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ELECTRICAL ENERGY SUPPLY TO RURAL COMMUNITIES DIRECTLY FROM TRANSMISSION LINES

FINAL REPORT

by

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CHAPTER I Generalities of Rural Electrification

I.1. The Problem

The problem of rural electrification has been a subject of a number of conferences sponsored by different organizations such as the World Bank. Besides the technical aspects that rural electrification presents in different areas, one of the major concerns is the high capital investment required.

In order to provide energy to rural communities, several alternatives for electrification have been contemplated and developed. These can be classified in the following categories:

a) Substation with double transformation,
b) Extension of the nearest distribution line,
c) Isolated ground shield wire of transmission lines,
d) Small generating plants (hydro or diesel),
e) Capacitive voltage divider,
f) Non-conventional sources of energy, such as biomass, solar energy and wind energy (aeolic generators).

However, this last category represents only complementary sources of energy due to their random generation nature or reduced power. The conventional scheme for rural distribution systems is a low or medium voltage radial circuit centered upon a local substation. This circuit represents a high capital cost for scattered rural areas. In addition to capital cost, the importance of losses associated with long circuits and the low and irregular loading, accounts for the high cost of each delivered kW. This cost is greatly increased if the feeding bulk power station or transmission line has a poor utilization factor.

In the case of a community which is close to a high voltage transmission line but too far from any existing substation or from a distribution network, it might be more economical to take small powers directly from the transmission line, without building a conventional distribution system. For example, several studies [1,2] were carried out to obtain energy from transmission lines by isolating some length of the shield wire. Its major drawback is the low power that can be obtained (0.1 kW per km of isolated groundwire for a 72 kV line with two groundwires) [3].

The alternative of building a capacitive voltage divider has been used to supply low loads ranging from 10 to 50 kVA as described by R. Wilde and J. Carr [3] and for instrumentation purposes. The circuit configuration used was a capacitive voltage divider connected between one phase of the transmission line and ground. This technique leads to important cost reductions when compared with conventional alternatives. However, several problems were reported, such as ferroresonance and flicker; most of them due to saturation of the ferromagnetic inductor and the distribution transformer used in the circuit.

Although substantial savings may be obtained by using a ferromagnetic inductor in the secondary side of the transformer, three major drawbacks may be pointed out: a) the input voltage of the transformer will have substantial variations in magnitude related to different load conditions, b) the configuration can only feed loads located close to the tap off, since the regulated voltage is too low. Consequently, its service area is small (a few hundred meters) due to voltage drops, c) inductor saturation can play an important role in ferroresonance appearance.

The main idea of this research is to use an air core reactor placed on the high voltage side of the distribution transformer. The air core characteristic will prevent saturation of the inductor. In addition, the sufficiently high regulated voltage obtained on the load side of the inductor

will increase the potential service area of the installation.

The major advantage for using a one-phase capacitive voltage divider is to provide a reduced voltage, say 7.6 kV (a normal distribution voltage) from a high voltage line, without using a high input voltage transformer, and the associated high capacity switchgear.

Electromagnetic transformers with the required voltage ratios are not available for power ratings below certain limits (500 kVA for a 115 kV to 13.8 kV or 7.6 kV). Since they are not mass produced, their cost is relatively high (approximately 5,000 U.S. dollars). Also, the use of a high input voltage transformer requires other expensive equipment, such as high interruptive capacity circuit breakers (approximate cost 10,000 U.S. Dollars) which are the conventional components of a bulk power substation.

1.2. The voltage Divider System

The purpose of a capacitive voltage divider is to reduce the high voltage of a transmission line to a distribution class voltage, i.e. 13.8 kV or 7.6 kV. For this reason, the system is often referred to as a capacitive transformer.

For versatility purposes, the capacitors used to perform the voltage division will be chosen among the wide variety of single phase capacitor depending on their nominal voltage and rated power. These capacitors should be connected in series between two phases of the transmission line, or between one phase and ground, for Y connected transmission lines with grounded neutral.

1.2.1. Operating Principle.

The operating principle of the voltage divider shall be explained, considering the phase to ground connection, as shown in Figure 1.

The voltage reduction obtained from the system depends on the impedances Z_1 and Z_2 (or capacitances C_1 and C_2) of the capacitor banks. Let V_ϕ be the phase to ground voltage of the transmission line and V_R the reduced voltage, then equation 1 expresses the relation between V_ϕ and V_R as a function of Z_1 and Z_2 as well as C_1 and C_2.

$$V_R = \frac{Z_2}{Z_1 + Z_2} V_\phi = \frac{C_1}{C_1 + C_2} V_\phi \qquad (1)$$

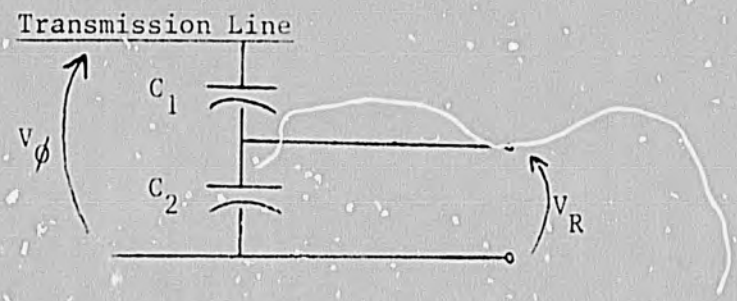


FIGURE 1 Capacitor Voltage Divider.

The coeficient $Z_2/(Z_1 + Z_2)$ is the transformation ratio of the system. If the Thèvenin equivalent circuit is considered, the steady state behaviour of the circuit becomes quite easy to understand. Figure 2 shows the equivalent circuit where the value of V_R is determined from equation 1 and that of C_p is expressed in equation 2.

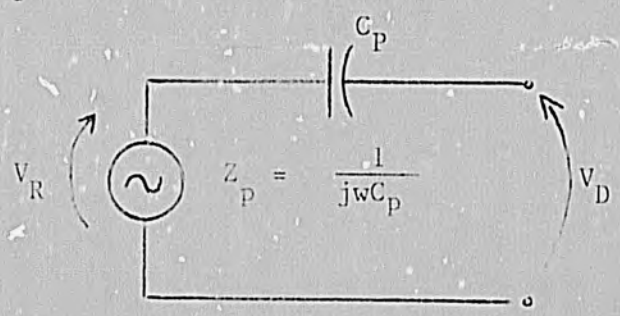


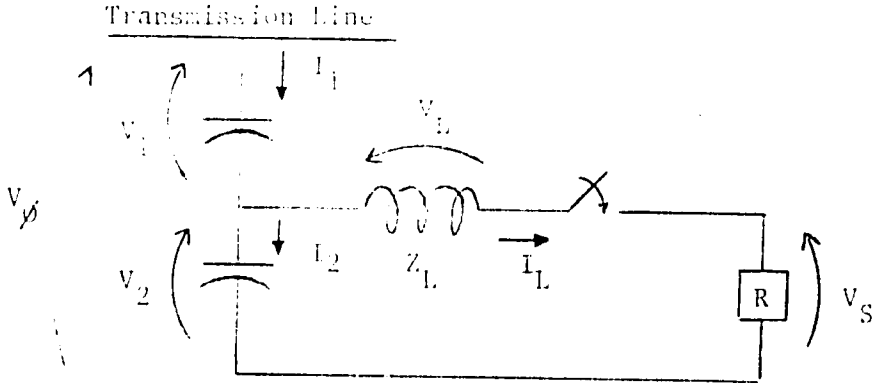
FIGURE 2 Thevenin equivalent circuit.

$$C_p = C_1 + C_2 \qquad (2)$$

$$Z_p = \frac{1}{jwC_p} = \frac{Z_1 \times Z_2}{Z_1 + Z_2} \qquad (3)$$

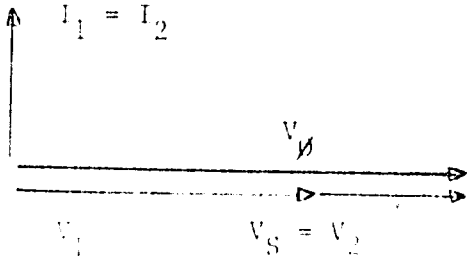
Provided that impedance Z_p is relatively high, if a load is connected to the system, the regulation of voltage V_D is very poor for important loads. In order to improve the circuit regulation, an inductance can be connected in series with the load in order to compensate partially or completely the series capacitive impedance introduced by the voltage divider.

Figure 3 shows the basic circuit and the associated phasor diagram of a fully compensated arrangement for both the loaded (see Fig. 3.c) and unloaded conditions (see Fig. 3.b).

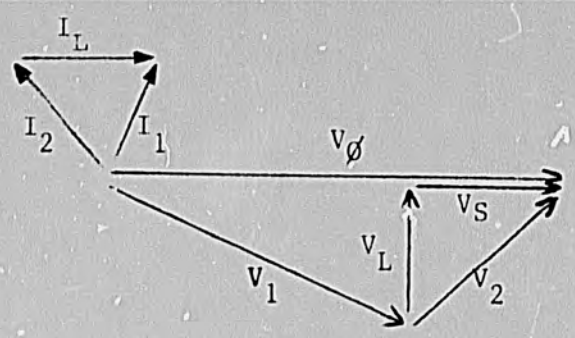


$$Z_L = - \frac{Z_1 \, Z_2}{Z_1 + Z_2}$$

a) Basic electrical circuit.



b) Phasor diagram for the unloaded condition.



c) Phasor diagram for a resistive loading condition.

FIGURE 3 Capacitive voltage divider circuit and steady state behaviour.

I.3. Pilot Installation Project

In order to test a prototype installation, the search of unelectrified populations with appropiate characteristics as discussed in Section I.4, was undertaken by "Comisión Federal de Electricidad" (C.F.E. - The National Electricity Council of México).

As much as 40 communities were considered in the states of Chiapas, Guerrero, and San Luis Potosí. At first, the population of Venta Vieja, in the state of Guerrero, was chosen. It is located 32 km northwest of the city of Chilpancingo, the state capital, with a population of 75 inhabitants. The nearest electrified population is 11 km away and a 115 kV line is 2.2 km from the town.

Nevertheless, after careful consideration of the implications of energizing a small rural community without having a proper stock of spare parts (reactor windings, zinc oxide arresters, capacitor units, etc.), Comisión Federal de Electricidad opted for testing the capacitive voltage divider in a community already energized.

The chosen site was a small rural neighborhood in the outskirts of the city of Chilpancingo.

This neigborhood is energized by two three-phase transformers supplying a load of approximately 30 kVA. One of the units will supply half of this load, including a three-phase motor. The other unit will be replaced by a single-phase unit connected to the voltage divider 360 m. away, close to a suspension tower of a 115 kV transmission line.

With this arrangement, and in this experimental stage, if for any reason the voltage divider is out of service, the other three-phase transformer will feed the total load.

I.4. Economical Aspects

The economical comparison of rural electrification alternatives is specially crucial due to the high investment costs involved per installed kVA. Eventhough this comparison is only truly meaningful for specific projects, some figures can be drawn out from previous studies in order to give a rough idea about the range of figures that can be encountered.

The first case to be examined is due to "BG CHECO International Limitee", a Canadian company from Quebec which studied the project of rural electrification of Ñahuimpuquio, a small population in the Peruvian Andes. Three alternatives were considered in this study as described by their document entitled "cable de pararrayos una toma de corriente económica". The first option considered was to install two diesel plants, the second option was to build a small hydraulic station. Finally, the third alternative consisted of a small electrical station powered by an isolated length of a ground wire of a 220 kV transmission line.

As revealed by the study for that specific population, the cheapest alternative turned out to be the ground wire project, followed by the hydraulic plant. It is worth while mentioning that the possibility of building a hydraulic station well suited to the energy requirements of a population is not opened to all rural communities.

