Short Circuit ABC—Learn It in an Hour, Use It Anywhere, Memorize No Formula

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Abstract—**Short circuit ABC—learn it in an hour, use it anywhere, memorize no formula. The MVA method for solving industrial power system short circuits appropriately fits this description. Indeed, solving short circuit problems with the MVA method is as easy as learning the ABC's.**

Introduction

SHORT CIRCUIT studies are necessary for any power distribution system to determine switchgear rating for protective relaying, and to determine the voltage drop during starting of large motors. One line diagrams are not complete unless the short circuit values are solved at various strategic points. No substation equipment, motor control centers, breaker panels, etc., can be purchased without knowledge of of the complete short circuit information of the entire power distribution system.

Knowing how to calculate short circuit problems is a must for every electrical engineer. To learn it may be easy for some, difficult for others. However, to do the problems anywhere in or out of the office where the references are not available may not be an easy task because the conventional methods of solving short circuits involve too many formulas. To memorize them at all times is impractical for the majority.

What Really Is the MVA Method?

Basically, the MVA method is a modification of the Ohmic method in which the impedance of a circuit is the sum of the impedances of the various components of the circuit. Since, by definition, admittance is the reciprocal of impedance, it follows that the reciprocal of the system admittance is the sum of the reciprocals of the admittances of the components. Also, by definition, the admittance of a circuit or component is the maximum current or KVA at unit voltage which would flow through the circuit or component to a short circuit or fault when supplied from a source of infinite capacity. Refer to Fig. 1.

$$Y = \frac{1}{Z_{\text{ohms}}} \tag{1}$$

$$\text{KVA}_{sc} = 1000 \times (\text{KV})^2 \times Y \tag{2}$$

$$\text{MVA}_{sc} = (\text{KV})^2 \times Y \tag{3}$$

$$\text{MVA}_{sc} = \frac{\text{MVA}}{Z_{\text{pu}}}. \tag{4}$$

Paper TOD-73-132, approved by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society for presentation at the 1973 Petroleum and Chemical Industry Conference, Houston, Tex., September 17–19. Manuscript released for publication October 31, 1973.

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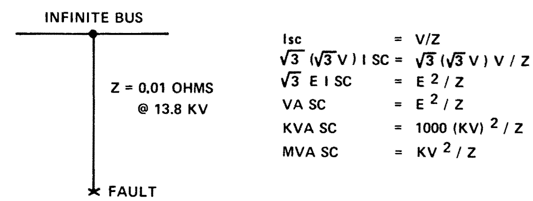
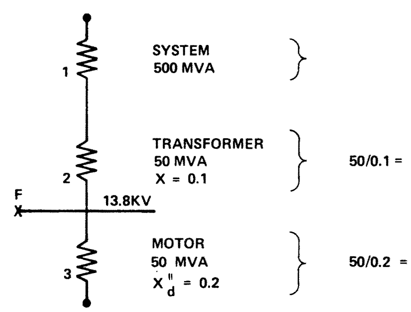
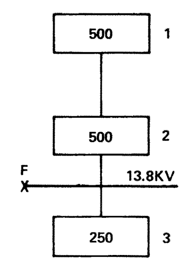


E = √3 V
I SC = SHORT CIRCUIT CURRENT IN AMPERES
E = LINE TO LINE VOLTAGE IN VOLTS
V = LINE TO NEUTRAL VOLTAGE IN VOLTS
Z = LINE TO NEUTRAL IMPEDANCE IN OHMS
MVA SC = SHORT CIRCUIT MVA

Fig. 1. One line diagram.





$\text{MVA}_{1,2} = \text{MVA}_1 \times \text{MVA}_2 / \text{MVA}_1 + \text{MVA}_2$
$= 500 \times 500 / 500 + 500 = 250$
$\text{MVA}_{1+3} = 250 + 250 = 500$
$\text{I SC} = 500 \times 1000 / \sqrt{3} \times 13.8 = 20900 \text{ AMPS}$

Fig. 2. Impedance diagram. Fig. 3. MVA diagram.

Y	admittance of a circuit
Z_{ohms}	impedance in ohms
Z_{pu}	impedance in per unit
KV	line to line voltage
KVA_{sc}	short circuit KVA
MVA_{sc}	short circuit MVA
MVA_{sc}	$(13.8)^2/0.01 = 19\,000$ (for Fig. 1).

Practically, the MVA method is used by separating the circuit into components, calculating each component with its own infinite bus as shown in Figs. 2 and 3. Fig. 2 is a typical impedance diagram of a one line diagram. Fig. 3 is an MVA diagram. The conversion from a one line diagram to an MVA diagram is simple arithmetic.

Component 1, the system, is normally given a short circuit MVA rating. So, one merely writes down 500, which is its system short circuit MVA. Sometimes, if the system MVA is not available, but its voltage and impedance are given, the short circuit MVA can be calculated with the application of (3).

Next, for component 2, use (4). The short circuit MVA of the transformer is equal to its own MVA base divided by its own per unit impedance. (Use reactance X with the MVA method.)

Next, for component 3, again use (4). The short circuit MVA contribution of the motor is equal to its own MVA base divided by its own per unit impedance. (Use reactance X with the MVA method.)

Now, let us examine the MVA diagram, Fig. 3. If a short circuit is taken at point F, there will be a series flow of MVA_1 and MVA_2, and their combination will be in parallel with MVA_3. The question now is: how do you combine the MVA values in series and in parallel? The answer is again simple arithmetic

$$\text{series} \qquad MVA_{1,2} = \frac{(MVA_1) \times (MVA_2)}{(MVA_1) + (MVA_2)} \tag{5}$$

$$\text{parallel} \qquad MVA_{1+2} = MVA_1 + MVA_2. \tag{6}$$

From (5) and (6), it can easily be recognized that series MVA combinations are exactly as resistances computed in parallel. Parallel MVA combinations are exactly as resistances computed in series.

The MVA_{sc} at point F of Fig. 2 then can be calculated as follows:

$$MVA_{1,2} = \frac{500 \times 500}{500 + 500} = 250$$

$$MVA_{sc} = MVA_1^* + MVA_3 = 250 + 250 = 500.$$

The term with the asterisk is the new MVA_1 value which is the result of combining MVA_1 and MVA_2. After the operation, the new MVA_1 which is 250 MVA, replaces the old MVA_1 and MVA_2. This scheme of replacing old quantities with new quantities relates to computer data memory storage system.

At this point the short circuit MVA is solved. To find the current value, only the voltage value is required. For example, if the voltage is 13.8 kV, the current I_{sc} is

$$\frac{MVA \times 1000}{\sqrt{3} \times KV} = \frac{500 \times 1000}{\sqrt{3} \times 13.8} = 20\,900 \text{ A}.$$

The ABC of the MVA

Up to now, the reader has spent about 15 min in slow reading. He has found that there has been nothing new, and the formulas are no more than good old Ohm's Law arithmetics. Now, he can forget the formulas and start the ABC.

A. Convert to MVA's

Convert all one line components to short circuit MVA's. Equipment such as generators, motors, transformers, etc., are normally given their own MVA and impedance or reactance ratings. The short circuit MVA of each is equal to its MVA rating divided by its own per unit impedance or reactance. For a feeder where voltage is given and its impedance or reactance is known, its short circuit MVA is equal to $(KV)^2$ divided by its impedance or reactance in ohms.

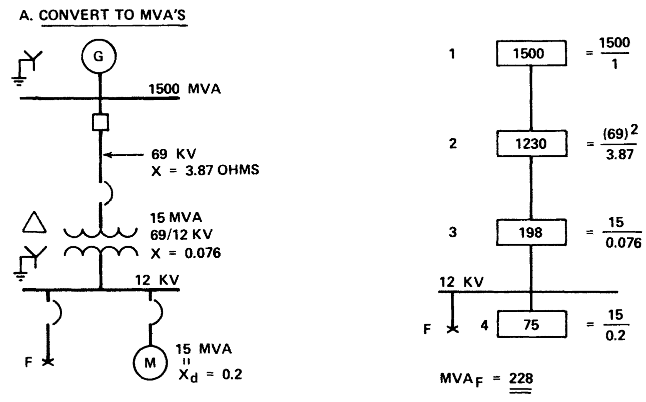


Fig. 4. The ABC of the MVA. (a) One line diagram. (b) MVA diagram.

