RECOVERY VOLTAGES AND SUSTAINED CURRENTS FOR A SINGLE PHASE LINE TO GROUND FAULT

By

K.S. JULIEN,

SUMMARY

This paper considers the effect of the electrostatic and electromagnetic couplings in a transmission system on the automatic reclosing operation when a single phase to line ground fault occurs.

These considerations are based on analytical expressions derived in this investigation and the more important preliminary results are discussed.

(1) INTRODUCTION

In an extra high voltage system with the neutral grounded, the most common type of outage is due to a single-phase line to ground fault.

For a long section of transmission line, the restoring of the electric strength of the arc path after switching off the faulty phase, is greatly influenced by the capacitive and electromagnetic coupling with the healthy phases. The line current in the faulted section - the so-called sustained current and the recovery voltage - i.e. the voltage between the faulted section and ground - are the quantities that result from these couplings.

The amplitude and duration of this current and voltage are the major factors that determine the success of a single-phase automatic reclosing operation. The line current in the faulted section sustain the electric arc for some time, even after the faulty phase has been disconnected and the existence of a coupling voltage hinders the restoration of the electric strength of the arc path, both obstacles to the next reclosing.

This matter has received some attention, particularly in the Russian literature and in order to give some appreciation of the practical aspects of the problem, data obtained experimentally are reproduced in Table 1. This data is for a configuration as shown in Figure 1. The line to ground fault occurred at the beginning of a section to which shunt reactors were connected at the opposite end. Previous field tests (1) indicated that these circumstances lead to the worst conditions.

The figure produced in Table I indicate that the magnitude of the sustained current seems to be the primary factor, although not the only one for successful reclosing. The persistence of the recovery voltage rather than its magnitude seems to be the effective factor.

In this study, theoretical methods of obtaining values for the sustained current and the recovery voltage were developed. The possibility of the use of a neutral reactor to minimise these quantities was also investigated using the analytical expressions developed in this study.