In order to draw some representative figures out of the Ñahuimpuquio study, the average investment and operating cost for each alternative are shown in Table I. These average values are taken for different periods of the 14 year horizon considered. The costs are expressed in 1983 U.S. dollars, which is the year the study was carried out.

The investment cost per MWh is computed as the equipment depreciation divided by the total energy consumption of a specific year. The operating cost

includes the following expresions for each alternative. Operation and maintenance, fuel and lubricant costs; the national transportation of fuel and lubricants is considered for the diesel alternative. Only operating and maintenance costs are considered in the hydraulic and ground wire alternatives.

TABLE 1 Comparative cost of investment operation per MWh delivered.

ALTERNATIVE					
DIESEL PLANT		HYDRAULIC PLANT		GROUND WIRE	
Invest.	Oper.	Invest.	Oper.	Invest.	Oper.
153.3	342.1	83.7	143.5	104.6	70.6
499.4		227.2		175.2	

The capacitive voltage divider installation had a cost for equipment of $16,765.00 U.S. dollars. The detailed description of this cost is presented in Table II below. Considering that the installation has a useful life of 20 years, with constant annuities the annual equipment cost D in U.S. dollars is:

$$D = \$\ 838.00 = \frac{16,765}{20} \text{ (U.S. Dollars)}$$

Given that the power rating is 25 kVA, the annual cost C per installed KVA considering only the equipment cost

$$C = \frac{838}{25} = \$\ 33.5 \text{ (\$/KVA-year)}$$

Assuming that the utilization factor is equal to the Ñahuimpuquio project, that is 1020 hours of rated power yearly with unit power factor the equipment cost per MWh is:

$$\frac{33.5}{1.02} \text{ (\$/MWh)} = 32.86 \text{ (\$/MWh)}$$

This cost has to be compared with the concurrent projects, three of which have been mentioned previously regarding the study by B.G. Checo. According to an aeolic project developed by the IIE, a generating unit of 1 MW rated capacity represents an investment cost per KVA of one thousand dollars. Two aspects have to be kept in mind. The first one is the random nature of energy availability of aeolic generators, the second is the economy of scale obtained from a 1 MW equipment.

One of the most widely used alternatives in rural electrification is the extension of distribution networks. Considering the estimate cost of U.S.$8,000.00 per kilometer of distribution line, if a population is located 2 km closer to a 115 kV line than to any existing distribution line, the installation of a capacitive voltage divider should be considered as an alternative project which could result in substantial savings:

TABLE II Pilot installation equipment costs.

N° of Units	Item	Cost
1	5 H Inductor	$ 4,725
1	0.6 mH Inductor	920
1	90 kV Surge arrester	1,885
2	8.4 kV Surge arrester	140
1	115 kV fuse disconnect	4,355
8	50 & 100 KVAR capacitors	2,770
1	50 kVA distrib. transformer	1,440
2	Wooden posts	240
2	15 kV and 120 V disconnects	120
	Various (hardware)	170
	T O T A L	$16,765

Costs are in 1986 U.S. dollars. Do not include taxes or transportation costs.

CHAPTER II Installation Design

The design of a voltage divider includes several steps. The sections of this chapter correspond to the chronological order followed during the project. The first point defines the criteria to specify the capacitor banks. The second part considers the transient behaviour of the installation by means of digital simulation. The third aspect considered is the proposed protective scheme. In point four the most relevant aspects regarding the components specification is presented. Finally, point five deals with the layout of the field installation.

II.1. Steady State Considerations

The selection of the capacitor banks C_1 and C_2 must satisfy two conditions. The first one is that the voltage through bank C_2, for the unloaded condition, corresponds to the selected distribution voltage V_R. Denoting V_ϕ the line to ground voltage of the transmission line, the ratio of impedances Z_{C_1} and Z_{C_2} of banks C_1 and C_2 is a function of V_R and V_ϕ expressed by equation 4.

$$\frac{Z_{C_1}}{Z_{C_2}} = \frac{V_\phi}{V_R} - 1 \qquad (4)$$

This defines the condition that Z_{C_1}/Z_{C_2} must fulfill. The second condition to be satisfied by the banks is that the maximum steady state operating voltage V_{Max} through each unit is less than or equal to its nominal voltage V_n.

$$V_{Max} \leqslant V_n$$

This condition can be stated for bank C_1 for the most critical situation which is a full resistive loading by the following inequality, where I_L is the maxi-

mum current through the load and P_{nC1} is the nominal power of bank C_1, and Z_L is the impedance of the inductor.

$$V_{C1\ Max} = \sqrt{(I_L\ Z_L)^2 + (V_Q - V_R)^2} \leq V_{nC1} = \sqrt{P_{nC1}\ Z_{C1}} \qquad (5)$$

The worst case for bank C_2 is an inductive full loading. Assuming that the lowest power factor that can be encountered is 0.8, the inequality can be expressed as follows:

$$V_{C_2\ Max} = \sqrt{(I_L\ Z_L \times 0.8)^2 + (V_R + I_L\ Z_L \times 0.6)^2} \leq V_{nC_2} = \sqrt{P_{nC2}\ Z_{C_2}} \qquad (6)$$

Given that:

$$Z_L = \frac{Z_{C_1}\ Z_{C_2}}{Z_{C_1} + Z_{C_2}} = Z_{C_1}\left[\frac{1}{1+\frac{Z_{C1}}{Z_{C2}}}\right] = Z_{C2}\left[\frac{1}{1+\frac{Z_{C2}}{Z_{C1}}}\right]$$

By substituting Z_L in both inequalities 5 and 6 and squaring both terms, two quadratic inequalities, having as variables respectively Z_{C_1} and Z_{C_2}, are obtained as expressed below:

$$Z_{C_1}^2 \left[I_L^2 \left(\frac{1}{1+\frac{Z_{C1}}{Z_{C2}}}\right)^2\right] - Z_{C_1}\ P_{n_1} + (V_Q - V_R)^2 \leq 0 \qquad (7)$$

$$Z_{C_2}^2 \left[I_L^2 \left(\frac{1}{1+\frac{Z_{C2}}{Z_{C1}}}\right)\right] - Z_{C2}\left[P_{n_2} - 1.2\ I_L\ V_R \left(\frac{1}{1+\frac{Z_{C2}}{Z_{C1}}}\right)\right] + V_R^2 \leq 0 \qquad (8)$$

These inequalities include coeficients that depend on the values of V_Q and V_R and have P_{n1} and P_{n2} as parameters, respectively.

By choosing the nominal power P_n of each bank, the inequalities 7 and 8 yield intervals of feasible values for Z_{C_1} and Z_{C_2}. The interval for Z_{C_2} can be converted into an interval for Z_{C_1} when multiplied by the constant ratio $\frac{Z_{C1}}{Z_{C2}}$.

The intersection of this interval with the one obtained from P_{n_1}, yields a range of feasible values of Z_{C_1} and its corresponding range of Z_{C_2} for the powers P_{n_1} and P_{n_2} previously selected.

This can be done iteratively by increasing the values of nominal powers until the feasible intervals allow a selection of single phase units that best approximates the ratio of impedances Z_{C_1} over Z_{C_2} determined by equation 4.

This technique can be directly applied when all the units of a bank are identical.

If the elements are different in voltage class or power rating, the nominal voltage V_{nC} of the bank may be determined as follows. First define the nominal current of each element j

$$I_{n_j} = \frac{P_{n_j}}{V_{n_j}} \qquad (9)$$

determine the minimum current $I_{n_{Min}}$ found and multiply it by the summation of their impedances

$$V_{n_c} = I_{n_{Min}} \left(\sum_j \frac{V_{n_j}^2}{P_{n_j}} \right) \qquad (10)$$

The prototype installation banks have the following elements:

Bank C_1

Four 50 kVA units rated 13.8 kV with an individual impedance of 3.81KΩ
plus two 50 kVA units rated 14.4 kV with an individual impedance of 4.15KΩ

Bank C_2

Two 100 kVA units rated 12.47 kV with an individual impedance of 1.55 KΩ

This is for a 115 kV transmission line and a 7.6 kV distribution line. The value for Z_L is 2.74 K Ω which correspond to an inductance of 7.27 Henries.

II.2. Transient State Considerations

The transient behaviour of voltage dividers is one of the major problems encountered in all the previously reported [4] installations. The analytical study for the pilot installation was made with the Electromagnetic Transient Program and three type of transients were considered. The first one is the short circuit in the 7.6 kV line. The second study considered the distribution transformer energization. The third and final case considered was the switching of the bank from the 115 kV side.

II.2.1. Short Circuit on the 7.6 kV Line

The first case studied is the short circuit with an inductor that fully compensates the Thèvenin capacitive impedance. After three cycles the fault is liberated.

The oscillogram is shown in Figure 4.

One major conclusion is drawn from this simulation. That is, the overvoltages are too important (close to ten times the operating values) even after the operation of a very rapid protective system that operates three cycles after the fault.

DIVISOR CAPACITIVO LINEA 115-FP=0.8 SNOM = 50KVA

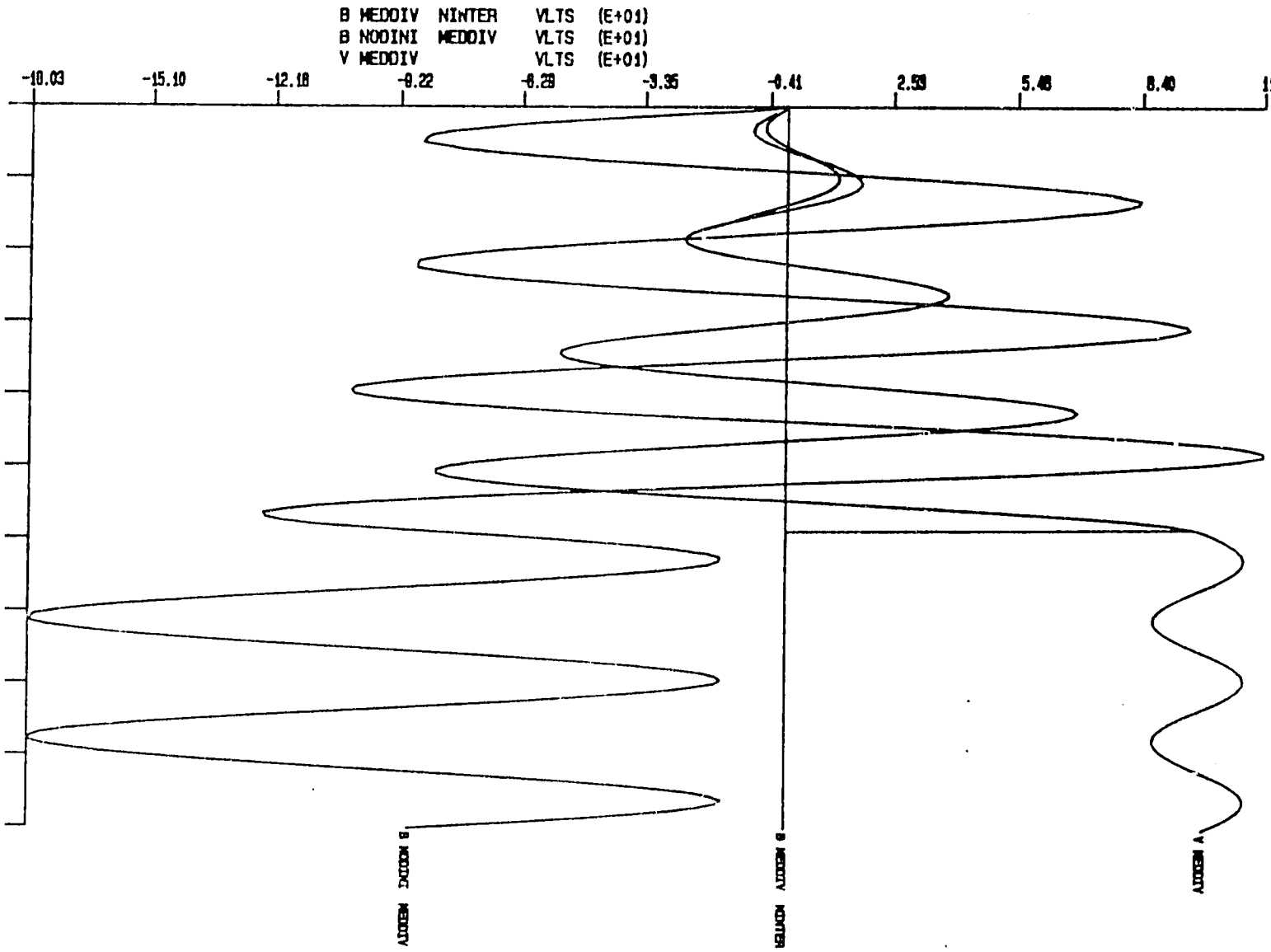


FIGURE 4 FULLY TUNED SHORT CIRCUIT.