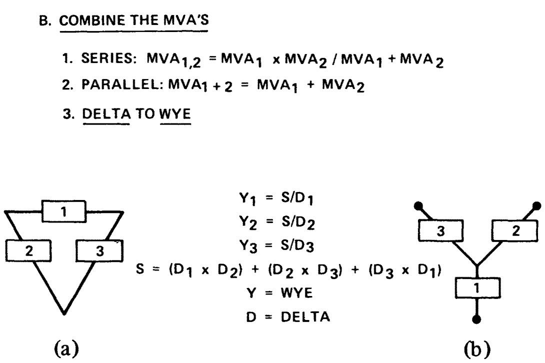


Fig. 5. The ABC of the MVA. (a) Delta connection. (b) Wye connection.

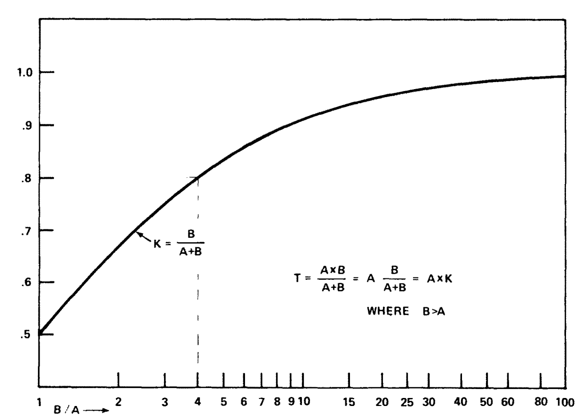


Fig. 6. Series combination ratio.

Incoming line short circuit duty in MVA is normally given by power companies. Therefore, use the value as given and no conversion is required. However, if impedance or reactance at the terminal is given, find its short circuit MVA by dividing its $(KV)^2$ by its ohms.

As conversion is being made, an MVA diagram is being developed. One line diagram 4(a) is replaced with MVA diagram 4(b).

B. Combine MVA's

1) Series MVA's are combined as resistances in parallel.

2) Parallel MVA's are added arithmetically. Refer to Fig.

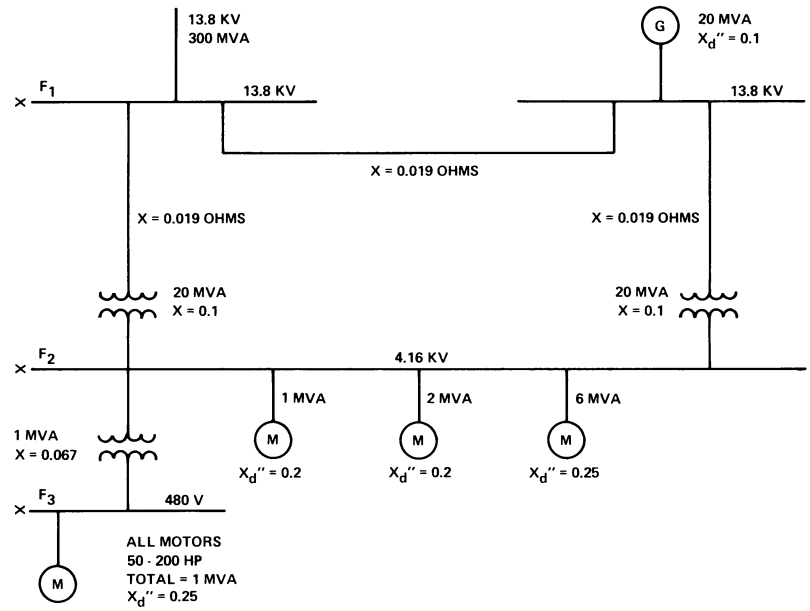


Fig. 7. One line diagram.

4(b) for the following:

$$\mathrm{MVA}_{1,2} = \frac{1500 \times 1230}{1500 + 1230} = 675$$

(this is the new MVA_1)

$$\mathrm{MVA}_{1,3} = \frac{675 \times 198}{675 + 198} = 153$$

$$\mathrm{MVA}_{1+4} = \mathrm{MVA}_1 + \mathrm{MVA}_4 = 153 + 75 = 228$$

$$I_{12} = \frac{228 \times 1000}{\sqrt{3} \times 12} = 11\ 000 \text{ A}.$$

For $\mathrm{MVA}_{1,2}$, add MVA_1 and MVA_2 in series. For MVA_{1+4}, add MVA_1 and MVA_4 in parallel. I_{12} is the short circuit current at 12 kV.

3) Delta to wye conversions are rarely used in industrial power distribution systems, but they are again simple arithmetic. Refer to Figs. 5(a) and (b).

4) The only point that needs more attention is the series combination if a slide rule is not available. The attempt here is to be able to solve most short circuit problems with reasonable accuracy without the use of a slide rule.

With the aid of the curve in Fig. 6, let us analyze the series combination

$$\mathrm{MVA}_{1,2} = \frac{(\mathrm{MVA}_1) \times (\mathrm{MVA}_2)}{(\mathrm{MVA}_1) + (\mathrm{MVA}_2)}.$$

Let $A = \mathrm{MVA}_1$, $B = \mathrm{MVA}_2$, and T = total MVA, so that

$$T = \frac{A \times B}{A + B} = \frac{A(B)}{A + B}, \qquad A < B.$$

$B/A + B$ is plotted as a constant on a log-log scale base from 1 to 100 which is the ratio of B/A. (Refer to Fig. 6.) For example, let $A = 10$, $B = 40$, and $B/A = 4$. Read 4, at horizontal scale. From 4 project upward until it intersects the curve. Read the horizontal value 0.8, which is the result of $B/A + B$; then

$$T = A(B/A + B)$$
$$= 10 \times 0.8 = 8.$$

It is also noted that when combining two quantities in series, the result is always smaller than the smallest of the two. The example shows the result to be 8 when combining 10 and 40.

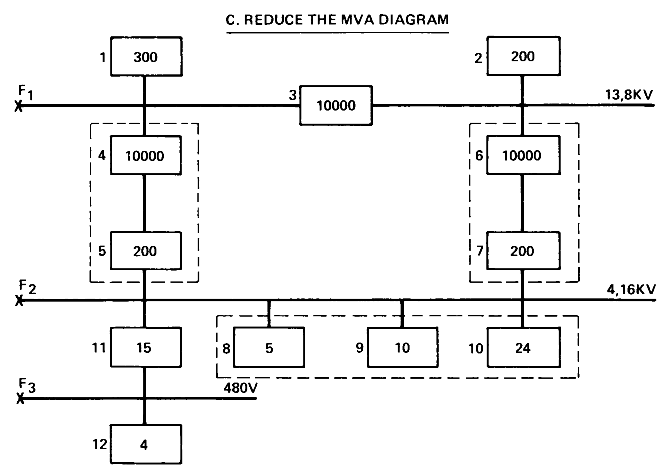


Fig. 8. MVA diagram.

C. Reduce MVA Diagram

Reducing an MVA diagram takes the same reduction process required for the per unit impedance diagram, except that MVA quantities are used instead of per unit impedances or reactances.