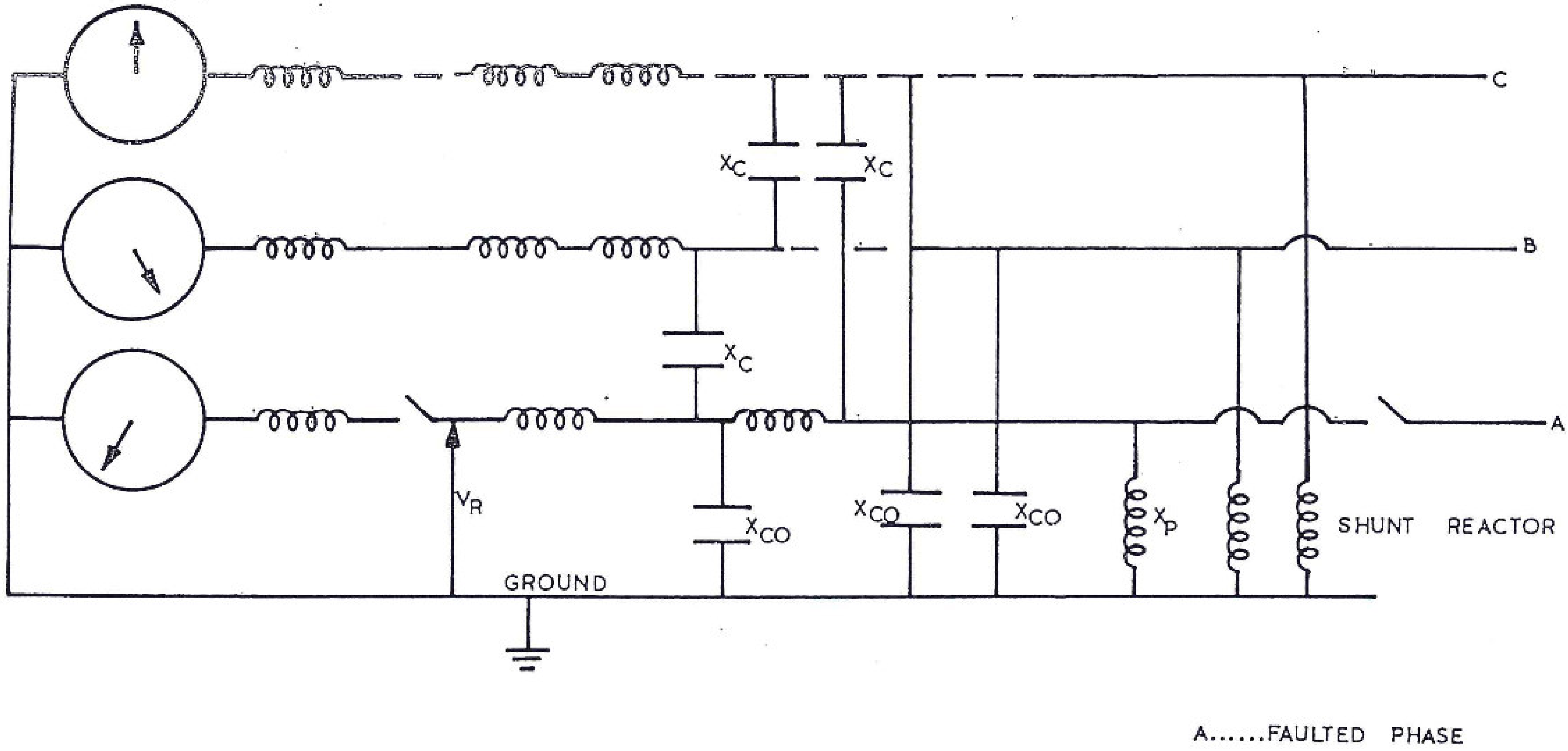

FIG. 1.— EXPERIMENTAL CIRCUIT DIAGRAM

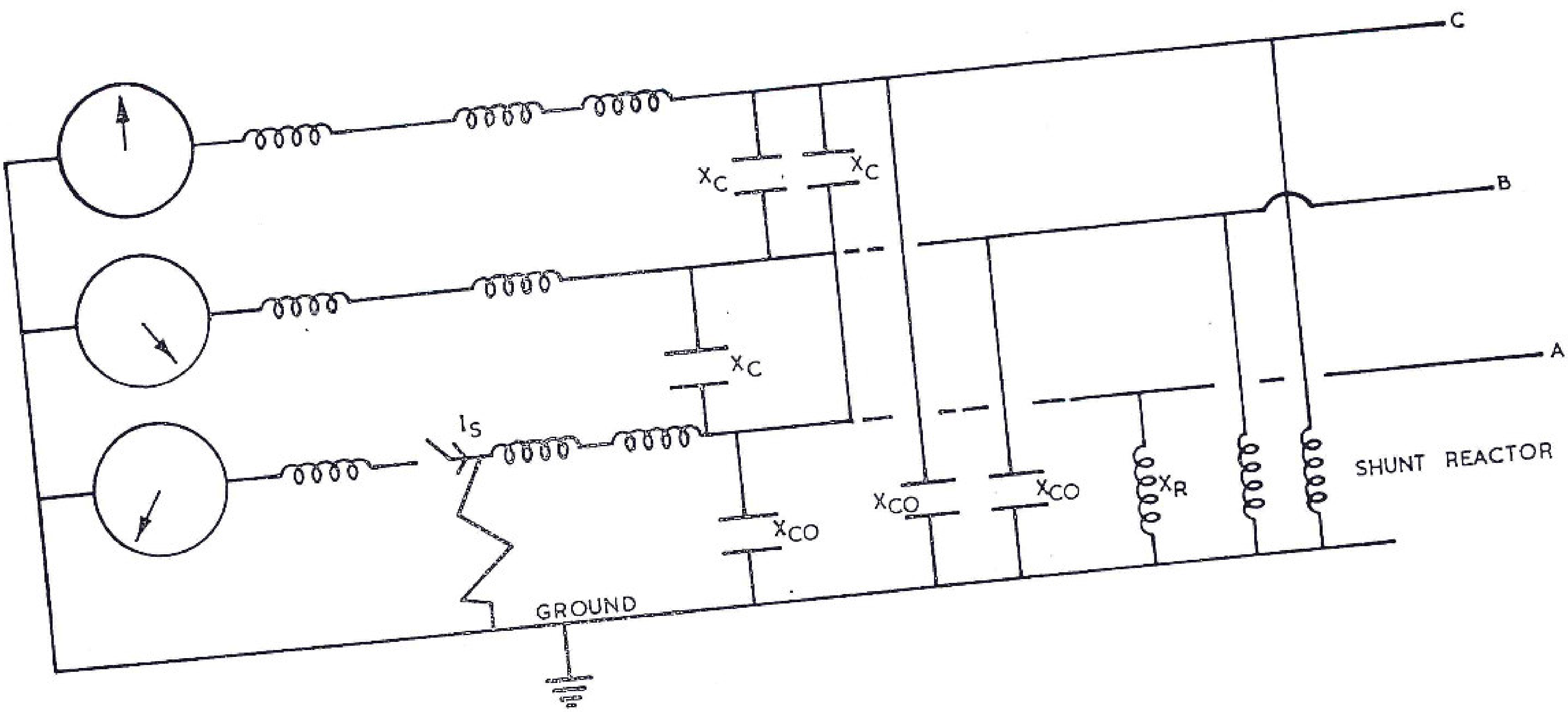

FIG. 2.– EXPERIMENTAL CIRCUIT DIAGRAM

) ANALYTICAL METHODS

In this study, two methods were developed and used to obtain expressions for the recovery voltage V_R and the sustained current I_S, as defined previously.

The detailed mathematical development of these methods is not produced in this paper but the pertinent expressions are quoted. In the first and simpler method, a lumped circuit representation of the line was used - Figure 3 - and mutual inductance coupling between the phases was ignored. This method simplifies the mathematics considerably and is reasonably accurate for no-load conditions.

A more elegant method, using the distributed constants of the line and including the mutual effects, was then developed. This was based on an approach used by Engstrom and Langstam (1) but the expressions derived independently in this study differed somewhat from those obtained in the reference.

2.1 Nomenclature and Assumptions

The following definitions and terms are used in both methods:

A neutral reactor X is introduced - Figure 3 - but its value can be equated to zero when the original conditions prevail.

The effect of the introduction of such a reactor will also be discussed in this paper.

All voltages and currents are assumed to be of the fundamental frequency. All parameters are treated as linear quantities and the voltages on the healthy phases are assumed to remain unchanged for the duration of the fault. The arc path to ground was further assumed to have zero impedance.