Several attempts were made to reduce the fault over voltages as described in point II.3. The final solution that was taken was to compensate only partially the circuit with a 4 Henry inductance on the 7.6 kV line. The rest of the compensation is done on the secondary of the transformer. The transient behaviour after the fault is described by the oscillogram of Figure 5.

The highest overvoltages detected in Banks C_1 and C_2 following the fault in per unit, are respectively of 1.2 and 1.28. They correspond to an under damped oscillating wave form, with two dominating frequencies. The first frequency is 60 Hz due to the system and the second one is a 15 Hz wave form that defines the amplitude of the voltage waves through banks C_1 and C_2.

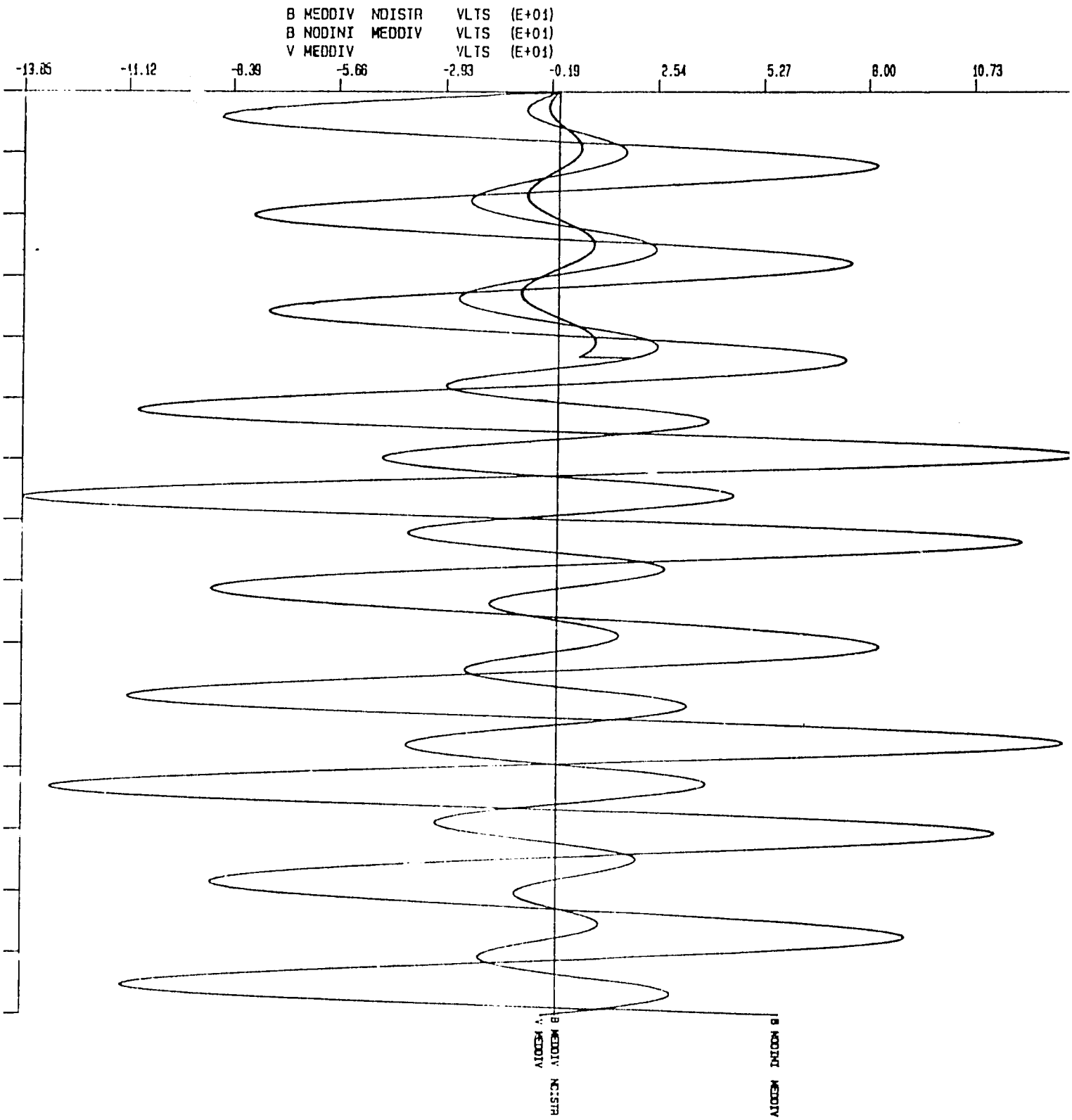


FIGURE 5 PARTIALLY TUNED SHORT CIRCUIT.

II.2.2. Distribution Transformer Energization

The purpose of these computer simulations was to determine the capacitor bank performance when the distribution transformer is energized at no-load. Transient voltages and currents were recorded in order to analyze the possibility of occurrence of ferroresonance due to core saturation. The transformer model used in the EMTP program was that of a 30 kVA, 13.2 kV unit with a magnetizing current of 5%. Several cases were analyzed, in each of them inrush and the voltage across C_2 (V_2 in Fig. 7) was plotted. Situations simulated were: maximum residual magnetism, positive and negative; 50% residual magnetism, positive and negative; and rated voltage V_2 passing thru zero and at its peak value.

In neither case was ferroresonance observed. Figure 6 shows the oscilogram of the worst case. The no-load energization was simulated with the voltage wave passing thru zero, and maximum positive residual magnetism. Simulation time was 250 ms. The current wave TRANS-SATURA corresponds to the inrush magnetizing current. Some negative peaks are observed caused by saturation (maximum peak value of 3.11 A). The maximum value of V_2 (voltage wave MEDDIV) is 12.85 kV. Neither of these values affects the general performance of the circuit.

II.2.3. Switching of the Capacitive Voltage Divider Bank

The purpose of these computer simulations was to determine the transient state performance of the voltage divider after switching operations under different circuit conditions. The parameters mainly recorded and plotted were: current in the 115 kV line and voltages V_1 & V_2 previously mentioned (See fig. 7).

1) With S_2 open, energize the capacitor bank at the instant the source voltage is positive maximum.

FIGURE 6.

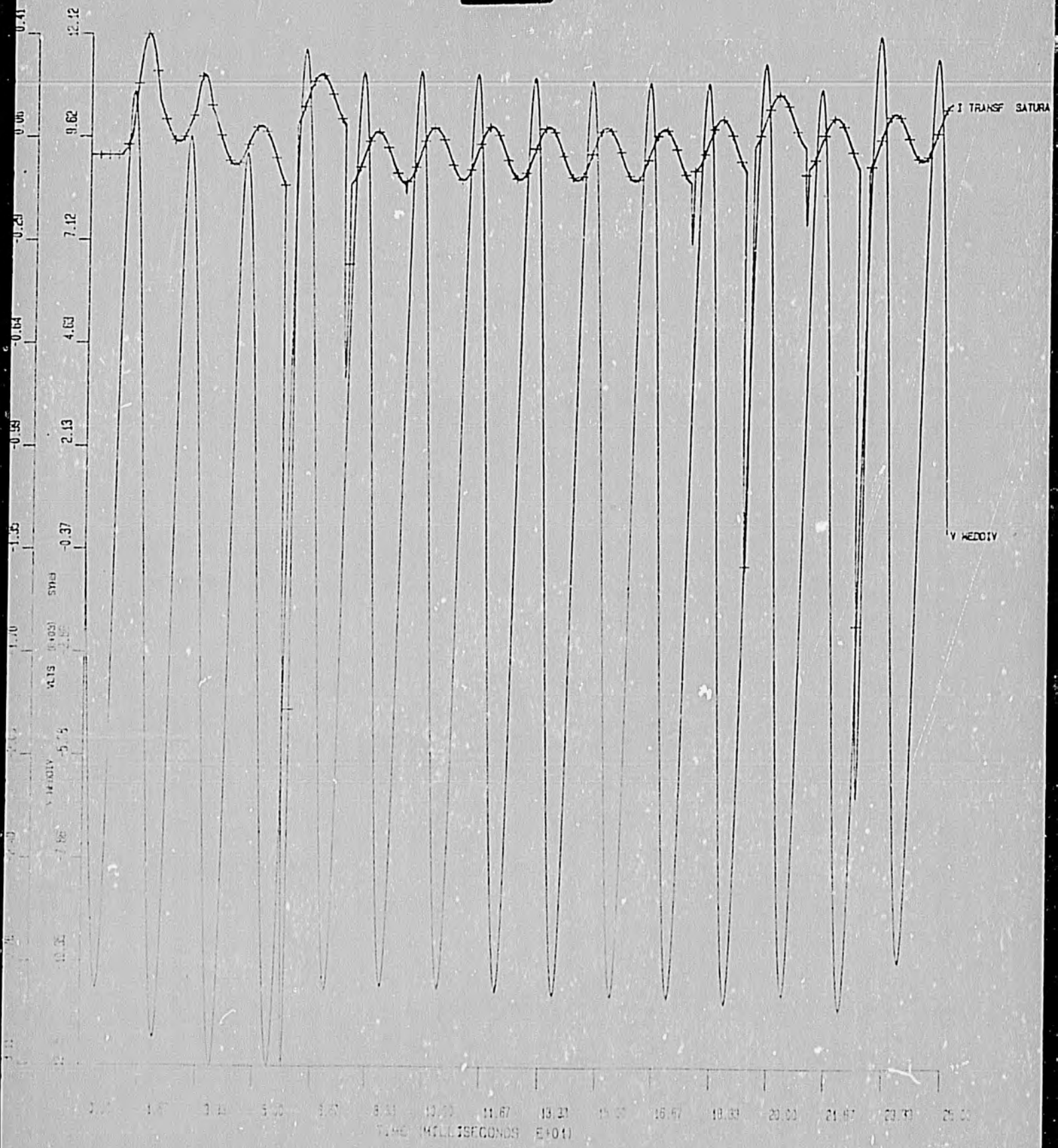


FIGURE 6. ENERGIZING THE DISTRIBUTION TRANSFORMER AT V. LOAD.