Fig. 7 is a typical distribution one line diagram including a delta connected feeder system. Reactances only are used for practical purposes. Fig. 8 is an MVA diagram that shows all elements in the one line in MVA quantities. Fig. 9(a) shows

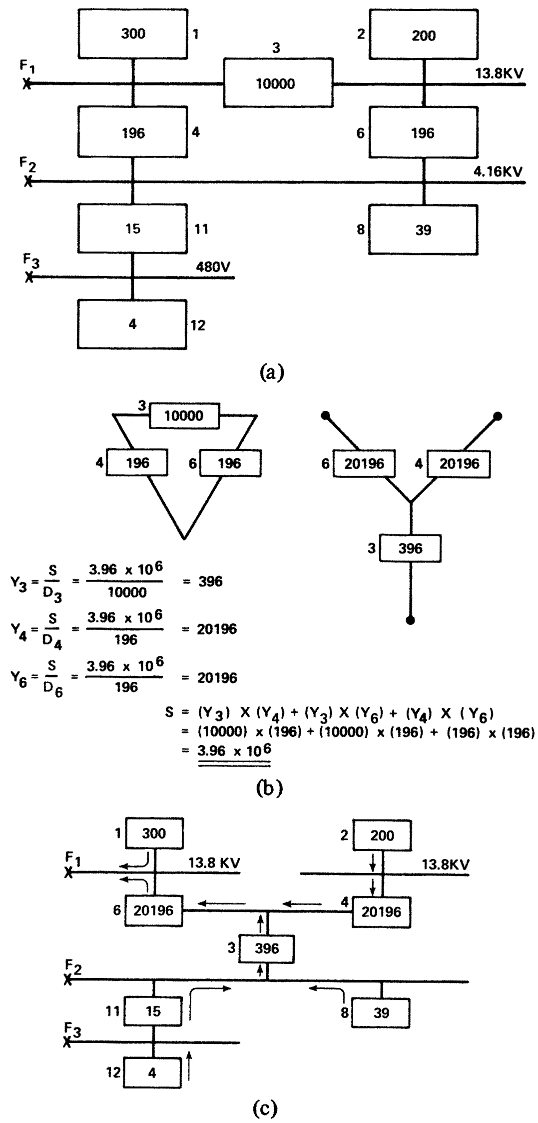


Fig. 9. MVA reduction.

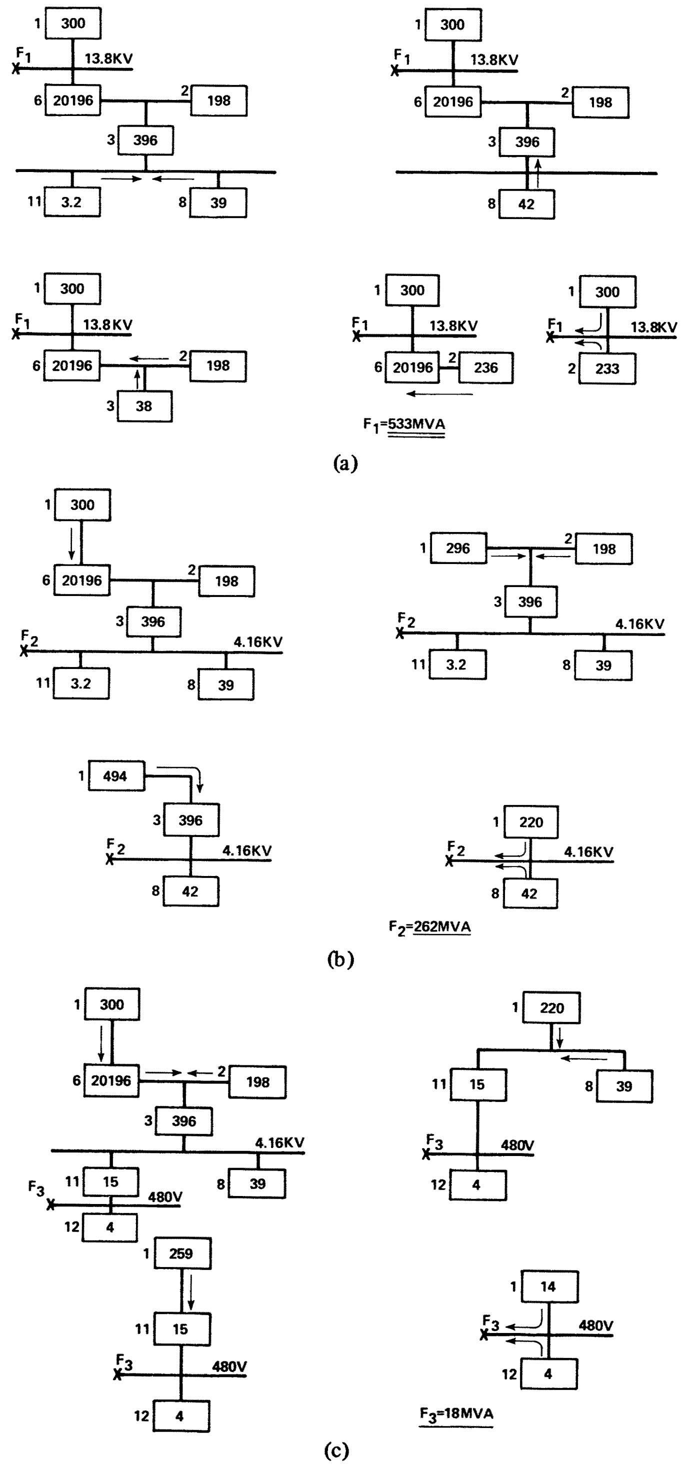


Fig. 10. MVA reduction.

the first step reduction sequence. Note that there are three faults to be calculated, F_1, F_2, and F_3.

The first step reduction combines the series and parallel components so that the simplest diagram can be accomplished, and that any fault can be solved in random fashion. Fig. 9(a) shows that items 4 and 5 have been combined to make a new 4; items 6 and 7 have been combined to make a new 6; items 8-10 have been combined to make a new 8. Fig. 9(b) converted a delta to a wye configuration. Fig. 9(c) is further reduced to Fig. 10(a), indicating items 2 and 4 have been combined to make a new 2. Figure 10(a) then is the simplest diagram that would allow the solving of any of the three faults in random selection. Figs. 10(a)-(c) show the reduction process in solving faults F_1, F_2, and F_3, respectively.

Why the MVA Method?

There are many reasons why the MVA method is recommended for industrial power short circuit calculations.

1) It does not require a common MVA base as required by the per unit method.

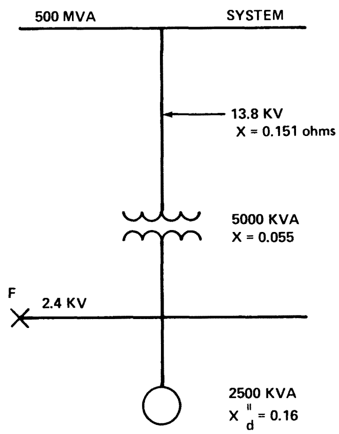


Fig. 11. One line diagram for comparison of methods.

2) It is not necessary to convert impedances from one voltage to another as required by the Ohmic method.

3) The conversion formulas as used for both the Ohmic and the per unit methods are complex and not easy to memorize.

4) Both the Ohmic and the per unit methods usually end up with small decimals resulting from converting impedances from one voltage to another or from converting impedances to the same common base. Therefore, one can make mistakes in the decimals, with resulting wrong answers.

5) The MVA method utilizes large whole numbers denoting MVA quantities. With a little practice, one can estimate the result by looking at the combination. For example, 10 and 10 in series become 5; 10 and 100 in series become 9.1; and 10 and 10 000 in series give 10. A small number combined with too large a number, 100 times larger or more, will have no effect on the small number.

In order to further prove the preceding points, it is necessary to give the following comparison of methods that are utilized in solving industrial power system short circuits.

Comparison of Methods

A one line diagram, Fig. 11, is shown. Solve the three-phase fault at point F with and without motor contribution.

Note that reactances only are considered in the three cases being compared. It is felt that using impedances would give the same result, but would complicate the calculations. It is also widely recognized and acceptable by industries to use reactances only in calculating industrial power system short circuits, in that it would result in a higher short circuit value, perhaps by 0-3 percent in most cases. Reference [1] exemplifies the use of reactances rather than impedances.

Figs. 12(a)-(c) tabulate the conversion calculations for the three methods. Figs. 13-15 show the three methods utilized for comparison. Fig. 16 tabulates the results of the three methods.

Can Phase-Ground Fault Be Solved?

The answer, of course, is yes. Solving phase-ground fault is as easy as solving three-phase fault.

Refer to Figs. 4(a) and (b). This problem is taken from the California State Professional Engineer Registration Examination of August, 1965. As noted, the three-phase fault has been solved to be 228 MVA at the 12-kV bus. Since the positive sequence fault is equal to the negative sequence fault, therefore,

$$MVA_{X1} = MVA_{X2} = 228.$$

The zero sequence fault MVA, however, must be calculated, and its MVA value then is combined with the positive and negative MVA values.