V ph – RMS phase to neutral voltage
I – RMS line load current
W – Angular Frequency
C – Coupling capacitance between phases in farads/mile
C_O – Zero - Sequence Capacitance in farads/mile

$$X_C = \frac{1}{WC} \quad ; \quad X_{CO} = \frac{1}{WCO}$$

L – Positive sequence inductance in henries/phase/mile
M – Mutual inductance coupling between phases in henries/mile

$$Z_C = \frac{L}{\sqrt{L(C_O + 2C)}}$$

$$B = W\sqrt{L(C_O + 2C)}$$

X_R — Ohmic value of shunt reactor per phase

X — Ohmic value of neutral reactor

X_T — $X + X_R$

l — length of the section of the line in miles

I_S — RMS sending-end line current (faulty phase) with the faulty path still in circuit. (This shall be referred to as condition (1)).

V_R — RMS recovery voltage, i.e. voltage between beginning of section and earth with faulty path removed. This shall be referred to as condition (2).

V_{X1} — Voltage across the neutral reactor under condition (1).

V_{X2} — Voltage across the neutral reactor under condition (2)

V_{Y2} — Voltage between the faulty phase and earth at a distance y miles from the beginning of the section - condition (2).

2.2 Lumped Circuit Representation

Fig. 3 shows the circuit diagram used. A T-equivalent for each phase is used including lumped elements for the capacitive coupling.

$$V_R = \frac{V_{ph}\left[X(3X_R - X_C) + X_R^2\right] X_{CO}}{X(6X_RX_{CO} - 2X_CX_{CO} + 3X_RX_C) + X_R^2(2X_{CO} + X_C) - X_{CO}X_RX_C} \quad (1)$$

$$I_S = \frac{V_R(2X_{CO}X_T + X_CX_{CO} + X_TX_C)}{X_{CO}X_TX_C} \quad (2)$$

$$V_{X2} = \frac{V_{ph}\, X_R\, X_C\, X}{X(6X_RX_{CO} - 2X_CX_{CO} + 3X_RX_C) + X_R^2(2X_{CO} + X_C) - X_{CO}X_RX_C} \quad (3)$$