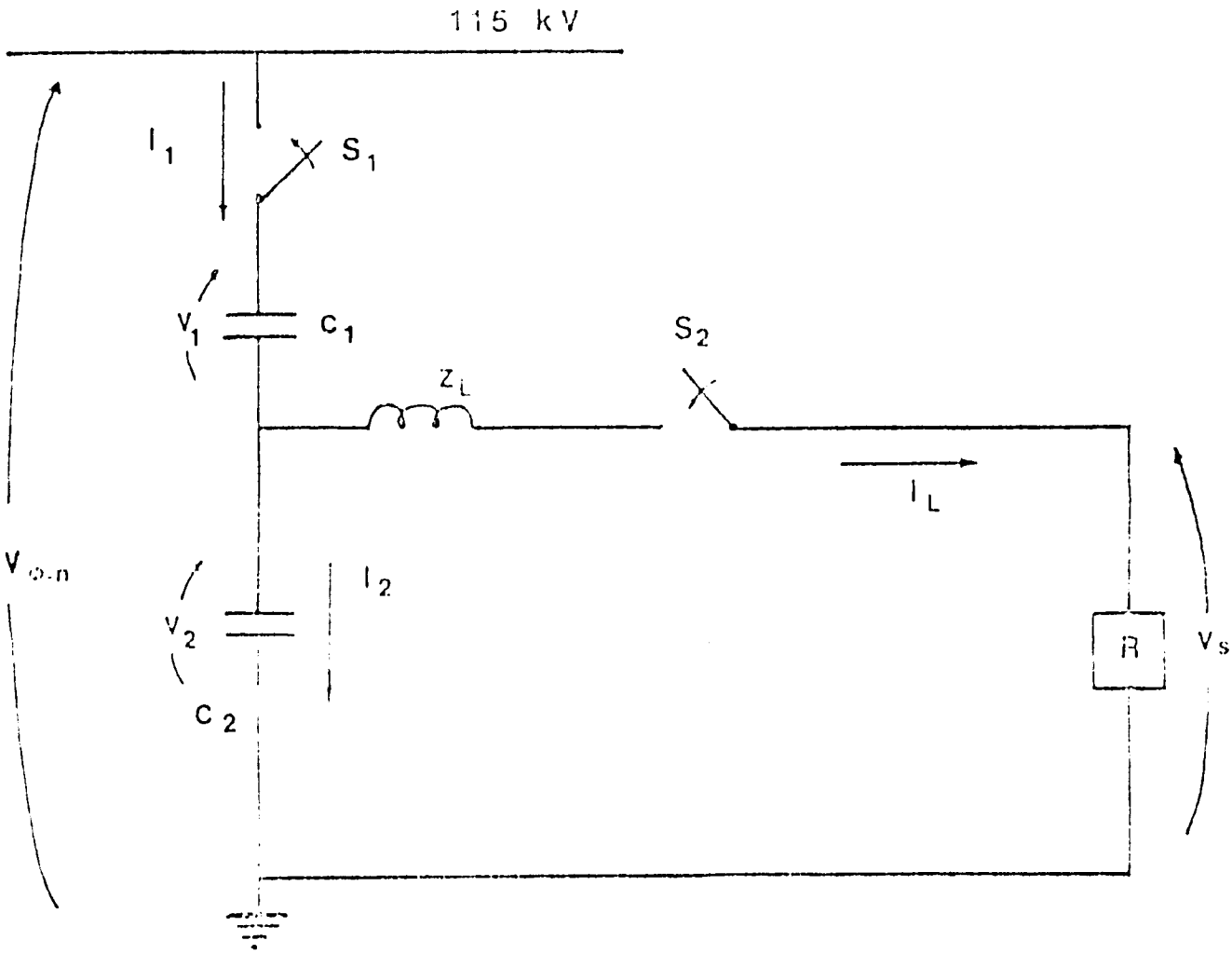


FIGURE 7.
CAPACITIVE VOLTAGE DIVIDER WITH COMPENSATION REACTOR.

2) With S2 closed, energize the capacitor bank with the distribution transformer in the circuit at no-load, at the instant the source voltage is positive maximum (see Fig. 8).

3) With S2 open and with the capacitor bank energized, de-energize it with maximum negative voltage, so that the bank is charged. Afterwards, re-energize the bank with maximum positive voltage.

In cases 1) and 2) no overcurrents or overvoltages that could damage the capacitor units or that would cause some protection to operate were observed. Nevertheless, case 3) showed overvoltages that could be harmful to C_1. In this case the automatic reclosing of the h.v. line was simulated. It is worth mentioning that in Mexico, 115 kV lines do not have automatic reclosing. In case a capacitive voltage divider is to be designed for a transmission line of higher rated voltage, this represents an important point for further analysis.

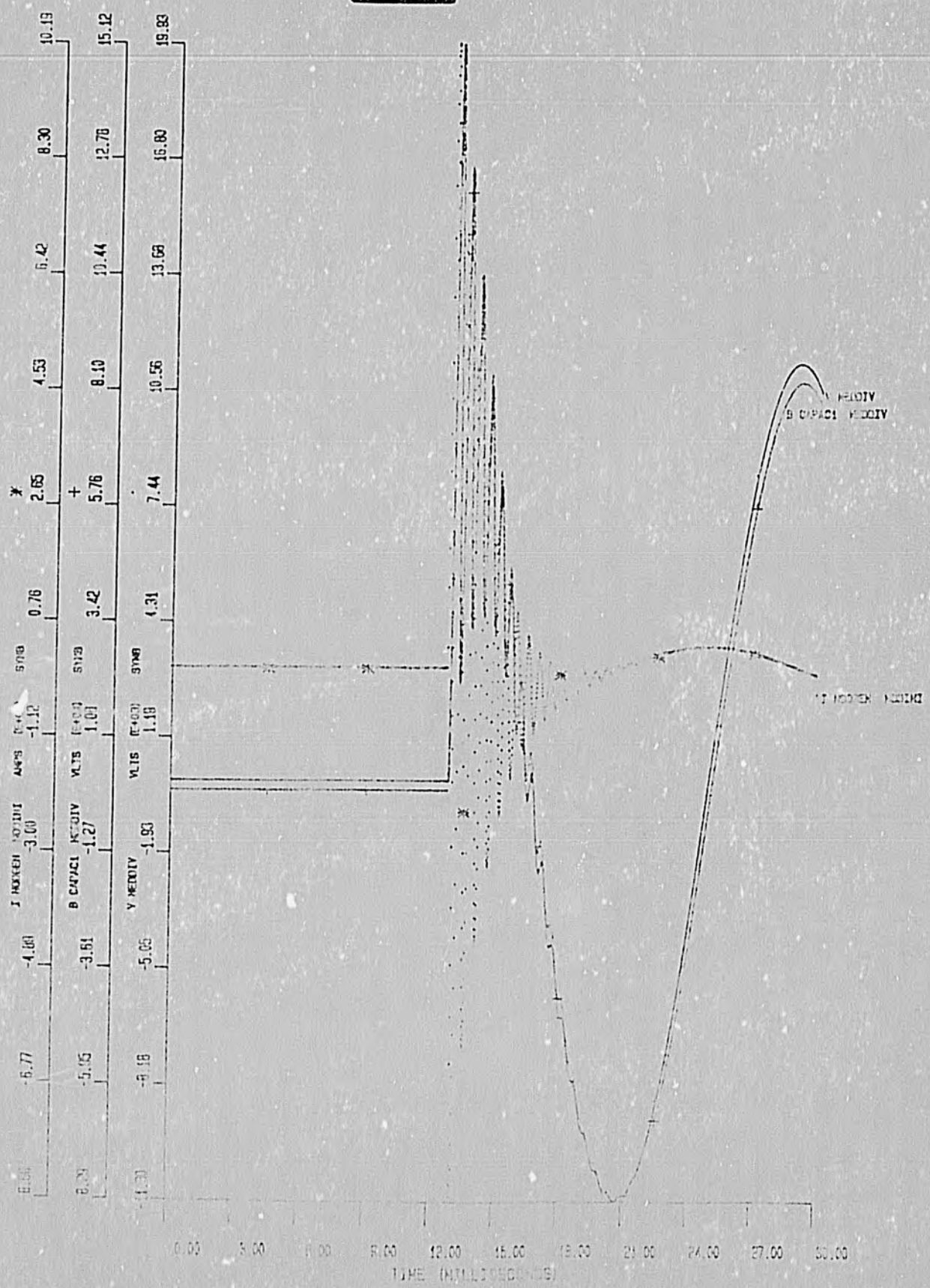


FIGURE 8. SWITCHING OF CAPACITOR BANK WITH TRANSFORMER AT NO LOAD.

II.3. Protective Scheme

The protective scheme for the capacitive voltage divider was designed taking into account its dynamic performance under the following events:

a) Short circuit
b) Distribution transformer energization
c) Switching surges and lightning overvoltages

a) Short circuit

As previously explained in section II.2.1., the short circuit currents were limited by separating the inductive reactance between the high and low voltage sides. The short circuit studies illustrated the following aspects:

- Short circuit currents and voltages in the capacitor bank (C_1 and C_2) show damp oscillations.
- By an adequate selection of the high voltage reactor, overvoltages in C_1 and C_2 are limited to values of less than 1.3 times their rated voltages.

This last point merits some attention. Several circuit configurations were studied with the purpose of lowering short circuit currents and therefore decreasing the overvoltages across C_1 and C_2. The configurations analyzed are illustrated in Figures 9, 10, 11, and 12.

Figure 9 shows the first case analyzed. It consisted of detuning the circuit with a shunting gap across the reactor. The purpose was to have the middle point MEDDIV at zero voltage when the gap sparkedover at voltage values greater than the ones at full-load.

Nevertheless, the transient analysis performed in the computer showed the following problems:

- The fault current signal is very small compared to the full load current and therefore is hard to detect by conventional protective devices.

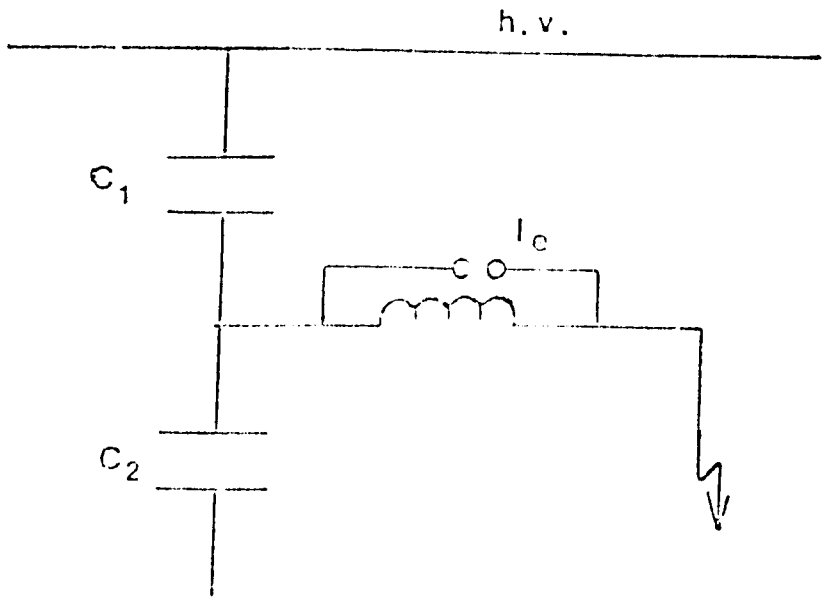


FIGURE 9. GAP SHUNTING REACTOR.