Refer to Fig. 4(a) again. During a fault on the 12-kV bus, only the transformer and the motor contribute to zero sequence MVA's. The delta primary of the transformer blocks

OHMIC METHOD	
SYSTEM 1.	$X = \frac{1000 \times (KV)^2}{KVA_b} = \frac{1000 \times (13.8)^2}{500000} = \underline{0.38\ OHMS}$
13.8KV FEEDER 2.	$X = \underline{0.151\ OHMS}$
TRANSFORMER 3.	$X = \frac{1000 \times (X\ P.U.) \times (KV)^2}{KVA_b} = \frac{1000 \times 0.055 \times (2.4)^2}{5000} = \underline{0.063\ OHMS}$
MOTOR 4.	$X = \frac{1000 \times (XP.U.) \times (KV)^2}{KVA_b} = \frac{1000 \times 0.16 \times (2.4)^2}{2500} = \underline{0.369\ OHMS}$

(a)

PER UNIT METHOD (500000 KVA BASE)	
SYSTEM 1.	$X_{P.U.} = \frac{BASE\ KVA \times (1)}{KVA\ S.C.} = \frac{500000 \times 1}{500000} = \underline{1.000}$
13.8KV FEEDER 2.	$X_{P.U.} = \frac{(OHMS) \times (BASE\ KVA)}{1000 \times (KV)^2} = \frac{(0.151) \times (500000)}{(13.8)^2 \times 1000} = \underline{0.396}$
TRANSFORMER 3.	$X_{P.U.} = \frac{(X\ P.U.) \times (BASE\ KVA)}{KVA_T} = \frac{(0.055) \times (500000)}{5000} = \underline{5.500}$
MOTOR 4.	$X_{P.U.} = \frac{(XP.U) \times (BASE\ KVA)}{KVAm} = \frac{(0.16) \times (500000)}{2500} = \underline{32.000}$

(b)

MVA METHOD	
SYSTEM	$MVA_1 = 500$
13.8KV FEEDER 2.	$MVA_2 = \frac{(KV)^2}{X_{OHMS}} = \frac{(13.8)^2}{0.151} = \underline{1260}$
TRANSFORMER	$MVA_3 = \frac{MVA_T}{XP.U.} = \frac{5}{0.055} = \underline{91}$
MOTOR 4.	$MVA_4 = \frac{MVAm}{XP.U.} = \frac{2.5}{0.16} = \underline{15.6}$

(c)

Fig. 12. (a) Ohmic conversion. (b) Per unit conversion. (c) MVA conversion.

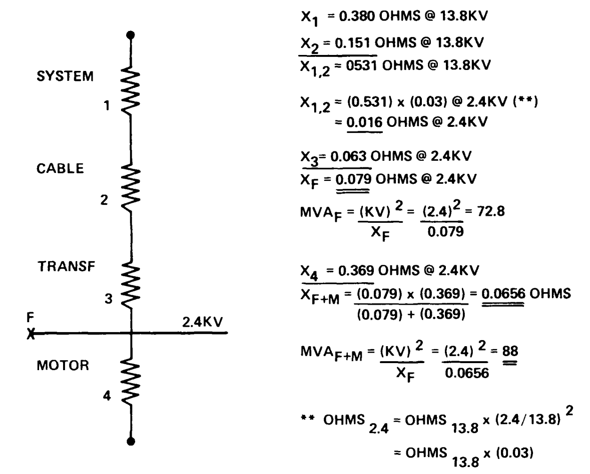


Fig. 13. Ohmic method reactance diagram.

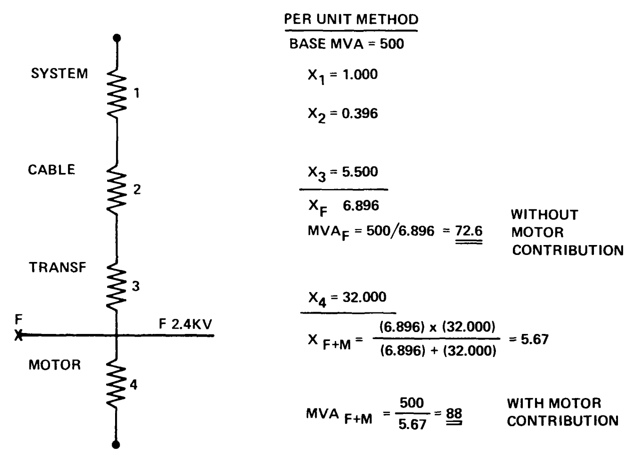


Fig. 14. Reactance diagram.

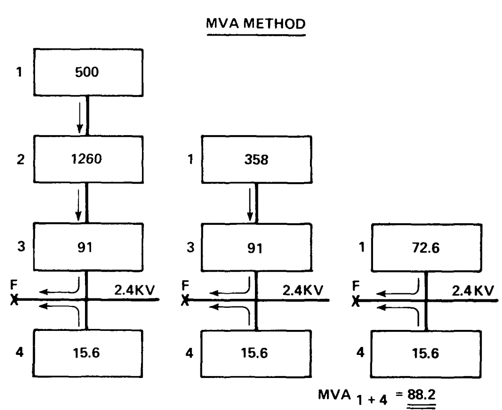


Fig. 15. MVA diagram.

METHODS / FAULT CONDITION	OHMIC METHOD	PER UNIT METHOD	MVA METHOD
FAULT @ 2.4KV BUS WITHOUT MOTOR CONTRIBUTION	72.8 MVA	72.6 MVA	72.6 MVA
FAULT @ 2.4KV BUS WITH MOTOR CONTRIBUTION	88MVA	88MVA	88.2MVA

Fig. 16. Result of comparison of methods.

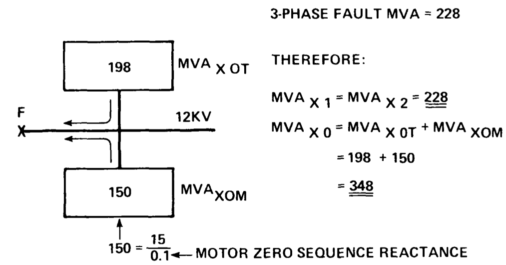


Fig. 17. Zero sequence fault power.

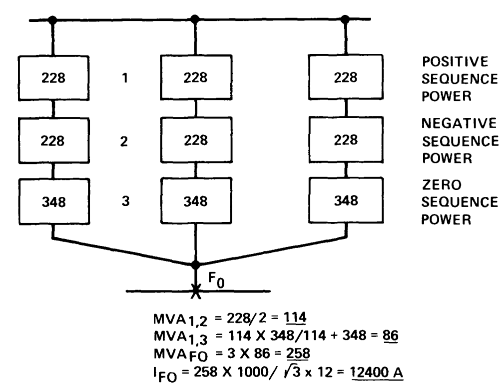


Fig. 18. Phase-ground fault of MVA circuit.

any zero sequence power flowing from the system and across the transformer. Therefore, Fig. 17 shows the zero sequence power circuit

$$\mathrm{MVA}_{XOT} = \mathrm{MVA}_{X1} = \mathrm{MVA}_{X2} = 198$$

(the transformer zero sequence reactance is equal to its positive and negative reactances)

$$\mathrm{MVA}_{XOM} = \frac{15}{0.1} = 150 \text{ MVA}$$

(since the zero sequence reactance of the motor is about $\frac{1}{2}$ of its positive sequence reactance). The total zero sequence fault power then is equal to the sum, which is

$$\mathrm{MVA}_{XOT} + \mathrm{MVA}_{XOM} = 198 + 150 = 348.$$

The phase-ground fault power is obtained with the use of Fig. 18. Since these are three branches in parallel, the simplest approach is to take one branch out of the circuit and solve its MVA value, then multiply the value by 3, which gives the final answer