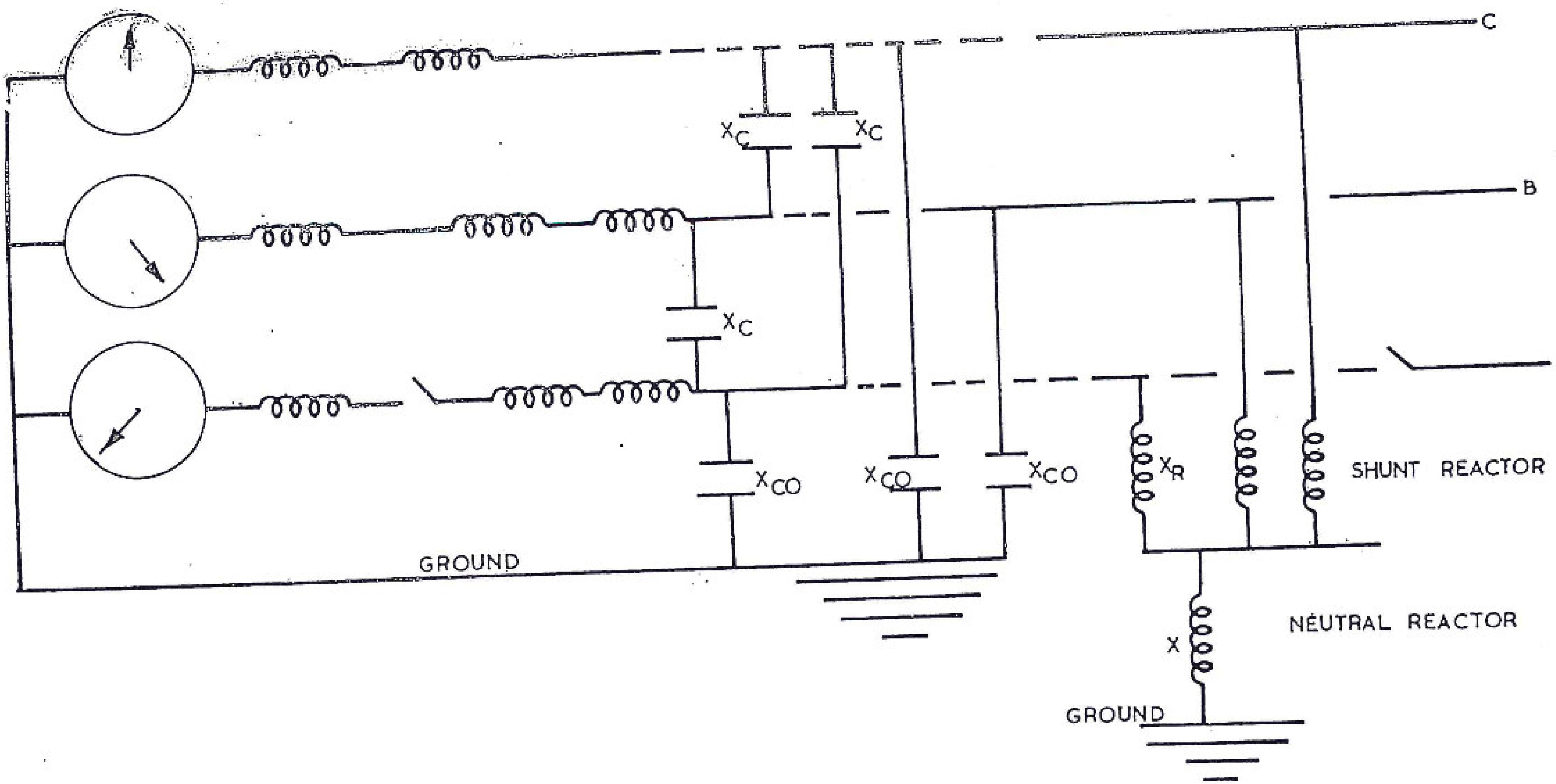

FIG. 3. — CIRCUIT DIAGRAM FOR SYSTEM WITH NEUTRAL REACTOR

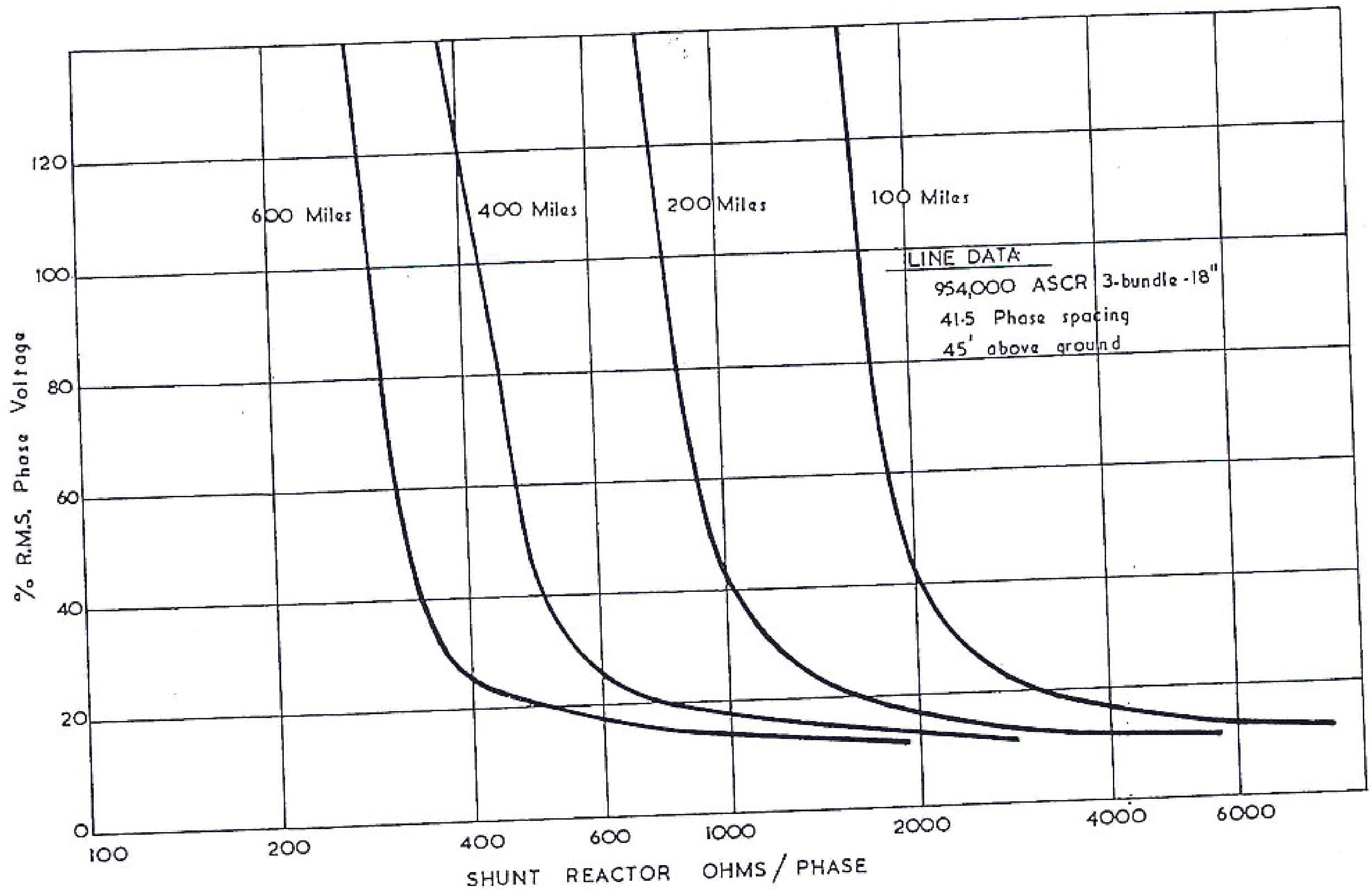

FIG. 4.—VOLTAGE TO EARTH OF FAULTED PHASE—V_R

(WITH NO NEUTRAL REACTOR IN CIRCUIT)

2.3 Distributed Parameters

This method takes into consideration the inductive effects and makes use of the complete differential equations describing a power transmission line. Resistances are ignored and hence, the hyperbolic functions are replaced by the simpler trignometric ones. Initial conditions are also taken into consideration.

The following expressions result for V_R, V_{X1}, V_{X2} and V_{Y2}:

$$I_S = jV_{ph}\,\frac{\dfrac{X}{X_T(X+X_T)}}{\mathrm{Cos}Bl + \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl} - \frac{jV_{ph}C\left(\mathrm{Sin}\,Bl - \dfrac{Z_c}{X_T}(1 - \mathrm{Cos}\,Bl)\right)}{\sqrt{L(C_o + 2C)}\;\left(\mathrm{Cos}\,Bl + \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl\right)} \qquad (4)$$

$$+\; I\,\frac{M}{L}\,\frac{\left(1 - \mathrm{Cos}\,Bl - \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl\right)}{\mathrm{Cos}\,Bl + \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl}$$