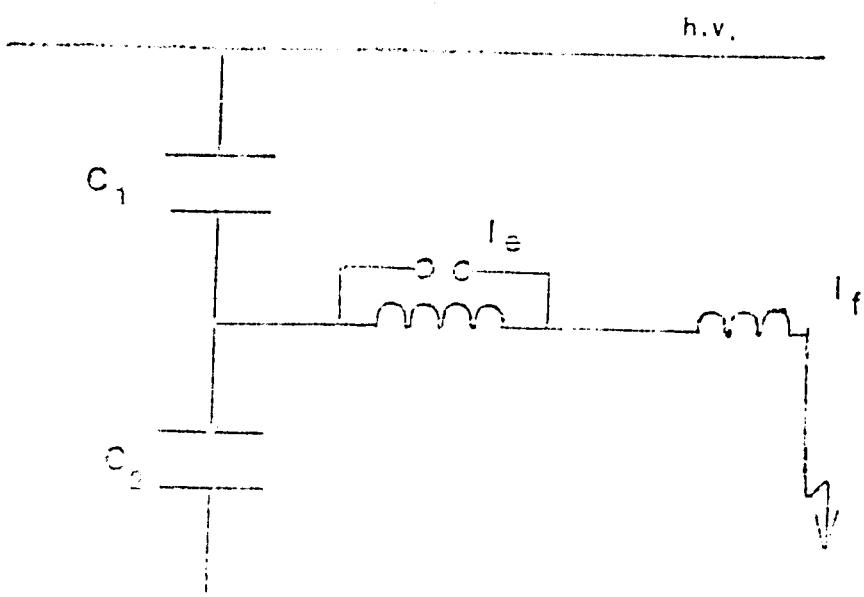


FIGURE 10. GAP SHUNTING A PORTION OF THE REACTOR.

- The possibility of using current I_e across the gap to operate a recloser was studied. The problem encountered was that this current is high in a very short period corresponding to the discharge of capacitors C_2 and then it becomes too small. This led to the second case studied shown in Figure 10. It consisted of placing the gap across one portion of the reactor so the values of I_e and I_f are increased and thus easier to detect. In the computer analysis significant overvoltages were observed in the capacitor banks due to the phase shift between overvoltage and current. Therefore, this configuration was discarded.

The next case analyzed is shown in Figure 11, which consisted in placing one reactor in the primary side, and a second reactor in the secondary side, in order to complete the tuning of the circuit. This was done with the purpose of limiting the short circuit value in the primary side since it is only partially compensated. The gap across C_2 was placed so as to limit overvoltages in C_2.

Computer simulations showed the following results:

- A high frequency component appears in the voltage across C_1 due to the gap sparkover.

- The frequent operation of the gap does not allow the overvoltage at C_2 to stabilize.

- The fault current waveform is too distortioned and could present rms values difficult to differentiate with the rated current.

Therefore, in the next case analyzed, shown in figure 12, the same circuit is used except the gap across C_2 is eliminated.

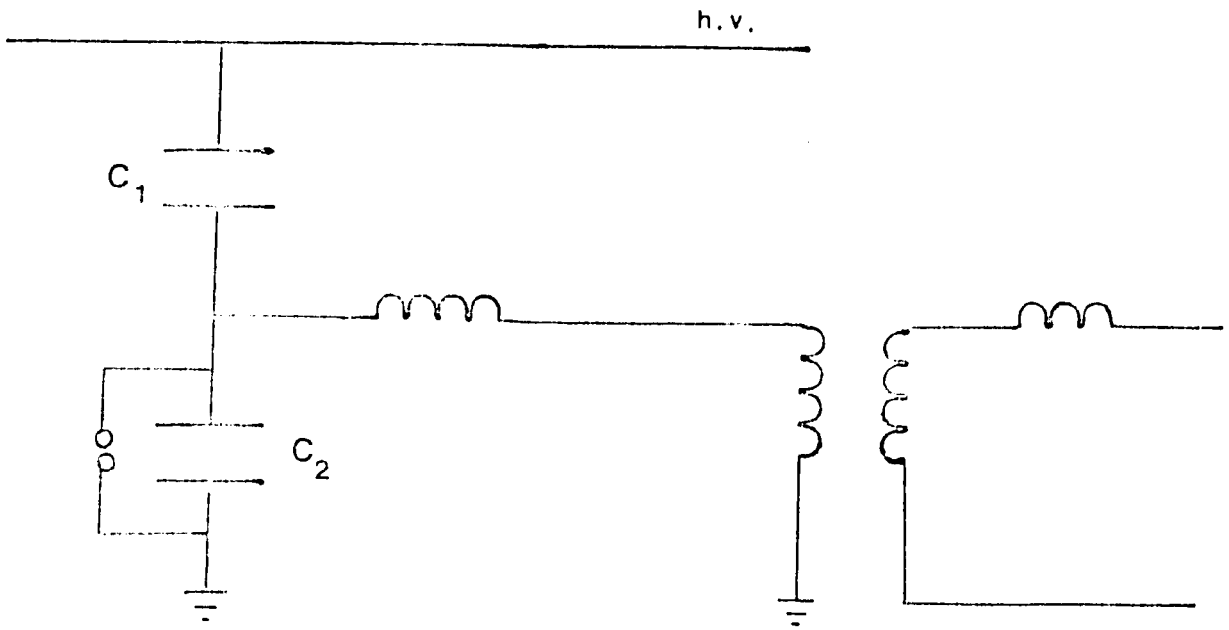


FIGURE 11. TWO COMPENSATING REACTORS, ONE IN THE PRIMARY, THE OTHER IN THE SECONDARY. GAP SHUNTING C_2.

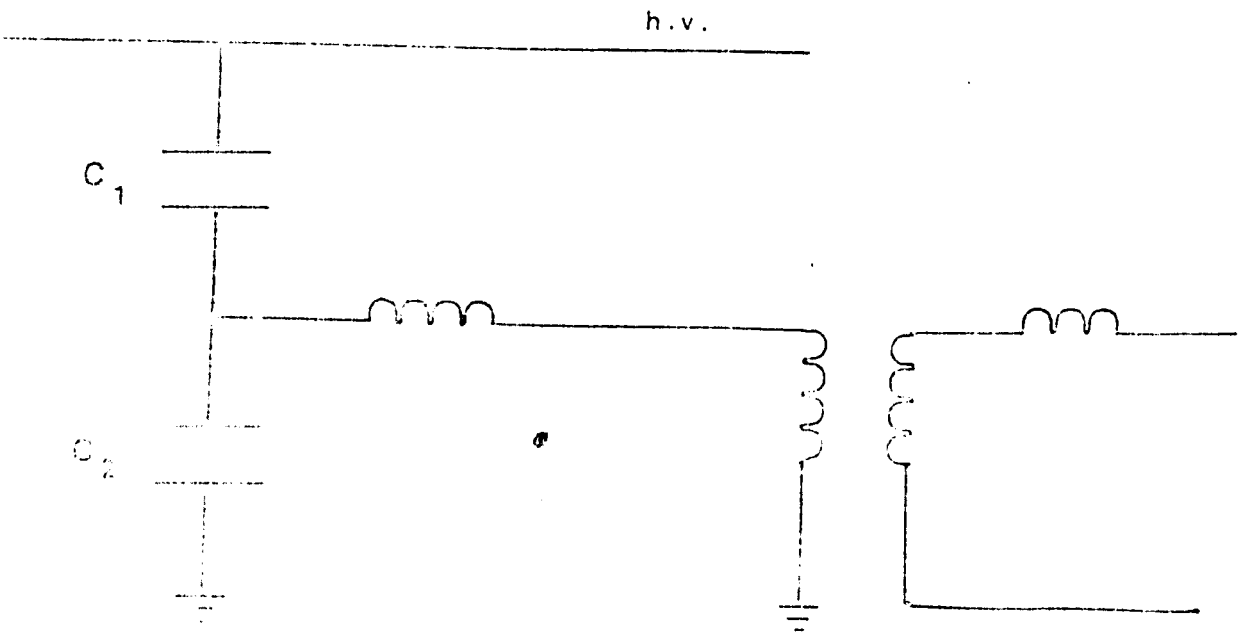


FIGURE 12. SAME AS BEFORE, EXCEPT WITHOUT GAP.

As explained before, by separating the tuning reactance between the primary and secondary sides, the short circuit currents in the primary side are reduced. The absence of the gap resulted in sinusoidal waveforms. This last scheme was the one adopted.

On the other hand, to disconnect the voltage divider from the 115 kV transmission line, a single pole power fuse disconnector was chosen. It will protect against faults between its terminals and the capacitor bank, faults in the units of C_1, and faults in the transmission line. It will not operate with a low voltage fault or with inrush currents. The next section will show all component specifications.

In the 7.6 kV distribution line a 2A fuse-cutout was chosen. The reason for this selection is discussed in the next chapter on laboratory tests.

b) Distribution Transformer Energization

The analytic studies concerning inrush currents when energizing the distribution transformer showed the following results:

At first, a 7.2 kV transformer was modelled, but core saturation was observed, which led to significant overvoltages and overcurrents. For this reason, and also considering the fact rated voltage is a little above 7.2 kV, a single-phase 13.2-0.240/0.120 kV unit was chosen, increasing the saturation knee in this way.

c) Switching surges and lightning overvoltages

With respect to line switching, it was concluded that the only dangerous operations were those occurring with the capacitors close to their rated charge. Since this is improbable for transmission lines without automatic reclosing, because the capacitors are discharged to less than half their value between operations, no protection was considered for this type of events.

For lightning protection, it was decided to use zinc oxide arresters in both the primary and secondary sides. Again, the chapter on laboratory tests will further discuss this point.

II.4. COMPONENT SPECIFICATION

As a reference, we will list each of the components in the capacitive voltage divider along with their specifications.

II.4.1. Capacitors

a) Single-phase units with two bushings each, for outdoor service.

	Quantity	Capacity (KVAR)	Rated Voltage (kV)	Capacitance (μF)
C_1	4	50	13.8	0.6964
	2	50	14.4	0.6396
C_2	2	100	12.47	1.7058

Each unit contains an integrated discharging resistance.

b) Insulation characteristics

Capacity (kVAR)	Rated Voltage (kV)	BIL
50	13.8	95
50	14.4	125
100	12.47	95

II.4.2. Reactor

a) Low voltage reactor

Current limiting series reactor, type AA, air core, single-phase, 60 Hz for outdoor service.

Measured inductance = 0.635 mH
Rated current = 200 A
Short circuit current = 2000 A in 2 s
Rated voltage = 1.2 kV
Temperature rise = 80°C
Measured impedance at 25°C = 0.240 ohms

b) High voltage reactor

Current limiting series reactor type AA, air core, single-phase, for outdoor service, 60 Hz.

Measured inductance = 3.9 H
Rated current = 3.3 A
Short circuit current = 40.0 A in 1 S
Rated voltage = 15 kV
Temperature rise = 80° C
Measured impedance = 1474.2 ohms
Weight = 225 kg
Impulse voltage = 95 kV

II.4.3. Protective equipment

a) Power fuse disconnector for outdoor service, single pole.

Rated voltage = 115 kV, 121 kV maximum
Maximum rated current = 250 A
Interruptive capacity = 12 500 A

BIL = 550 kV

Fuse element = 10 A

Insulators = Station post

Weight = 207 kg

2) Distribution fuse-cutouts, single pole

Rated voltage = 14.4 kV

Maximum voltage = 15 kV

Maximum current = 200 A

BIL= 125 kV

Interruptive capacity = 8000 A asymmetrical

3) Distribution class lightning arrester

Zinc oxide surge arrester, outdoor service

Rated voltage = 10 kV

Maximum continuous operating voltage = 8.4 kV

4) Intermediate class lightning arrester

Zinc oxide surge arrester, outdoor service

Rated voltage = 90 kV

Maximum continuous operating voltage = 70 kV

Weight = 38 kg

II.4.4. Distribution Transformer

Single-phase, 60 Hz

13 200 - 240/120 V

50 kVA

Four position tap changer of 2.5% (+2,-2)

II.5. Installation Layout

Figure 13 illustrates how the avove equipment is connected to form the complete capacitive voltage divider.