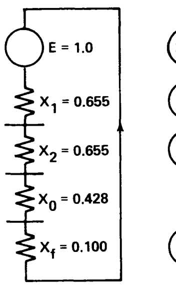
$$\mathrm{MVA}_{1,2} = 228/2 = 114$$

$$\mathrm{MVA}_{1,3} = \frac{114 \times 348}{114 + 348} = 86$$

$$\mathrm{MVA}_{F0} = 3 \times 86 = 258$$

$$I_{F0} = \frac{258 \times 1000}{\sqrt{3} \times 12} = 12\,400 \text{ A}.$$

The problem, as shown in Fig. 4(a), is also solved with the per unit method as Appendix I. This gives further comparison of



$480 = \frac{(KV)^2}{.3} = \frac{(12)^2}{.3} = 480$

$MVA_{F0} = 3X\left(\frac{86 \times 480}{86 + 480}\right) = 221\ MVA$

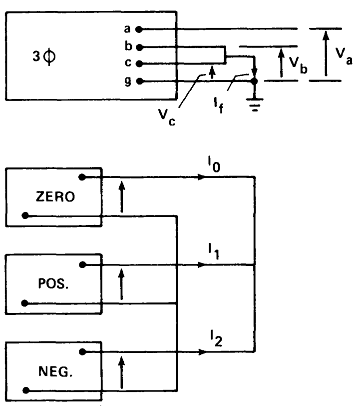
$I = \frac{221 \times 1000}{\sqrt{3} \times 12} = \underline{\underline{10600}}$

$I_{a1} = I_{a2} = I_{ao} = \frac{E}{X_1 + X_2 + X_0 + 3X_f} = \frac{1.0}{0.655 + 0.655 + 0.428 + 0.3} = \frac{1.0}{2.038} = \underline{0.491}$

$I_{f_{pu}} = 3I_{a1} = 3 \times 0.492 = 1.472$ A

$I_f = 1.472 \times 7230 = \underline{10600\ A}$

Fig. 19. Phase to ground fault with added fault reactance X_f.



OPERATORS

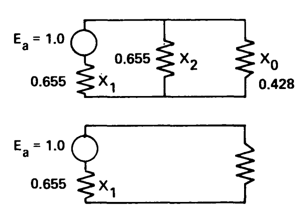
$a = \angle 120^\circ = e^a = -0.500 + J\,0.866$

$a^2 = \angle 240^\circ = e^{2a} = -0.500 - J\,0.866$

$a^3 = 1.0 \quad a^4 = a$

CONNECTIONS BETWEEN SEQUENCE NETWORKS

Fig. 20. Two lines to ground fault.



$I_1 = \frac{E}{X_1 + \frac{(X_2)(X_0)}{X_2 + X_0}} = \frac{1}{0.655 + \frac{0.655 \times 0.428}{0.655 + 0.428}} = 1.09$

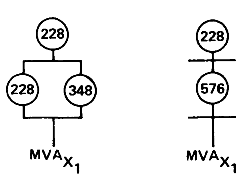
$I_0 = I_1 \times \frac{X_2}{X_0 + X_2} = 1.09 \times \frac{0.655}{0.655 + 0.428} = 0.659$

$I_F = 3I_0 = 3 \times 0.66 = 1.978$

$= 1.978 \times I_{p.u}$

$= 1.978 \times 7230 = \underline{14{,}300\ A}$

Fig. 21. Two-phase to ground fault by per unit method.



$MVA_{X_1} = \frac{228 \times 576}{228 + 576} = \underline{163.5}$

$MVA_{X_0} = MVA_1 \times \frac{MVA_0}{MVA_0 + MVA_2}$

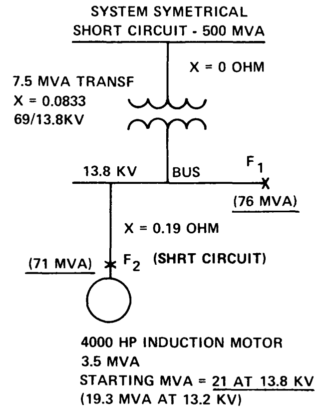
$= 163.5 \times \frac{348}{348 + 228}$

$= \underline{98.8}$

$MVA_F = 3\,MVA_{X_0} = 3 \times 98.8 = \underline{296.4}$

$I_F = \underline{14260\ A}$

Fig. 22. Two-phase to ground fault by MVA method.



$V\,d = \frac{SMVA}{SMVA + MVA\ SC}$ ---------- (26)

SMVA = STARTING MVA
MVA SC = SHORT CIRCUIT MVA
V d = INSTANTANEOUS VOLTAGE DROP

V d = 21/21 + 71 = 21/92 = 0.228
V T13.8 = 1-0.228 = 0.772

$V\,T13.2 = 0.772 \times \left(\frac{13.8}{13.2}\right)^2$

= 0.805 OR 80.5%

V T13.8 = MOTOR TERMINAL VOLTAGE @ 13.8 KV
V T13.2 = MOTOR TERMINAL VOLTAGE @ 13.2 KV

Fig. 23. Motor starting voltage drop calculation.

the amount of calculation involved between the MVA and the per unit methods.

Phase-ground fault with an added fault neutral reactance also can be calculated with the MVA method. Fig. 19 illustrates the preceding problem with an added fault neutral reactance X_f. Note that using both the MVA and the per unit methods obtain the same result except that the MVA method shows much less calculation.

Two-Phase to Ground Fault

Can two-phase to ground fault be solved with the MVA method? The answer is again, yes. Fig. 20 shows a two-phase to ground fault diagram and connections between sequence networks. As indicated, I_f is the fault current between phases C, B, and ground.

In order to develop an MVA equation for two-phase to ground fault calculations, the classical symmetrical component equations are utilized as basis. Relationships between phase and sequence quantities are expressed by the following:

$$V_a = V_0 + V_1 + V_2 \qquad (7)$$

$$V_b = V_0 + a^2 V_1 + a V_2 \qquad (8)$$

$$V_c = V_0 + a V_1 + a^2 V_2 \qquad (9)$$

$$I_a = I_0 + I_1 + I_2 \qquad (10)$$

$$I_b = I_0 + a^2 I_1 + a I_2 \qquad (11)$$

$$I_c = I_0 + a I_1 + a^2 I_2. \qquad (12)$$

From the preceding equations, the following relationships are obtained:

$$V_0 = \tfrac{1}{3}(V_a + V_b + V_c) \qquad (13)$$

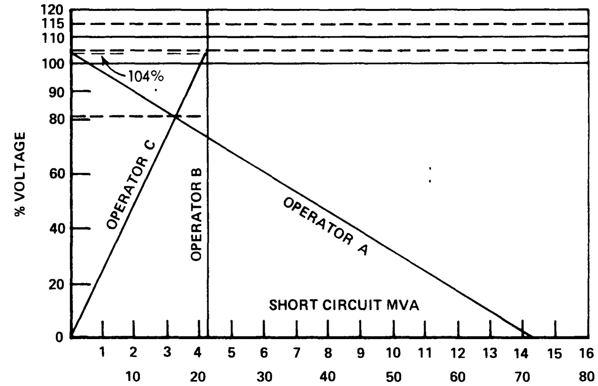
$$V_1 = \tfrac{1}{3}(V_a + a V_b + a^2 V_c) \qquad (14)$$

$$V_2 = \tfrac{1}{3}(V_a + a^2 V_b + a V_c) \qquad (15)$$

$$I_0 = \tfrac{1}{3}(I_a + I_b + I_c) \qquad (16)$$

$$I_1 = \tfrac{1}{3}(I_a + a I_b + a^2 I_c) \qquad (17)$$

$$I_2 = \tfrac{1}{3}(I_a + a^2 I_b + a I_c). \qquad (18)$$



(a)

$$V_S = y = \frac{MVA_{sc}}{MVA_{sc} + SMVA}$$

EQUATION FOR LINE "C",

$$y = MX = \frac{104}{MVA_s} X$$

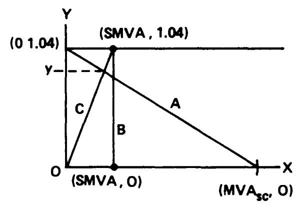
$$\text{while } M = \frac{y}{x} = \frac{1.04}{SMVA}$$

EQUATION FOR LINE "A",

$$\frac{y - y_1}{x - x_1} = \frac{y_2 - y_1}{x_2 - x_1}$$

$$\frac{y - 0}{X - MVA_{sc}} = \frac{1.04 - 0}{0 - MVA_{sc}}$$

$$\text{OR } \frac{y}{MVA_{sc} - X} = \frac{1.04}{MVA_{sc}}$$



SOLVE FOR X WITH "C"

$$x = y\,(SMVA)$$

SUBSTITUTE X INTO "A"

$$\frac{y}{MVA_{sc} - y\,(SMVA)} = \frac{1.04}{MVA_{sc}}$$

$$y(MVA_{sc}) = 1.04\left[MVA_{sc} - y(SMVA)\right]$$

$$y = 1.04\ MVA_{sc}/MVA_{sc} + SMVA$$

SMVA = STARTING MVA

MVA_{sc} = SHORT CIRCUIT MVA

V_s = Y = STARTING VOLTAGE

$$= \frac{1.04 \times 71}{71 + 21}$$

$$= 0.805$$

$$= 80.5\%\ \text{APPROX.}$$

(b)

Fig. 24. (a) Voltage drop by graphic solution. (b) Graphic solution proven by analytic geometry.

