mutual inductance; therefore, a "T" equivalent model must be used with this program. Although, both MINI SCEPTRE and SPICE II can handle mutual inductance, at this time only SPICE II has been used successfully with a mutual inductance transformer model. Thus, a "T" equivalent model must also be used with the MINI SPECTRE program. As seen in Fig. 3, the "T" equivalent model used is a simplified version with some of the standard parameters missing, not because of any modeling difficulties, but because they had no significant function in the overall circuit. The mutual inductance of the transformer model used in SPICE II is described by the primary and secondary winding inductances along with the coefficient of coupling for the two windings. A three-phase transformer is modeled using three identical, individual transformers. Examples of three-phase "T" equivalent and mutual inductance transformers are shown in Fig. 4.

All three programs have diode models available that can be used to create a rectifier circuit. The diode models in the MINI SCEPTRE program are based on the Ebers-Moll diode model for specific diodes, e.g., 1N649. However, these specific diode models

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need not be used: the parameters for any diode can be used along with any diode model. The diode model used in SPICE I and II is different in that only the diode parameters are specified. Although the parameters from any diode can be used in the model, the type of model is fixed.

Switches are modeled slightly differently from circuit breakers because they are not current-dependent: they represent the theoretically perfect switch that will interrupt current flow regardless of level. For their purpose in this power-supply system, this is an adequate model. In the MINI SCEPTRE program, we once again used a resistance element. The value of resistance was specified in a table format in which the table represents a set of discrete points taken from a time versus value curve that describes the behavior of the switch element during the time of simulated system operation. With this switch element, a load resistance can be switched on and off by changing the resistance value at the desired time from a high value to the load value and back again. The switch element can also be used to represent a short circuit. Figure 5 shows an example of a table of values used as a switch. Switch elements in SPICE I and II were modeled as a diode with a bias voltage. Figure 6 is an example of this type of switch. To turn the switch off, the diode is reverse biased by a voltage that is greater than any other voltage in the circuit which might forward bias the diode. To turn the switch on, the reverse bias is turned off, and the diode is allowed to conduct whenever the circuit voltage applies a forward bias to it. As mentioned previously, the diode parameters can be independently selected, which means that the diode can have a zero forward voltage drop. This simulates a zero-resistance switch contact.

Each of the programs has certain restrictions concerning the methods used to construct a circuit model. Some of these are listed in the associated user's manual. However, while using the programs we found some restrictions that are not mentioned. For example, in the acceleration power-supply system the surge networks are connected in a wye configuration with the neutral point floating. The circuit model used in SPICE I and II requires the neutral point to have a ground path. We satisfied this requirement by placing a very large-value resistor between the neutral point and ground. Also, the transformer model used in SPICE II has a delta-connected primary, and the program would not accept the connection of three inductors in a loop without some resistance present. We solved this problem by adding a small resistance to the windings. This did not cause any degradation in the overall operation of the system since there is a resistive component present in the transformer windings. The secondary windings of this transformer model are connected in a wye configuration with the neutral floating. Here again, the program required a ground path for the neutral point and we again used a large resistance. In the SPICE programs, current levels can only be obtained from voltage sources. If it is desired to output the current level in a branch circuit that does not contain a voltage source, the voltage across a resistive element can be used to infer the current level by using Ohm's law.

We tested the model elements discussed here to determine their validity. The tests consisted of comparisons between the operation of the model elements and known or theoretically calculated performance characteristics of the system components. Also, because we found that a simplified circuit model could often be used without degradation of the results, we used simplified circuit models as often as possible. Examples of these models with corresponding results will be presented in the next section.

Simulated Operations

One of the first simulations of a normal operation was performed to determine the effectiveness of the surge network in the secondary circuit of the rectifier transformer. The network was designed to suppress the commutation surges of the rectifier circuit. The circuit model used for this simulation is shown in Fig. 7. Figure 8 indicates that the surges are suppressed, as evidenced by the lack of oscillations on the waveshape at the commutation points. To determine if simplification had any significant effects on the results, we repeated this operation using a simplified circuit model with a "T" equivalent transformer. Other than a difference in voltage amplitudes caused by a lack of a turns ratio in the "T" equivalent model, there were no significant differences between the two results. Figures 9 and 10 show the simplified model and the corresponding results.