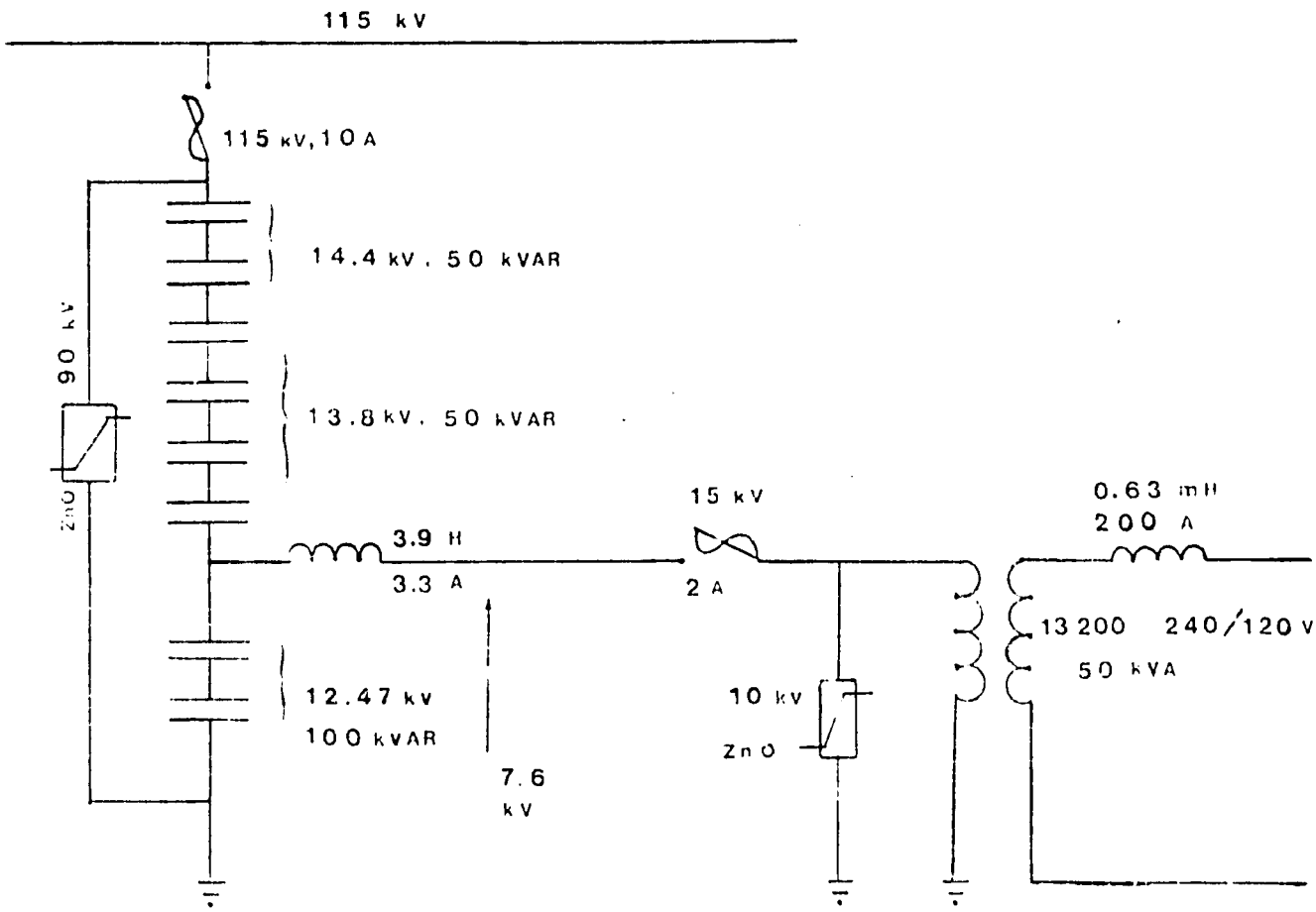


FIGURE 13. FINAL INSTALLATION LAYOUT.

Chapter III. Prototype Laboratory Tests and Operating Characteristics

III.1. Introduction

In this chapter, laboratory tests of the complete voltage divider scheme are described. These series of tests were performed at the Mexican Electrical Research Institute's Lab located in Salazar, Edo. de México.

The objectives were to:

a) Determine service quality (voltage regulation) and system reliability; from the consumer point of view, and with the protective devices chosen.

b) Determine possible effects in the 115 kV transmission line.

c) Check the adequate operation of all components under severe conditions.

d) Verify the final design.

e) Evaluate operating practices.

The test program was divided into three main areas:

- Short circuit
- Distribution transformer energization
- Load rejection

Description of the tests and results under these areas appear in the following sections.

III.2. Short Circuit Testing

In the tests described below, no lightning arrester was used on the primary side.

a) Short circuit in the 7.6 kV line

These first series of tests consisted in simulating short circuit faults in the 7.6 kV line (see Fig. 13) under the following situations:

a.1.) Closing the 115 kV breaker with the reactor on the primary side short circuited. Recorded values are shown in Table II, and the circuit used is displayed in Figure 14. Current peaks in the order of 17 A were observed when energizing the circuit and when the fuse operates. A peak voltage value of 28.6 kV across C_2 was recorded at the beginning and at the end of the transient condition.

a.2.) Energizing the voltage divider at no load, and then closing a switch to short circuit the primary side.

Again, recorded values are shown in Table II. The same peak current values of 17 A were recorded during the transient condition. The maximum peak voltage registered across C_2 was 29.9 kV.

a.3.) The same as before, but with a fault resistance of 7.7 ohms.

Recorded values are displayed in Table II. In this case, current peaks reached 19.4 A and voltage peaks across C_2 attained 30.88 kV.

It is important to stand out the fact that in every case the 2A fuse (see Fig. 13) operated satisfactorily; and that in neither test, the voltage in the 115 kV line varied more than 2%.

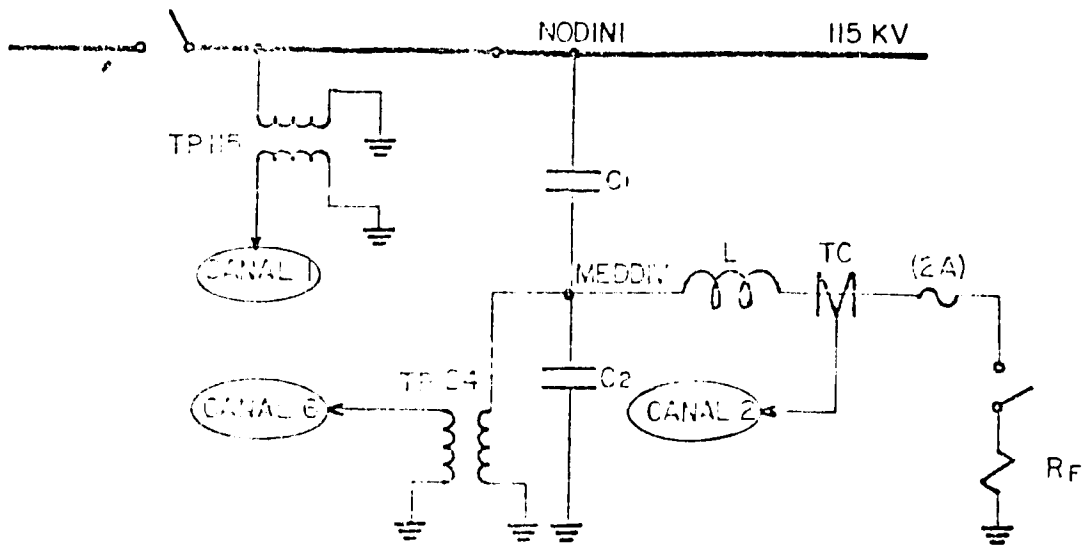


FIGURE 14. ARRANGEMENT FOR THE SHORT CIRCUIT TEST IN THE 7.6 kV LINE

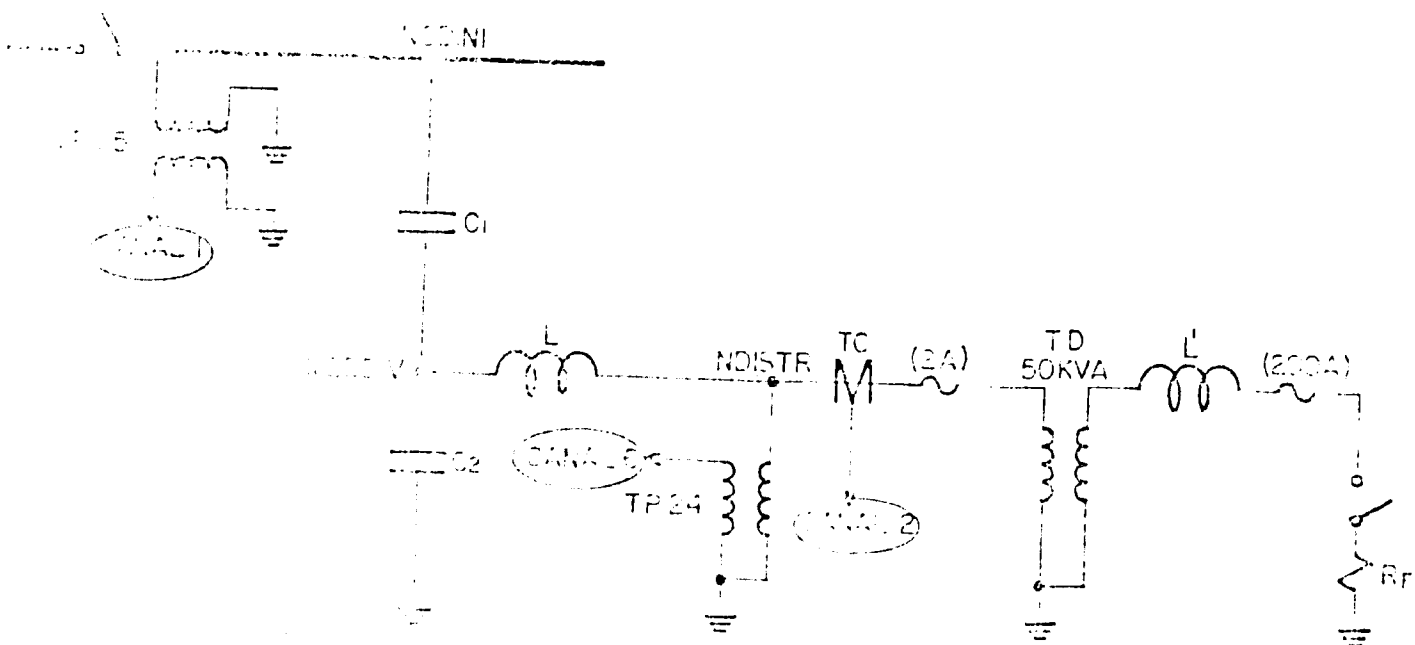


FIGURE 15. ARRANGEMENT FOR THE SHORT CIRCUIT IN THE TRANSFORMER SECONDARY.

TABLE II

SHORT CIRCUIT TESTS IN THE 7.6 KV LINE

Test #	Fault Resistance (Ohms)	Voltage at NODINI (kVrms)	Voltage at MEDDIV (kVrms)	Current (Irms)	Interrupting time (s)
1)	0	66.4	11.26	7.43	1.1
2)	0	65.03	9.42	7.55	0.9
3)	7.7	67.74	10.57	7.58	1.03

b) Short circuit in the transformer secondary, after the low voltage reactor (see Fig. 13). The circuit used for these tests appears in Figure 15. The 50 kVA transformer has a turns ratio of 57.75 (13 860-240 kV). Two different tests were performed and are described below:

b.1.) The circuit was energized at no load, and then the secondary side was short circuited as shown in Figure 15. Current peaks in the primary side were recorded with values up to 29.96 A. This corresponds to a peak current of 1672 (1182 A rms) in the distribution transformer secondary. On the other hand, voltage in the primary side was measured to be 7.58 kV rms at no load, and during the short circuit it reached peak values of 30.87 kV (21.83 kV rms). Other measured values are shown in Table III.

b.2.) The above test was repeated, except the 2 A fuse was replaced by a 6 A element. The short circuit was interrupted by the 115 kV breaker in 1.6 seconds, the 6A fuse did not operate. The voltage at the primary terminals of the transformer reached 15.63 kV rms, while the fault current reached 21.39 A rms. This corresponds to 1235 A rms in the low voltage side (1 747 A peak).