Connections between sequence networks can be found from (13)-(18):

$$V_b = 0 \qquad V_c = 0 \qquad V_a = ? \qquad I_a = 0$$

$$I_0 + I_1 + I_2 = 0 \tag{19}$$

$$V_0 = V_1 = V_2. \tag{20}$$

Equations (19) and (20) are satisfied if the sequence networks are connected as follows:

$$I_F = I_b + I_c$$

and by addition of (11) and (12)

$$I_b + I_c = 2I_0 + (a^2 + a)(I_1 + I_2).$$

Since $a^2 + a = -1$, therefore

$$I_b + I_c = I_f = 2I_0 - (I_1 + I_2).$$

Since

$$I_0 + I_1 + I_2 = 0$$

$$I_1 + I_2 = -I_0$$

therefore

$$I_F = 2I_0 - (-I_0) = 3I_0. \tag{21}$$

From the preceding analysis, (22)-(25) can be derived for the application of both the per unit method

$$I_1 = \frac{E}{X_1 + \dfrac{(X_2)(X_0)}{(X_2) + (X_0)}} \tag{22}$$

$$I_0 = I_1 \times \frac{X_2}{X_0 + X_2} \tag{23}$$

and the MVA method

$$MVA_{x_1} = \frac{MVA_1 + (MVA_2 + MVA_0)}{MVA_1 \times (MVA_2 + MVA_0)} \tag{24}$$

$$MVA_{x_0} = (MVA_{x_1}) \frac{MVA_0}{MVA_0 + MVA_2}. \tag{25}$$

Fig. 21 shows the use of (22) and (23) for solving the two-phase to ground fault of the same problem, the per unit method. Fig. 22 indicates the utilization of (24) and (25) for solving the two-phase to ground fault of the same problem, the MVA method. It is obvious as shown, that the use of the MVA method is simpler.

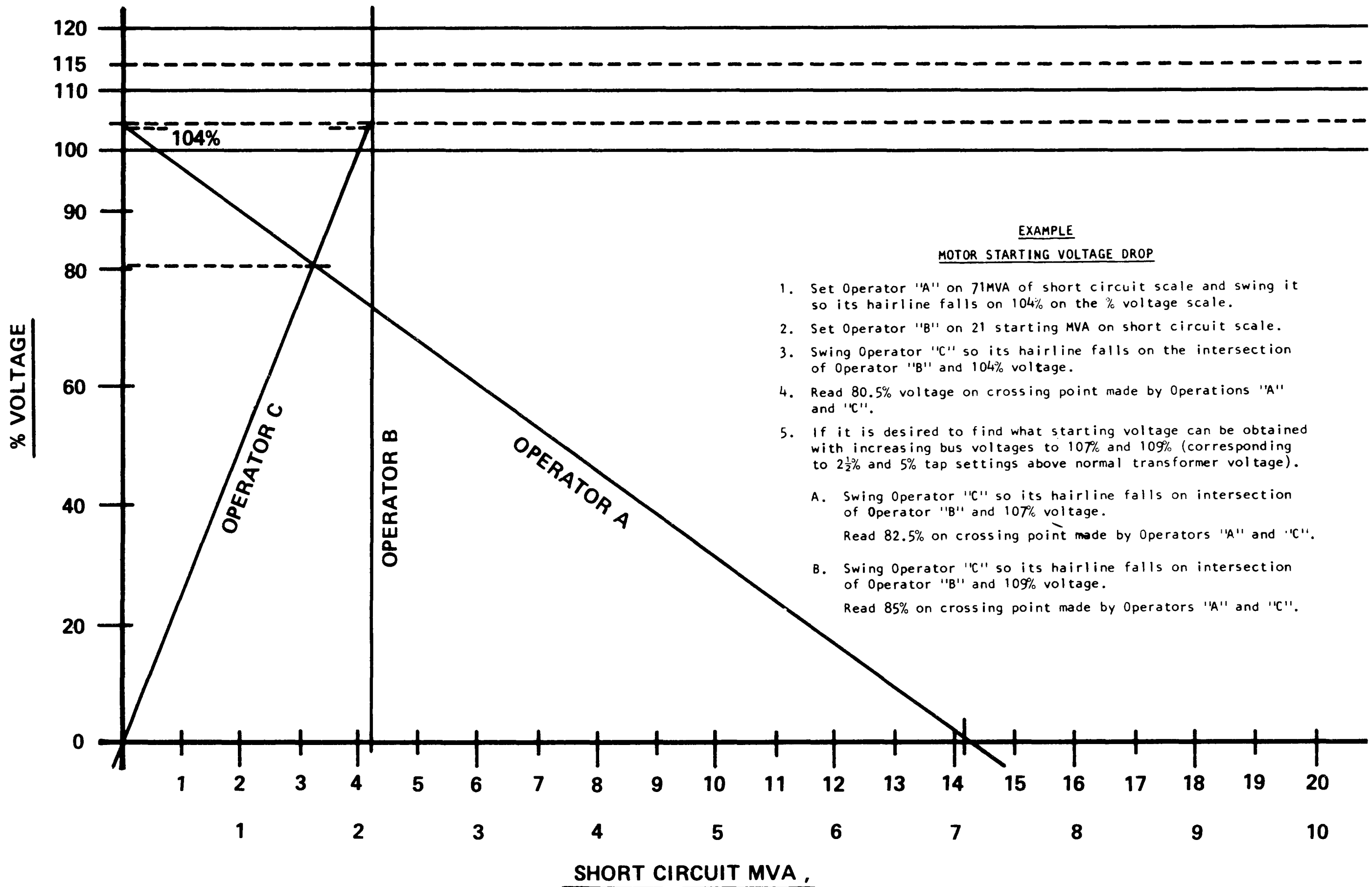


Fig. 25. Slide rule model.

MVA Method for Instantaneous Voltage Estimate

Large motors are frequently connected to power systems consisting of complicated networks of lines and cables for which a calculation of the voltage drop would be difficult. Yet, it may be critical to know approximately what the voltage at certain bus must be. This is because the voltage affects the motor torque in a square function; i.e., motor torque varies as the square of the voltage for a 10-percent voltage drop

$$\text{torque } \alpha \, (E)^2$$

$$T = (0.9)^2 = 0.81 \text{ or } 81 \text{ percent.}$$

The torque loss is 19 percent.

The voltage drop may be estimated with reasonable accuracy, however, if the short circuit MVA is known at the point of power delivery. When motor starting MVA is drawn from a system, the voltage drop in per unit of the initial voltage is approximately equal to the motor starting MVA divided by the sum of this MVA and the short circuit MVA

$$V_{\text{pu}} = \frac{\text{MVA}_s}{\text{MVA}_s + \text{MVA}_{\text{sc}}}. \tag{26}$$

Fig. 23 shows an example applying the MVA method in estimating the voltage at the 13.8-kV bus when a large motor is started.

Fig. 24(a) shows a graphic solution of the problem. Figure 24(b) illustrates the validity of the graphic solution by analytic geometry. Fig. 25 shows a slide rule made for the sole purpose of solving instantaneous voltage drop in starting large motors. The instruction for the use of the slide rule as shown is self-explanatory.