$$V_R = \frac{V_{ph}C\;\mathrm{Sin}\,Bl + \dfrac{Z_C}{X_T}(1 - \mathrm{Cos}\,Bl)}{C_O + 2C\;(\mathrm{Sin}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Cos}\,Bl)} - \frac{V_{ph}\,Z_C\,X}{X_T(X + X_T)}\cdot\frac{1}{\mathrm{Sin}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Cos}\,Bl}$$

$$+\; j\,\frac{I\,M}{\sqrt{L(C_O + 2C}}\cdot\frac{1 - \mathrm{Cos}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Sin}\,Bl}{\mathrm{Sin}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Cos}\,Bl} \qquad (5)$$

$$V_{X1} = \frac{V_{ph}\,X}{X + X_T} - \frac{V_{ph}\,X^2}{X_T(X+X_T)}\cdot\frac{\mathrm{Cos}\,Bl}{\mathrm{Cos}\,Bl + \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl}$$

$$+\; \frac{V_{ph}\,C\,X(\mathrm{Cos}\,2\,Bl - \mathrm{Cos}\,Bl)}{(C_o + 2C)X_T(\mathrm{Cos}\,Bl + \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl)} - j\,\frac{IX}{X_T}\,\frac{(\mathrm{Sin}\,Bl - \mathrm{Sin}\,2\,Bl)}{(\mathrm{Cos}\,Bl + \dfrac{Z_c}{X_T}\,\mathrm{Sin}\,Bl)} \qquad 6)$$

$$V_{X2} = \frac{V_{ph}\,C}{C_O + 2C}\;\frac{X\,\mathrm{Sin}\,Bl}{X_T(\mathrm{Sin}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Cos}\,Bl)} + \frac{V_{ph}X}{X + X_T}$$

$$-\; \frac{V_{ph}X^2\;\mathrm{Sin}\,Bl}{X_T(X + X_T)\;(\mathrm{Sin}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Cos}\,Bl)} \qquad (7)$$

$$j\,\frac{I_A\,M}{\sqrt{L(C_O + 2C}}\;\;\frac{X\,(1 - \mathrm{Cos}\,Bl)}{X_T\left[\mathrm{Sin}\,Bl - \dfrac{Z_C}{X_T}\,\mathrm{Cos}\,Bl\right]}$$

$$V_{Y2} = \frac{V_{ph}\, C}{C_0 + 2C} \; \frac{\left[\operatorname{Sin} Bl + \frac{Z_C}{X_T} (\operatorname{Cos} By - \operatorname{Cos} Bl)\right]}{\operatorname{Sin} Bl - \frac{Z_C}{X_T} \operatorname{Cos} Bl} \tag{8}$$

$$- \frac{V_{ph}\, Z_C\, X \operatorname{Cos} By}{X_T (Y + X_T) \left(\operatorname{Sin} Bl - \frac{Z_C}{X_T} \operatorname{Cos} Bl\right)}$$

$$+ j \frac{I\, M}{\sqrt{L(C_0 + 2C)}} \; \frac{(\operatorname{Cos} Bx - \operatorname{Cos} Bl\text{-}y) - \frac{Z_C}{X_T} \operatorname{Sin} Bl\text{-}y}{\operatorname{Sin} Bl - \frac{Z_C}{X_T} \operatorname{Cos} Bl}$$

These expressions are much more tedious for computation and almost certainly, a digital computer becomes necessary.

(3) RESULTS

3.1 Comparison Between Experimental and Theoretical Results

A set of experimental no-load tests were done on a 400 kV line (2). In order to assess the accuracy of the expressions derived in this study, results from these tests for the recovery voltage and the sustained currents were compared with those obtained from the purely theoretical considerations as given by equations (1), (2), (4) and (5).

Table 2 summarises these comparisons. This table shows that both methods give results that compare favourably with the experimental results, especially in the calculation of the recovery voltages. The entire set of values compared are for no-load conditions. The presence of a current in the line at the occurrence of the fault can appreciably affect the value of both the recovery voltage and the sustained current. In the example studied, there is almost a 300% increase in the magnitude of the recovery voltage when the no-load condition is compared with a load condition of 1000 MW. Table 3 shows a similar increase in the sustained current values for certain conditions.

3.2 Application of the Method

The more accurate method from which resulted the expressions given by equations (4), (5), (6), (7) and (8), was used to calculate recovery voltages sustained currents for a particular system. The effect of the variation of the shunt reactors was studied as was the introduction of the neutral reactor.