TABLE III

SHORT CIRCUIT TESTS IN THE TRANSFOMER SECONDARY

Test #	Voltage at NODINI (kV rms)	Voltage at NDISR (kV rms)	Peak Current at 120 V (A)	Interrupting time (S)
1)	69	- -	1672	0.4 (2A fuse)
2)	73.16	15.63	1747	1.6 (115 kv breaker)

Again, it is noted that the voltage in the 115 kV line never varied more than 10%.

c) Short circuit on the transformer secondary, after the low voltage reactor, with a lightning arrester on the primary side.

In these tests, a 75 kVA unit was used, and a distribution 10 kV class lightning arrester was connected on the transformer primary. The test circuit is shown in Figure 16.

With this arrangement, two different tests were executed as follows:

c.1.) This test was similar to the one described in b.1.) above. It is worth noting that the peak voltages of 30.87 kV recorded in test b.1.) were reduced to values in the order of 23.44 kV peak (16.5 kV rms), 24.4% less. The fault current measured was 34.18 A peak, greater than the one measured in b.1.) because of the increased capacity of the transformer. The 2 A fuse operated in 0.33 s.

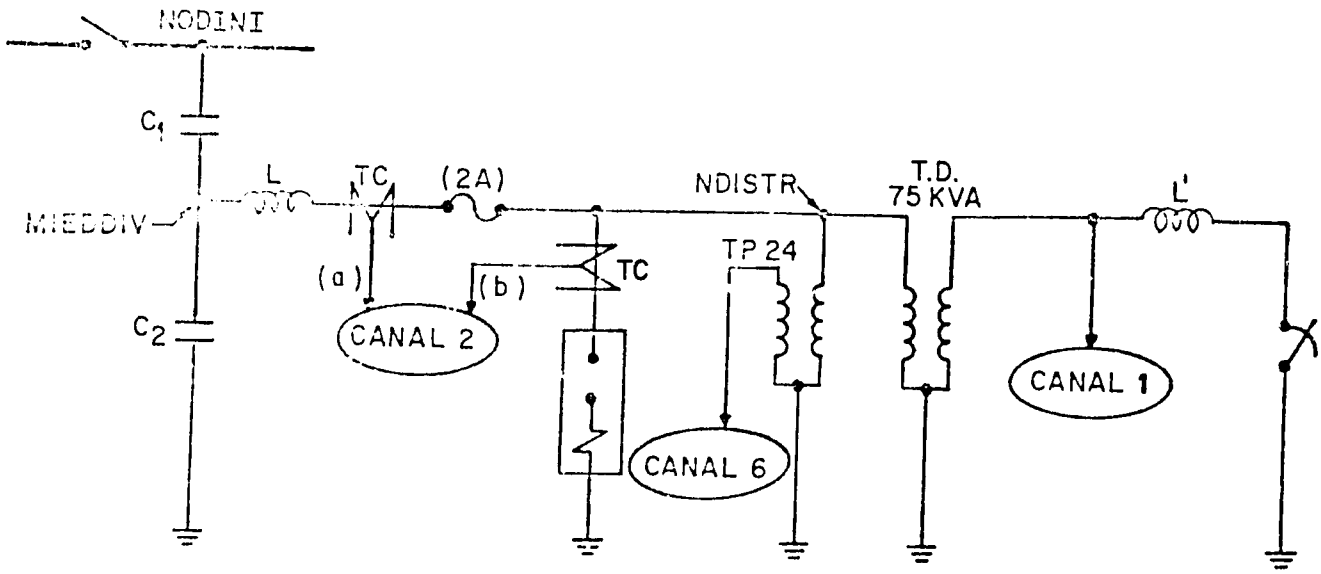


FIGURE 16. TRANSFORMER SECONDARY SHORT CIRCUIT, WITH LIGHTNING ARRESTER.

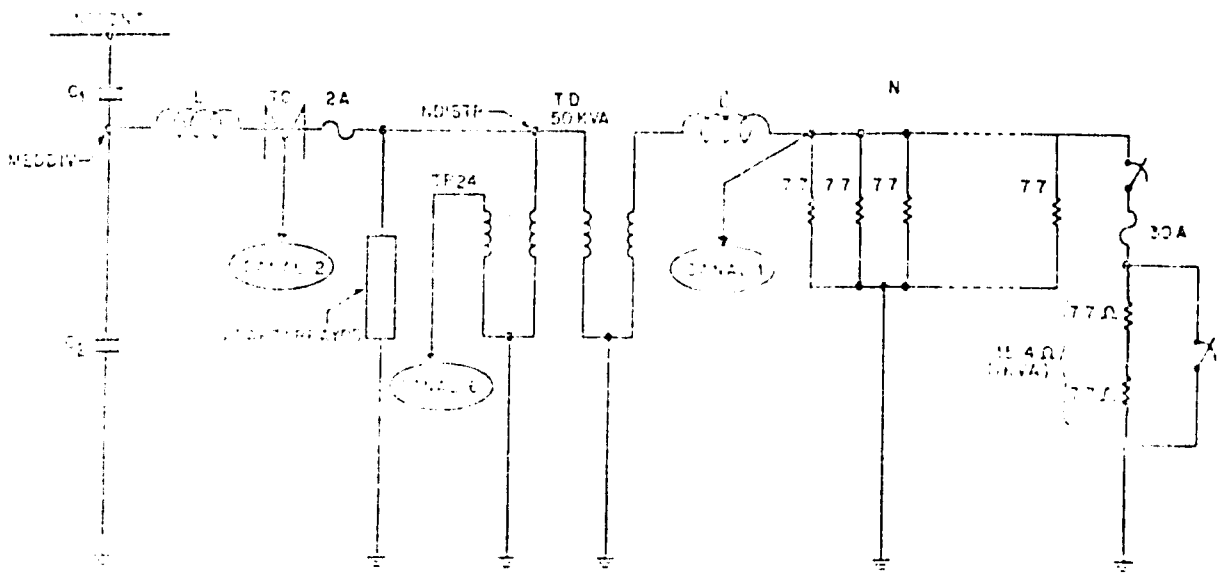


FIGURE 17. TEST CIRCUIT FOR FAULT AT CONSUMER'S LOCATION.

c.2.) The above test was repeated to measure the lightning arrester current (indicated by letter "L" in Figure 16). The resultant current was too low and could not be measured.

d) Short circuit at the consumer's location.

The capacitive voltage divider has no secondary protection. A fault in the low voltage side will be cleared by the 2 A fuse. It is considered then that any fault at the consumer location will be cleared by its own protective system (fuses or thermomagnetic breakers). The following tests were made to verify this condition. The SiC lightning arrester was replaced by a ZnO unit of the same 10 kV class. The load resistances were located at a distance of approximately 50 m from the transformer. The original 50 kVA distribution transformer was again used. The test circuit is shown in Figure 17, where "N" represents the number of resistances used in each case. Note the 30 A fuse in series with two 7.7 ohm resistances which are short circuited to simulate a household fault.

d.1.) Household short circuit with 25% of load.

The fault was interrupted by the 30 A fuse in less than 3 cycles. Measured low voltage fault current was 519 A peak. During interruption, voltage peaks were reduced by the ZnO arrester to 19.2 kV.

On the transformer primary, measured low current was 57 A rms.

d.2.) Household short circuit with 50% of load.

The fault was interrupted by the 30 A fuse in less than 3 cycles. Measured low voltage fault current was 455 A peak, with load current being 109.5 A rms. Again, oscillograms show a succesful operation of the lightning arrester in limiting overvoltages.

d.3.) Household short circuit with 75% of load.

Measured parameters are practically the same compared to the previous test, except the load current was 127 A rms.

d.4.) Household short circuit with 100% of load.

Measured load current was 155 A, all other measured values remaining practically the same.

In each of the last four tests, the 30 A fuse operated in less than 3 cyles. Fault currents measured were not greater than 520 A.

d.5.) Short circuit on the transformer primary side.

This test was executed with a 3A fuse on the primary side. After 3 seconds of fault current circulation, the 3 A fuse did not operate; and the fault was cleared with the 115 kV breaker. The permanent fault current measured was 5.79 A rms with peak values in the transient period of 13.0 A. Therefore, circuit protection with a 3A fuse was discarded.

For the above tests, figure 18 show the voltage drop in the load with a size # 6 cable and length of 60 m.

III.3. Distribution Transformer Energization

The circuit used for these tests is the same as the one shown in Fig. 15, except RF represents a load resistance with values as follows:

a) Transformer at no load.

This test was performed with the purpose of determining the transformer inrush current and its associated overvoltages. The unit was energized at no load for almost 7 seconds, without significant overvoltages or wave distortion being recorded. Moreover, no value of inrush current was observed. In the transmission line a value of 65 kV rms was sustained during the test, while the voltage in the transformer primary side reached 7.81 kV rms.

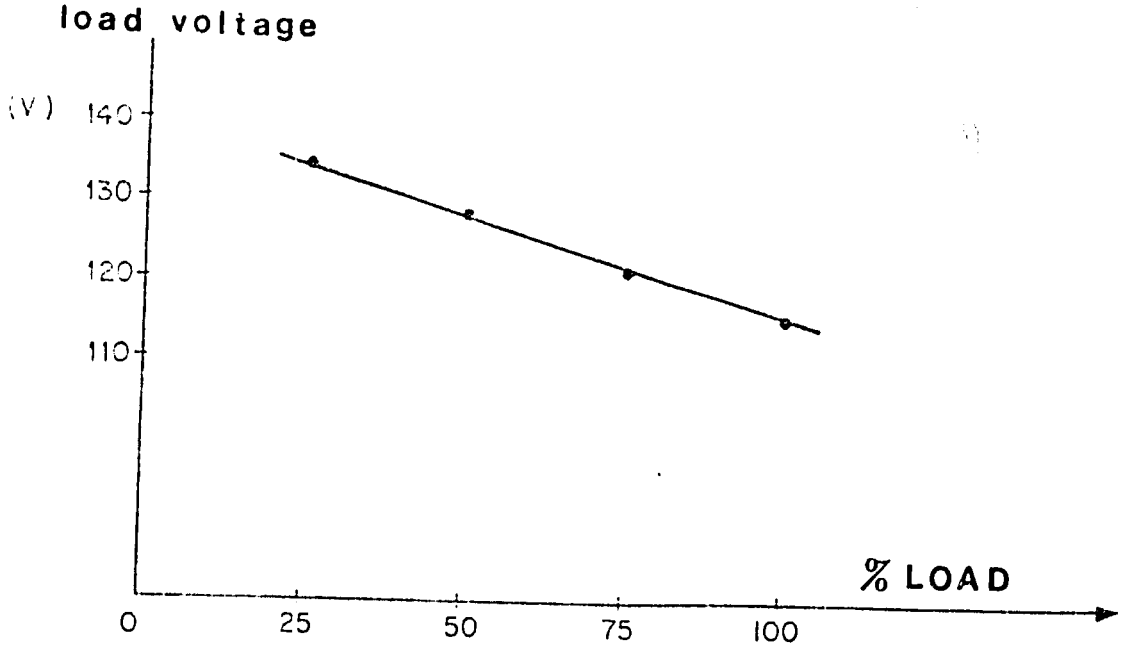


FIGURE 18. LOAD VOLTAGE REGULATION.