Fig. 26 is a compilation of standard industrial nominal voltages and motor terminal voltages. Note that the unique relationship between the nominal and terminal voltages is 4 percent different. This unique relationship aids the slide rule operation in solving instantaneous voltage drop during motor starting.

The Simple Computer Time Share Program

Why is it necessary to develop a computer program for such an easy method? The answer is simply economics. True, the MVA method enables the engineer to quickly calculate the faults on a power system, but how about documentation? After the engineer finishes his calculation, the result needs typing, proofreading, etc. From manual calculation to printing, the estimated cost for a problem as shown in Appendix II, having 12 components and three faults, is approximately \$100 including the engineer's pay. But the time share program solution from input to print-out costs approximately \$24 (\$12 for engineering time and \$12 for computer and terminal

A = TRANSFORMER SECONDARY VOLTAGE
B = MOTOR TERMINAL VOLTAGE

A/B = 480/460 = 2400/2300 = 4160/4000 = 12000/11500
= 13800/13200 = 22900/22000 = 104%

WHEN ONE 2 1/2 TRANSFORMER TAP IS USED:

A/B = 490/460 = 2460/2300 = 4260/4000 = 12300/11500
= 14100/13200 = 23500/22000 = 107%

2 – 2 1/2 TAPS ABOVE WILL GIVE - A/B = 110%

Fig. 26. Percent motor terminal voltage related to transformer secondary voltage.

time). As the problem involves more components and more faults, the cost differential increases noticeably.

Appendix II is a time share computer solution of Fig. 7. The program itself is a conversational type. The user of the program can input the data by a prepared tape or by typing the data as the computer is ready to receive the data.

The input data are separated into two sections. Section one is to use lines 200 through 399 for MVA items as shown with the use of the MVA method. For example, item 1 is 300 MVA, item 2 is 200 MVA, etc. Section two is to use lines 400 through 999 for command sequence. For example, line 400 data 1, 4, 5 instructs the computer to combine items 4 and 5 in series; the first number, 1, is for a series operation. In line 400 data, there is a 2, 8, and 9, which instructs the computer to combine items 8 and 9 in parallel; the first number, 2, is for a parallel operation. A 3, 3, 4, 6 command instructs the computer to convert a delta to wye operation of items 3, 4, and 6.

Refer to Appendix II. The fault 1 result is 533.4 MVA, which is close to the manual solution result of 533 MVA. Note the computer asked for a kilovolt input. The user entered the voltage. The computer then asked whether the user prefers an interrupting duty or a momentary duty computation. As shown, fault 1 requires an interrupting calculation and the computer gave a series of output selections to meet ANSI Standard latest requirement of multipliers. The computer solution sequence is exactly as shown on Fig. 10(a) for fault 1, manual solution.

For fault 2, line 410 data are replaced with new commands as shown. Notice that the sequence follows the MVA diagram, Fig. 10(b). The result of fault 2 is 261.9 MVA which was manually solved to be 262 MVA, Fig. 10(b). The computer again asked for a kilovolt input and a 4.16 was given.

The next question again was for interrupting duty or momentary duty. The answer was momentary so the computer gave two answers that are in accordance with [2].

For fault 3, line 410 data are replaced with new commands that follow the sequence as shown on Fig. 10(c). The computer asked for a kilovolt input, and 0.48 was given. Because 0.48 kV is a low-voltage system, the computer automatically printed out five answers to suit the user's choice. The multipliers are all in accordance with the *IEEE Red Book* #141, Section IV.

After the MVA method is mastered in about an hour's time, it will take no more than fifteen minutes to learn to use the computer program. Appendix III is a pre-made graph for quick estimate of instantaneous voltage in starting large motors.

CONCLUSION

The paper described a unique easy to learn and easy to remember method for solving industrial power distribution system short circuit problems. The examples given proved its effectiveness in terms of speed, accuracy, and economy over other conventional Ohmic and per unit methods. The writer has been using it for the past twenty years for many projects, small and large, and found it most effective because it seldom required one to memorize formulas as with other methods.

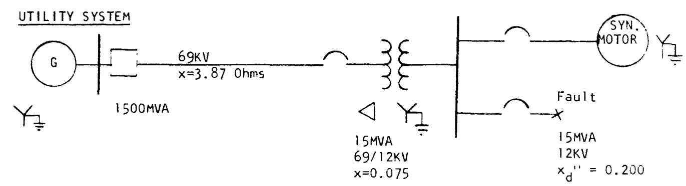
The MVA method also has been taught in various evening schools and corporation sponsored seminars, including the University of California Extension, ITC College, Bechtel Corporation, Pacific Gas and Electric Co., etc., in the San Francisco Bay area for the past seven years.

REFERENCES

[1] *Electrical Power Distribution for Industrial Plants*, IEEE Standard 141, 1969, ch. IV.
[2] *IEEE Red Book*, IEEE Standard 141, 1969, sect. IV.

APPENDIX I

The following problem is taken from the California State P.E. Registration Examination of August, 1965. The problem will be solved with the per unit method.



A. Solve for 3-phase fault
B. Solve for single line to ground fault

A. 3-PHASE FAULT

$KVA_{base} = 150MVA$

$KV_{base} = 69$ and 12 respectively

$$X_{base69} = \frac{(KV)^2 \times 1000}{KVA_{base}} = \frac{(69)^2 \times 1000}{150000} = 31.8 \text{ Ohms}$$

$$X_{base12} = \frac{(12)^2 \times 1000}{150000} = 0.96 \text{ Ohms}$$

$$I_{base69} = \frac{KVAbase}{\sqrt{3}\, KV_{base}} = \frac{150000}{\sqrt{3} \times 69} = 1250 \text{ A}$$

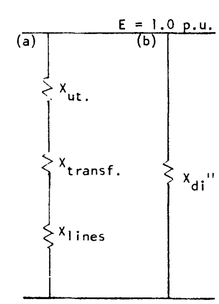
$$I_{base12} = \frac{150000}{\sqrt{3} \times 12} = 7230 \text{ A}$$

$$X_{utility\ p.u.} = \frac{1.0 \times KVAbase}{KVA_{s.c.}} = \frac{150000}{1500000} = 0.100 p.u.$$

$$X_{transf.\ p.u.} = Z_{rated\ p.u.} \frac{KVAbase}{KVA_{rated}} = \frac{0.075 \times 150000}{15000} = 0.750 \text{ p.u.}$$

$$X_{line\ p.u.} = \frac{Xrated\ Ohms}{X_{base}} = \frac{3.87}{31.8} = 0.121 \text{ p.u.}$$

$$X_{motor\ dl''} = 0.200 \times \frac{150000}{15000} = 2.00 \text{ p.u.}$$



$X_a = X_{ut.} + X_{line} + X_{transf}$
$= 0.100 + 0.121 + 0.750$
$= 0.971$

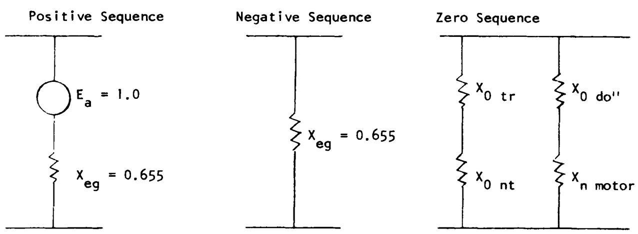
$X_b = 0.200$

$$X_{eg} = \frac{0.971 \times 2}{2.971} = 0.655$$

$$I_{fault} = \frac{E}{X_{eg}} = \frac{1.0}{0.655} = 1.525 \text{ A}$$

$$I_{fault\ 3\ ph\ @\ 12KV} = I_{fault\ p.u.} \times I_{base\ 12\ KV} = 1.525 \times 7230 = \underline{\underline{11{,}000 \text{ A}}}$$