We performed another simulated operation to determine what effect the use of standard, inductive power resistors in the power-supply filter would have on the operation of the filter. Although the inductance is an integral part of the resistor, it can be modeled as a separate element. For comparison purposes, the model shown in Fig. 9 was used both with and without the inductive element in the filter. The results are shown in Fig. 11. Needless to say, non-inductive resistors are used in the filter.

Other simulations of normal operations were performed to test the validity of some of the model elements. For example, we used the model circuit shown in Figure 7 to test the model of the mutual inductance transformer. Data for the secondary voltage and primary current of the transformer taken under full load conditions were compared to calculated theoretical values. The agreement between the values was excellent.

To test the effectiveness of the surge networks designed to suppress switching transients generated by the opening of circuit breaker contacts, we simulated fault condition operation. One of the circuit models used for this test is shown in Fig. 12. Since the magnitude of the transients generated at the time of circuit breaker opening is proportional to the chopping current level of the circuit breaker, we made tests at several different current levels within the chopping current margin. The results of one of these tests are shown in Fig. 13. A comparative test was performed using an industry standard surge arrestor in place of one of the surge networks. The surge arrestor in this case is a 0.25 μF capacitor. From the results indicate in Fig. 14, it is easy to see why equipment failures can be caused by switching transients.

Conclusions

The programs have proven to be a valuable tool for evaluating the design of the acceleration power supply in the High Voltage Test Stand. The time and effort saved through their use is beyond estimation.

At the present time, no one program discussed in this paper can provide all of the desired features. Therefore, work on all three programs will continue until one of them satisfies all the requirements.

A fourth program, which was developed by the Bonneville Power Administration, has recently been added to the MFE national computer system. This program is designed specifically for analyzing three-phase power systems. At the time of this writing, there has not been sufficient use of this program for us to present any information about it. However, because a preliminary study indicates that this program has great potential for use as a design analysis aid, work on it will continue.

Since the presentation of this paper may create an interest in using these program beyond LLL, we shall develop a method of disseminating information about the programs. In the interim, questions concerning the programs can be directed to either of the following:

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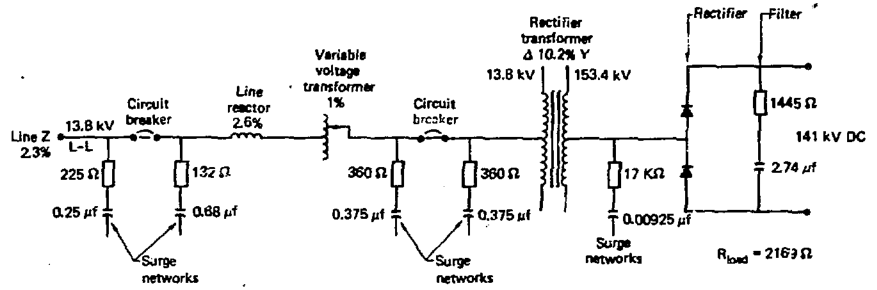

5 MVA BASE

Fig. 1 H.V.T.S. acceleration power supply one line diagram (TFTR mode)

```
      Function SW(T,C)
      SW = 0.1
      If (T.LT.45.E-3) GO TO 1
      If ((C.GE.-5.).and.(C.LE.5.)) SW = 1.0E9
    1 CONTINUE
      RETURN
      END
```

Fig. 2 Fortran function subprogram used to simulate a circuit breaker

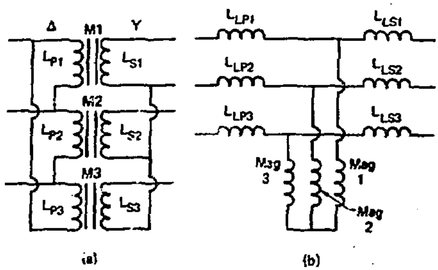

Fig. 4 Three phase transformer models
(a) Mutual inductance
(b) "T" equivalent

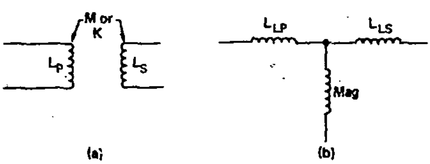

Fig. 3 Transformer models
(a) Mutual inductance
(b) "T" equivalent

```
SW1, 40-41 = TABLE 1 (TIME)

TABLE 1 = 0.0,       1.0E9
          64.0E-3,   1.0E9
          65.0E-3,   38.1
          100.E-3,   38.1
          101.E-3,   1.0E9
          150.E-3,   1.0E9
          (TIME),    (VALUE)
```