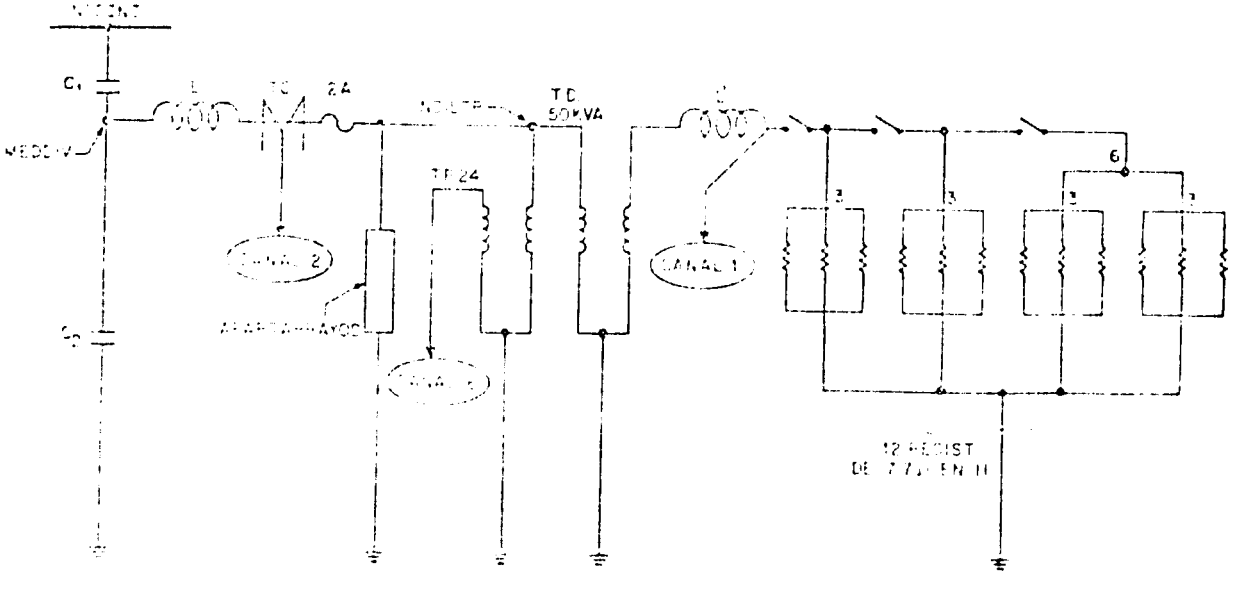


FIGURE 19. TEST CIRCUIT FOR LOAD REJECTION.

b) Transformer energization with a load of 2.57 ohms.
Current measured had a value of 1.06 A rms corresponding to 61.31 A rms on the secondary side.

c) Transformer energization with a load of 1.28 ohms.
An initial voltage wave distortion is observed, but considered negligible. Values measured were 62.3 kV rms in the transmission line, 7.81 kV rms in the transformer primary, and 1.97 A rms in the high voltage side. Table IV shows a summary of these results. Main points to note from these tests are:

- Maximum peak inrush current measured was 2.8 A, less than the 3.11 A peak calculated in II.2.2.
- Maximum change in the 115 kV line was 6.2%.

TABLE IV

DISTRIBUTION TRANSFORMER ENERGIZATION

Test #	Voltage at NODINI (kV rms)	Load Transformer (ohms)	Low Voltage current (A)
a)	65	open	0.00
b)	66.38	2.57	61.31
c)	62.3	1.28	113.87

III.4. Load Rejection

The circuit used for these tests is shown in Figure 19. Four tests were executed with varying load conditions.

a) Load change from 50 to 75 to 50%.
On the transformer primary side, load current changes from 1.64 A rms to 2.32 A rms and back to 1.64 A. Both primary and secondary voltages remain practically the same during this change of load.

b) Load change from 8.3 to 50 to 8.3%.

Again, primary and secondary voltages remain practically the same during the load change. It is only at the instant of disconnecting the bigger load that a small overvoltage is observed (one cycle).

c) Load change from 8.3 to 75 to 8.3%.

During the first cycle after disconnecting the first load, an overvoltage was registered. The oscilogram also shows the arrester operation.

d) 100% Load rejection.

This test is considered the most severe that can possible occur. When the total load is disconeected, an overvoltage appears on the primary side. This surge is limited by the ZnO arrester to 19.5 kV peak. The waveform appears with trimmed peaks. Successful arrester operation is also observed in the current peak, which coincides with the voltage crest.

The main conclusions drawn from the test program are included in the next chapter.

III.5. Experimental Field Installation

As discussed in Section I.3, CFE's choice for the experimental stage of this project was a small rural neighbourhood called La Pradera, in the outskirts of the city of Chilpancingo, state of Guerrero. An schematic drawing of the experimental site is shown in figure 20.

Immediately after the tests were finished and this last site chosen, all the equipment from the pilot installation in lab was moved to Chilpancingo, where the necessary construction began immediately. Unfortunately, one section of the high voltage reactor was damaged during transportation and had to be repaired. The repaired section was ready on October 14, 1987 and was taken to Chilpancingo two days later.

All construction work was concluded on October 23, 1987. The date selected for energizing the voltage divider was October 29th. At first, a visual inspection was performed of the whole installation, checking distances and connections. At the lab, we had an insulation to ground problem with the first capacitor unit. This problem was solved in the field by increasing the distance between the two wooden poles that hold the voltage divider, and by insulating the capacitor units from ground with 69 kV insulators.

The next step was to verify the inductance values both from the high and low voltage reactors, and the capacitance value from the high voltage capacitor bank. It was not possible to perform the measurement of the low voltage capacitor bank, since it is located just underneath the high voltage bank, and there was no way to avoid interference.

At 15:00 h, the capacitive voltage divider was energized by closing the 115 kV power fuse. Nothing unexpected happend, and subsequently the transformer was energized at no load. At 15:47 h, the measured secondary voltage was 140 V. The transformer secondary was connected at 16.10 hours, and the same 140 volts at the terminals was recorded. Several measurements were taken at

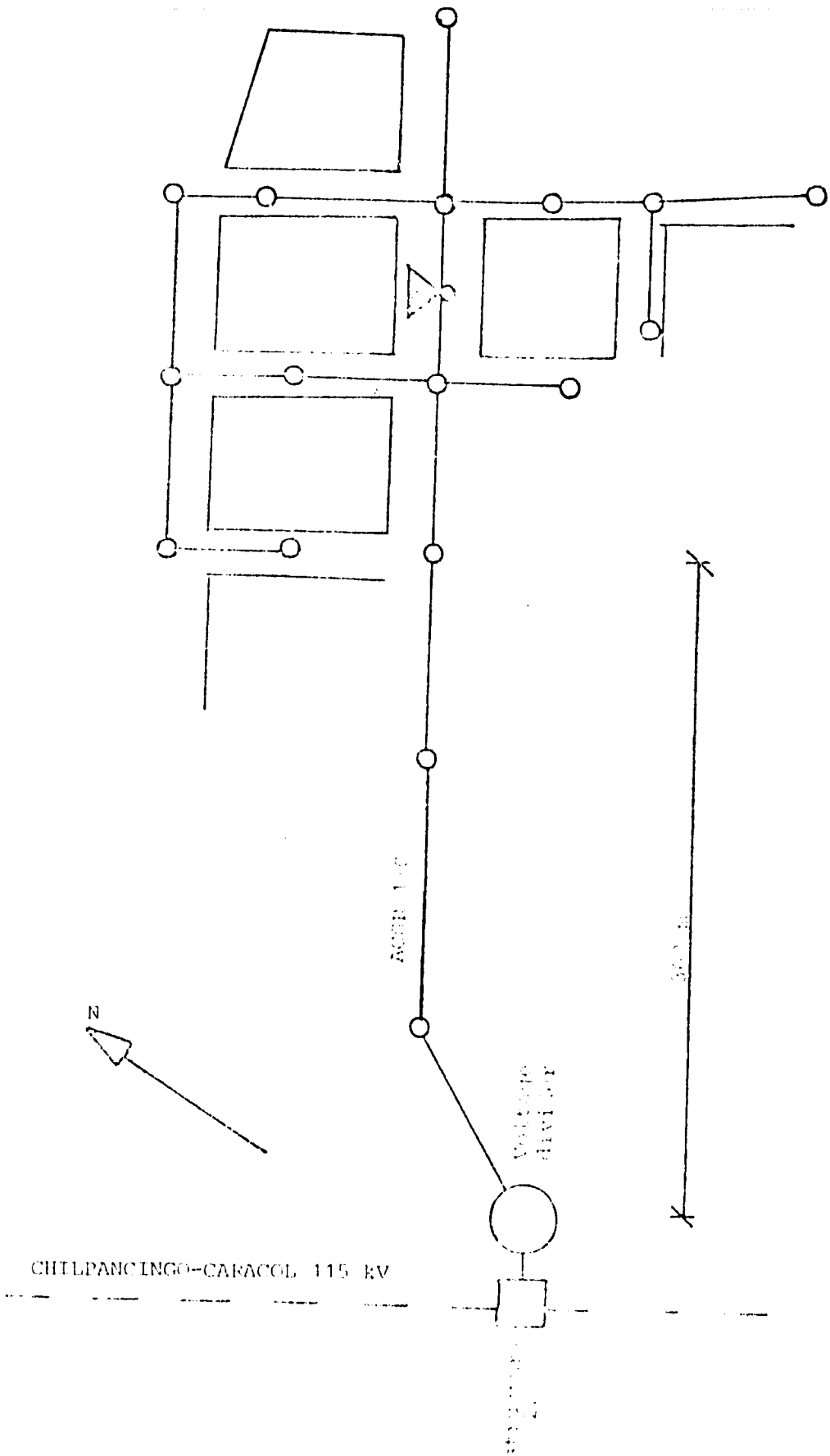


FIGURE 20.
SCHEMATIC
DRAWING OF THE
EXPERIMENTAL SITE.

different dwellings, and the same voltage magnitude was obtained. This is due to the fact that the load is primarily lighting. Prompted by the high voltage magnitude, the transformer was opened the next day, and the tap changer was found at the # 3 position. It was changed to position # 1 and the readings taken were 132 V in light load periods and 125 V during the peak demand. Later measurements have shown that the voltage divider is supplying a load in the order of 20 A (minimum demand) and 50 A (maximum demand).

CHAPTER IV Conclusions

The following conclusions were drawn after the laboratory testing described in Chapter III was finished:

1) In several of the tests performed, it was verified that the voltage magnitude just after the low voltage reactor has insignificant variations, which agrees with theory and represents an additional advantage of the voltage divider.

2) No dangerous overvoltages were measured in the 115 kV supply line. Nevertheless, the field installation is protected with a 90 kV zinc oxide arrester.

3) The maximum transient peak voltage measured at C_1 was 110% of the rated peak voltage of that bank, and should pose no problems for the units forming C_1.

4) The maximum transient peak voltage measured at C_2 was 100% of the rated peak voltage of that bank, and should not be a problem for the units forming C_2.

5) During the short circuit tests described in section III.2.C a SiC arrester was installed on the transformer primary. Two units failed due to repeated operations as the 60 Hz voltage peaks are sustained until the fault is cleared. For subsequent tests this type of arrester was replaced by a ZnO unit. A better system performance was observed from then on.

6) When simulating household faults, the 30 A fuse typically used un rural areas operated in less than 3 cycles in every case.

7) Both analytically and expermentally, the air-core reactor design has shown that the probability of occurrence of ferroresonance is minimized.

In fact, neither in the computer simulations or in the lab did we register this phenomenon.

With regard to the overall project:

8) It has been shown that the capacitive voltage divider represents an alternative, both technically and economically speaking, to supply electric energy to rural communites located near a transmission line.

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  - Pedro Avelino
  - Andrés López
  - Inocente Rosales

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  - Daniel García
  - Ramón de la Rosa
  - Sabás López

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  - Marcos Ayala