B. Single Phase Fault



$X_{0\ nt}$ = Zero Sequence Reactance of the Transformer Neutral

$X_{0\ tr}$ = Zero Sequence Reactance of the Transformer

$X_{motor\ d0''}$ = Zero Sequence Subtransient Reactance of the Motor

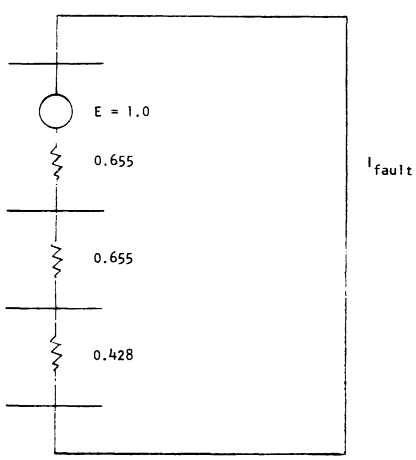
$X_{motor\ d1''}$ = Positive Sequence Subtransient Reactance of the Motor

$X_{0\ nt} = 3X_{n\ motor} = 0$

$X_{0\ tr} = 0.750$

$X_{motor\ d0''} = \frac{1}{2} \times \text{motor } d1'' = 1.000$

$X_{eg} = \frac{0.750 \times 1}{0.750 + 1} = \frac{.750}{1.750} = \underline{\underline{0.428}}$



$$I_{a1} = I_{a2} = I_{a0} = \frac{Ea}{X_1 + X_2 + X_0 + 3X_n + 3X_{fault}}$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{1}{0.655 + 0.655 + 0.428} = \frac{1}{1.738} = 0.575$$

$$I_{fault\ p.u.} = (I_{a1} + I_{a2} + I_{a0}) = 3\ (0.575) = 1.72$$

$$I_{fault} = I_{fault\ p.u.} \times I_{base\ 12\ KV} = 1.72 \times 7230 = \underline{\underline{12,400\ A}}$$

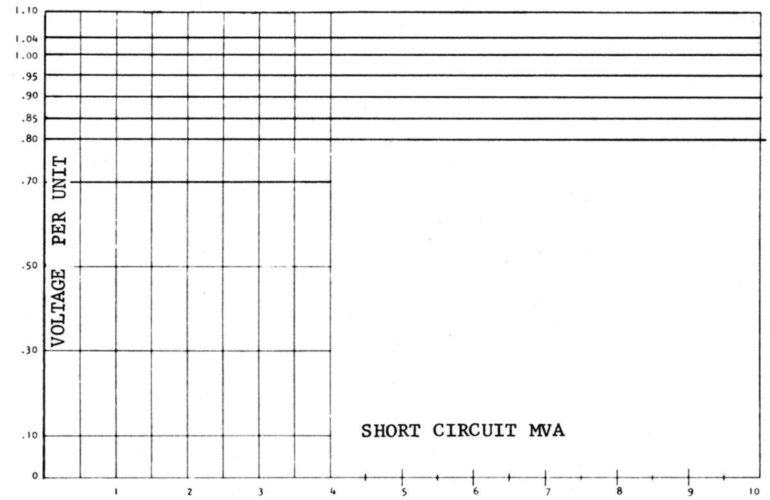
Appendix II
Time Share Computer Program

```
READY
 TAPE
READY
200 DATA 300, 200, 10000, 10000, 200, 10000
210 DATA 200, 5, 10, 24, 15, 4

400 DATA 1, 4, 5,  1, 6, 7,  2, 8, 9,  2, 8, 10,  3, 3, 4, 6
410 DATA 1, 11, 12,  2, 8, 11,  1, 3, 8,  1, 2, 4,  2, 2, 3, 1, 2, 6,  2, 1, 2

 RUN

IS THIS THE FIRST FAULT TØ BE RUN?  1=YES, 0=NØ.
?1
   NØDE NØ      MVA
     1         300.0
     2         200.0
     3       10000.0
     4       10000.0
     5         200.0
     6       10000.0
     7         200.0
     8           5.0
     9          10.0
    10          24.0
    11          15.0
    12           4.0

                              A          B        A AND B      NØDES
    1  SERIES             10000.0      200.0       196.1       4    5
    2  SERIES             10000.0      200.0       196.1       6    7
    3  PARALLEL               5.0       10.0        15.0       8    9
    4  PARALLEL              15.0       24.0        39.0       8   10
    5  DELTA              10000.0      196.1       196.1       3    4    6
       WYE                  396.0    20196.1     20196.1
    6  SERIES                15.0        4.0         3.2      11   12
    7  PARALLEL              39.0        3.2        42.2       8   11
    8  SERIES               396.0       42.2        38.1       3    8
    9  SERIES               200.0    20196.1       198.0       2    4
   10  PARALLEL             198.0       38.1       236.1       2    3
   11  SERIES               236.1    20196.1       233.4       2    6
   12  PARALLEL             300.0      233.4      [533.4]      1    2

INPUT KV  ?13.8

ENTER 1 FØR INTERRUPTING DUTY, 2 FØR MØMENTARY DUTY ?1

INTERRUPTING DUTY
X/R RATIØ                 0-25       26-40       41-60       ØVER 60
X/R MULTIPLIER             1.0         1.1         1.2           1.3
MVA AT FAULT             533.4       586.8       640.1         693.4
I SYMMETRICAL          22316.3     24547.9     26779.6       29011.2


READY
 TAPE
READY
410 DATA  1, 11, 12,  2, 8, 11,  1, 1, 6,   1, 2, 4,  2, 1, 2,  1, 1, 3,  2, 1, 8



 RUN


 IS THIS THE FIRST FAULT TØ BE RUN?   1=YES,  0= NØ.
?0
INPUT TWØ LINE NØS WHERE PRINTØUT STARTS
?12,5
NØDE     NO     MVA
  12            4.0


                          A          B        A AND B       NØDES
 5  DELTA             10000.0      196.1       196.1        3       4      6
    WYE                 396.0    20196.1     20196.1
 6  SERIES               15.0        4.0         3.2       11      12
 7  PARALLEL             39.0        3.2        42.2        8      11
 8  SERIES              300.0    20196.1       295.6        1       6
 9  SERIES              200.0    20196.1       198.0        2       4
10  PARALLEL            295.6      198.0       493.6        1       2
11  SERIES              493.6      396.0       219.7        1       3
12  PARALLEL            219.7       42.2      [261.9]       1       8

INPUT  KV  ?4.16


ENTER 1 FØR INTERRUPTING DUTY,  2 FØR MØMENTARY DUTY   ?2


MØMENTARY DUTY
X/R RATIØ                0-10        ØVER 10
X/R MULTIPLIER            1.5            1.6
MVA AT FAULT            392.8          419.0
I SYMMETRICAL         54520.2        58154.9
```

Appendix II Continued

```
READY
*TAPE
READY
410 DATA  1,1,6, 1,2,4,  2,1,1,  1, 1, 3,  2,1,8,  1,1,11,  2,1,12


*RUN


 IS THIS THE FIRST FAULT TØ BE RUN?  1=YES, 0=NØ.
?0
INPUT TWØ LINE NØS WHERE PRINTØUT STARTS
?12,6
NØDE  NØ     MVA
 12            4.0


                                  A             B          A AND B     NØDES
 6  SERIES                      300.0       20196.1         295.6    1     6
 7  SERIES                      200.0       20196.1         198.0    2     4
 8  PARALLEL                    295.6         198.0         493.6    1     2
 9  SERIES                      493.6         396.0         219.7    1     3
10  PARALLEL                    219.7          39.0         258.7    1     8
11  SERIES                      258.7          15.0          14.2    1    11
12  PARALLEL                     14.2           4.0         [18.2]   1    12

INPUT KV  ?.48


MULTIPLIER          1.0              1.25           1.4             1.6
              L/V MØLDED         L/V MOTOR     HIGH SPEED      HIGH SPEED
              CASE CIRCUIT      STARTER WITH    FUSE FØR        FUSE FØR
              BREAKER ØR          MOLDED         FEEDER       MØTØR STARTER
              L/V FUSES       CIRCUIT BREAKER  (0.004 SEC     (0.004 SEC
                                  ØR FUSE       ØR LESS)        ØR LESS)

MVA AT FAULT        18.2             22.7           25.4            29.1
1 SYMMETRICAL     21864.8          27331.0        30610.7         34983.6
```

Appendix III
A Ready-Made Graph for Quick Estimate of Instantaneous Voltage in Starting Large Motors



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