3.2.1 Transmission Line Design Data

The line chosen was typical of a 200 mile, 500 kV, 1000 MW system. The data are as follows:

954,000 ACSR conductor, 3 conductors per bundle. Bundle spacing 18 inches; phase spacing 41.5 feet. Height of conductors above ground 45 feet.

The transmission line parameters calculated for this line are as follows:

Terms have been defined in Section 2.1

$C = 1.55 \times 10^{-9}$ F/mile $\qquad C_o = 14.2 \times 10^{-9}$ F/mile

$L = 1.52 \times 10^{-3}$ H/phase/mile $\qquad M = 1.40 \times 10^{-3}$ H/mile

$B = 1.93 \times 10^{-3}$ radians $\qquad Z_c = 296$ Ohms.

Table 3 contains the more important results arising from these calculations. The effect of two values of shunt reactors and the presence of load can be clearly seen. On no-load, the presence of a shunt reactor considerably increases the magnitude of the recovery voltage but has little effect on the value of sustained current. The existence of load on the system when the fault occurs has a decided effect on the magnitude of both the recovery voltages and the sustained currents.

3.2.2 The Effect of the Shunt Reactor

Fig. 4 shows the variation of the magnitude of the recovery voltage with the value of shunt reactor in circuit. From these graphs, it can be seen that undesirably high recovery voltages can occur if the shunt reactor MVAR value exceeds a certain value.

Examination of the expressions for the recovery voltages shows that a resonant condition dependent on the value of the shunt reactor may arise. In the simplified method, this value is given by

$$X_R = \frac{X_{CO} X_C}{2X_{CO} + X_C} \qquad (9)$$

and in Method 2, the corresponding quantity is given by

$$X_R = Z_C \text{ Cotan } wl \sqrt{L(C_O + 2C)} \qquad (10)$$

Shunt reactors have become an integral part of most large transmission systems.

The possibility of large recovery voltages arising and preventing successful reclosing is a real one and must be carefully considered in the design of such systems.

(4) THE USE OF A NEUTRAL REACTOR

Fig. 3 shows the circuit diagram of a system that includes a neutral reactor. The ohmic value - X - of such a reactor is included in the derived expressions. The effect of the presence of such a device can then be easily studied.

Three inter-related quantities are important in the study of this effect:

(i) the reduction of V_R and I_S produced by the introduction of a Neutral Reactor

(ii) the voltage rating of the required neutral reactor.

(iii) the required MVAR rating of the neutral reactor.

These quantities were computed for a variety of conditions. The more significant results are summarised in Table 4.

Marked effects are noticeable at low loads in both the recovery voltages and sustained currents, but these effects diminish at heavy loads.

From purely theoretical considerations, the introduction of a neutral reactor produces very desirable effects but other considerations in overall system performance have retarded its use in practical systems.

CONCLUSIONS

Examination of the results obtained by calculation, points out certain facts.

(1) Load current has a definite effect on both the recovery voltage and sustained current and must be considered in their evaluation. This inductive coupling voltage is in quadrature with the capacitive coupling voltage and may be the major contribution to the recovery voltage at high loads.

(2) With a shunt reactor in circuit, dangerous resonant conditions may occur for certain parameter values if single phase reclosing is attempted. In the actual system studies, these conditions were not approached but Figure (4) shows this effect for no load conditions for different lengths of line. The high recovery voltages are dangerous to the reactors and transformers and may prevent extinction of the secondary arc.

(3) The introduction of a neutral reactor of the correct size can reduce the values of the recovery voltage and the sustained current but its effect is minimized in a heavily loaded circuit.

(4) A relationship between the duration of the secondary arc and the quantities discussed in this study has not been obtained. There have been various suggestions based on experimental results about such a relationship and the strongest held view is that there is a linear relationship between the duration time of the arc and the "steady-state" value of the sustained current (2).

REFERENCES

1. R. Engstrom and S. Langstam "Single-Phase High-Speed Reclosure Justifiable at Higher Voltages" - Electric Light and Power No. 7, 1957.

2. A. S. Maikoper "Minimum Time of Automatic Reclosing" - Electric Technology U.S.S.R., Vol. 2, May 1960, Pergamon Press, New York.

Background Literature:

Cabanes, Dietsch, Divan "Does the Length of Line Limit the Automatic Reclosure in Very High Voltage Transmission Systems?" C.I.G.R.E. No. 142, 1954.