Fig. 5 Table values for switch model

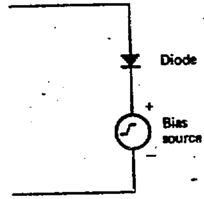

Fig. 6 Diode switch model

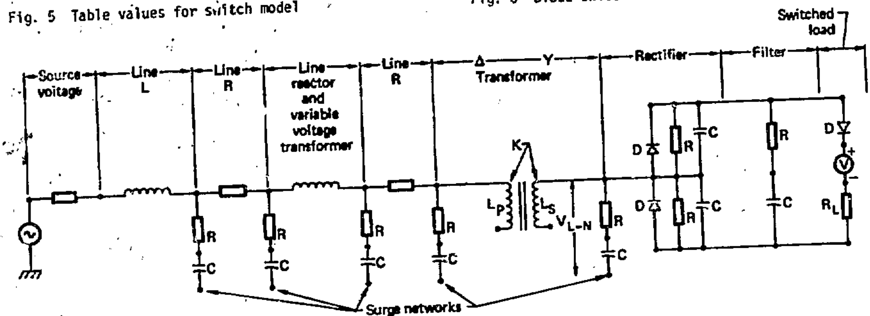

Fig. 7 TFTR mode model circuit one line diagram

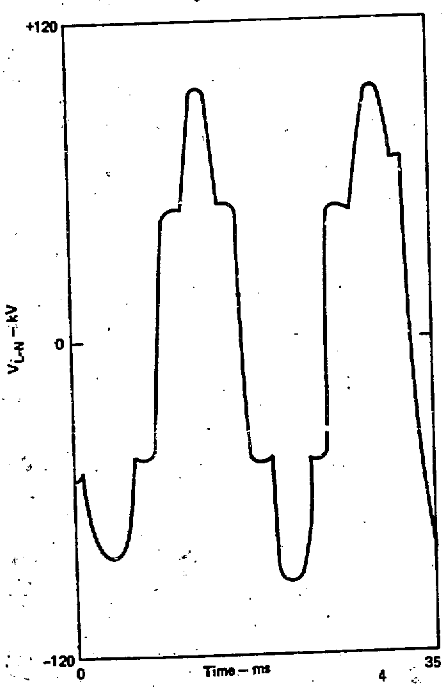

Fig. 8 Commutation surges

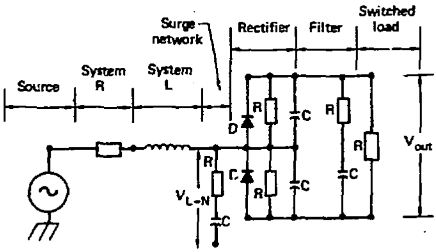

Fig. 9 Simplified TFTR mode model circuit one line diagram

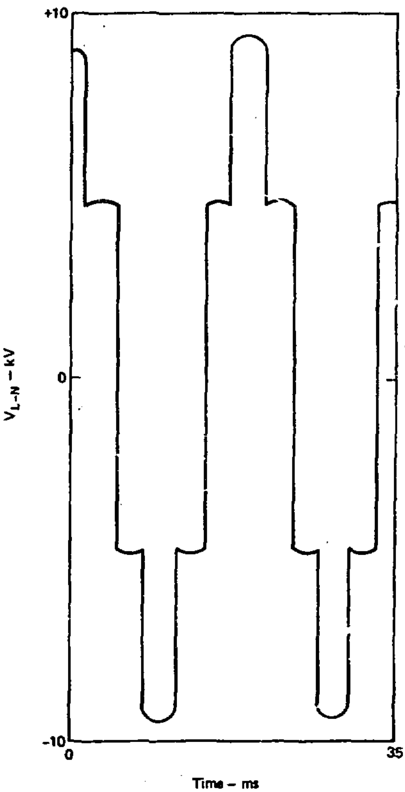

Fig. 10 Commutation surges

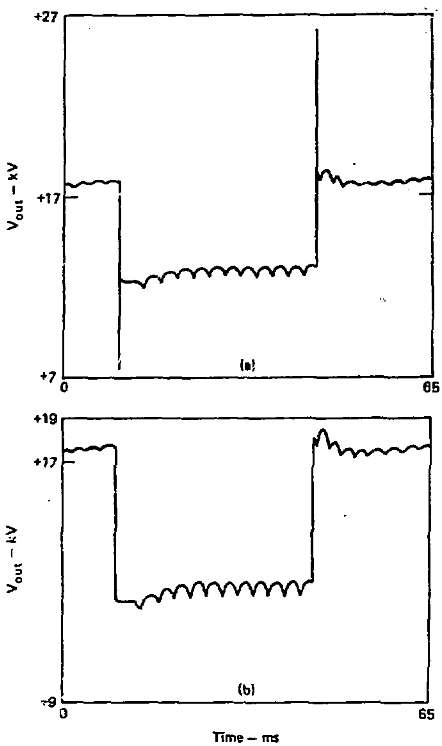