A. S. Maikopar and N. N. Beliakov "Arcing Short-Circuits on 400 kv. Transmission Lines and Methods of Dealing with Them". U.S.S.R., Vol. 4 December 1958, Pergamon Press, New York.

Table 1

—Some Experimental Values for Sustained Currents and Recovery Voltages.

System	Ground Fault Current	Sustained Current		Recovery Voltage	Remarks
		Duration	Current		
	Amps (RMS)	Sec.	Amps (RMS)	Kv. (RMS)	
300 miles 230 Kv.	570 - 330	0 - .15	12.5 - 13	12	completely successful extinction
	735 - 620	.11 - .19	14.5	12	
	1270 - 1295	.14 - .23	14.5	12	
260 miles 400 Kv.	690 - 415	.29 - .74	47 - 25	20.8 - 21.8	unreliable extinction
	815 - 510	.92	60 - 42	-	
	535 - 320	.03 - .58	34 - 22	14.8 - 16.6	
135 miles 400 Kv.	755 - 540	.02 - .13	16	21	successful extinction
	880 - 860	.02 - .17	-	-	

Table 2

—Comparison of Experimental and Theoretical Values of Recovery Voltage and Sustained Current.

Conditions	Length of Line	Recovery Voltage Kv. (RMS)			Sustained Current Amps (RMS)		
			Theoretical			Theoretical	
	Kms.	Expt.	Method 1	Method 2	Expt.	Method 1	Method 2
No Shunt Reactor In the Line	117	28	26	26	17	11	10.8
	391	28	26	26	38	36.5	38
	635	28	26	26	62	59	67
	815	28	26	26	80	76	96
A 150 MVAR reactor at the end of the Line.	391	92	92	87	25	36.5	32
	635	50	46	45	47	59	54
	—	—	—	—	—	—	—

Table 3

—Calculated Recovery Voltages and Sustained Currents with no Neutral Reactor in Circuit.

Conditions	Recovery Voltage Kv. (RMS)			Sustained Currents Amps (RMS)		
	No Load	500 MW	1000 MW	No Load	500 MW	1000 MW
No Reactor	25.8	40	67	35	55	91
100 MVAR Shunt Reactor	37	41	51	33	36	46
200 MVAR Shunt Reactor	65	67	72	30	31	34

Table 4

–Calculated Values of Neutral Rectars for Optimum Reduction of Recovery Voltages and Sustained Currents.

Conditions	Optimum Reduction of V_R — Values in Kv. (RMS)			Optimum Reduction of I_s — Values in Amps (RMS)			Req'd Value of Neutral Reactor		
	No Load	500 MW	1000 MW	No Load	500 MW	1000 MW	X-Ohms	Max. Voltage across X RMS	MVAR of X
100 MVAR Shunt Reactor	37 to 20	41 to 29	51 to 45	33 to 20	36 to 27	45 to 45	500	40	3.2
200 MVAR Shunt Reactor	65 to 17	67 to 17	72 to 17	30 to 8	31 to 8	34 to 8	200	40	8

NOTES ON CONTRIBUTORS

A. E. ABRAHAMS	is Associate Professor of Industrial Management, Polytechnic Institute of Brooklyn, New York, U.S.A.
P. A. D. ALLSOPP	is Chief Engineer of the Roads Division, Ministry of Works and Hydraulics, Guyana.
R. K. BATES	is Superintending Engineer, Sanitation, Water and Sewerage Authority, Trinidad and Tobago.
C. W. DANIEL	was formerly General Manager, Point Fortin, Shell Trinidad. He is now Production Manager, Shell, Canada.
W. G. DEMAS	was Head of the Economic Planning Division and is now Permanent Secretary, Ministry of Planning and Development, Trinidad and Tobago.
K. S. JULIEN	is Head of the Department of Electrical Engineering and Dean of the Faculty of Engineering, University of the West Indies.
R. MUNOZ CANDELARIO	is Professor of Chemical Engineering at the University of Puerto Rico.
G. R. ROBSON	is head of the Seismic Research Unit, University of the West Indies.
K. F. SEHEULT	is General Manager of the Trinidad and Tobago Electricity Commission.
K. G. WHILLOCK	was Senior Resident Engineer during the construction of the "B" Power Station for the Trinidad and Tobago Electricity Commission. He is employed by Preece, Cardew and Rider.