Fig. 11 (a) Output voltage with standard power resistors in filter
(b) Output voltage with non-inductive resistors in filter

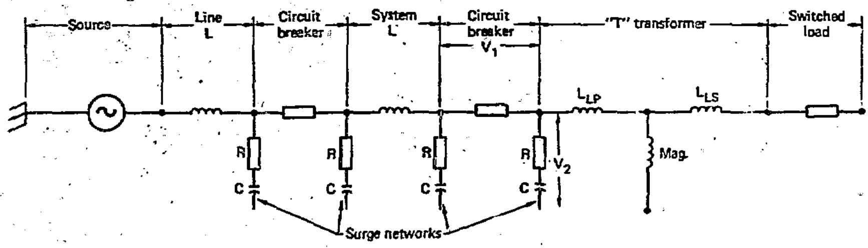

Fig. 12 Surge network test model one line diagram

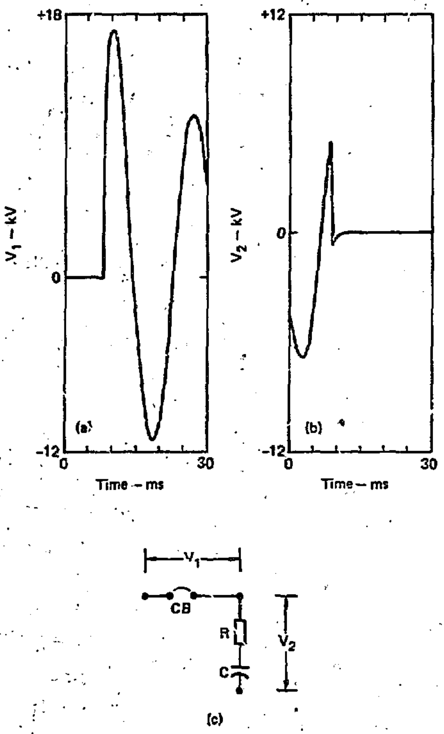

Fig. 13 (a) Circuit breaker contact voltage
(b) Surge network voltage
(c) Measurement points

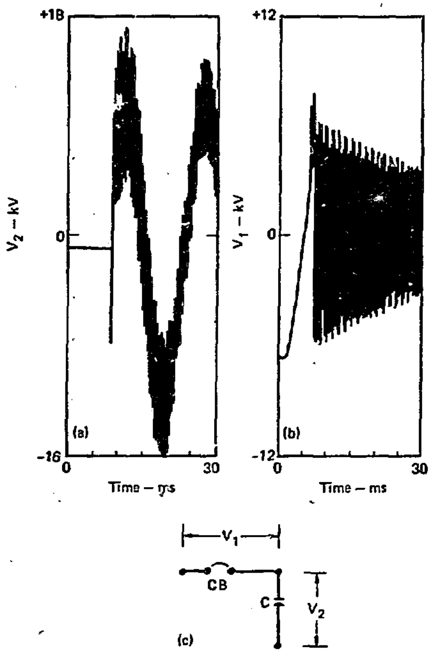

Fig. 14 (a) Circuit breaker contact voltage
(b) Surge network voltage
(c) Measurement points