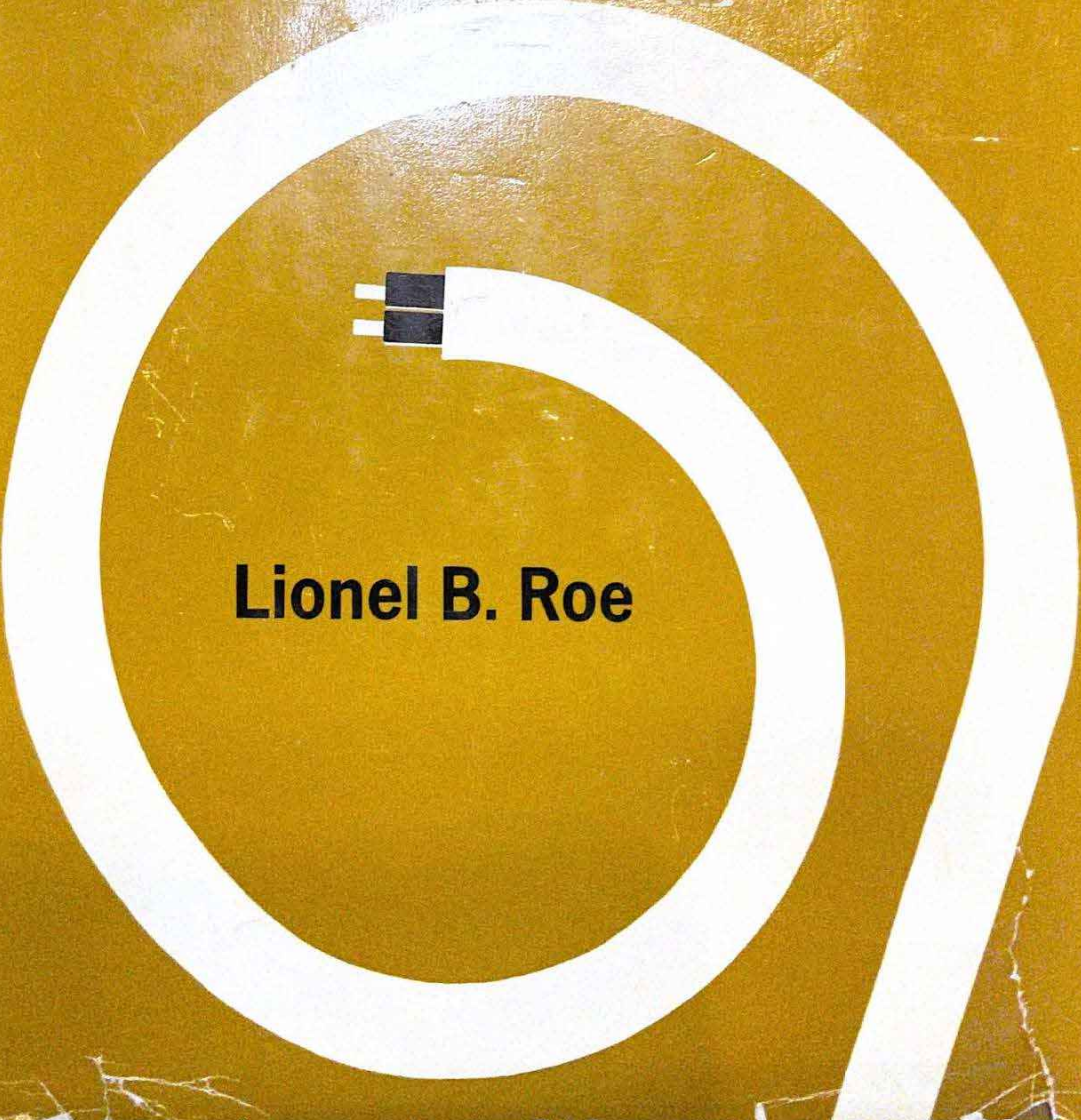


Practices and Procedures of Industrial Electrical Design



Lionel B. Roe

Practices and Procedures of Industrial Electrical Design

L. B. Roe

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McGRAW-HILL BOOK COMPANY

New York	St. Louis	San Francisco	Düsseldorf	Johannesburg
Kuala Lumpur	London	Mexico	Montreal	New Delhi
Panama	Rio de Janeiro	Singapore	Sydney	Toronto



Library of Congress Cataloging in Publication Data

Roe, L B

Practices and procedures of industrial electrical
design.

1. Electric engineering. I. Title.

TK145.R74 621.3 70-168754

ISBN 0-07-053390-3

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5 6 7 8 9 0 KPKP 7 6

*The editors for this book were Tyler G. Hicks and Stanley E. Redka,
the designer was Naomi Auerbach, and its production
was supervised by George E. Oechsner. It was set in Caledonia
by The Maple Press Company.*

It was printed and bound by The Kingsport Press.



*Dedicated to my parents
Mr. and Mrs. G. B. Roe and B. J. W.*

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Preface

This book is written for the whole of the engineering profession, for practicing engineers as well as for students. Thus it is a reference book containing facts which all members of the field may find useful. However, it is aimed at the workhorse of the industry: the designer.

Because the book is an electrical book, naturally it is written with the electrical designer in mind. It assumes that the designer has some previous experience, but that there will always be problems arising with which he is not completely familiar.

Depending upon the reader's background, then, the contents of the book may occasionally seem "out of order" or possibly too advanced or too elementary. The subject matter was selected and arranged in accordance with two criteria:

1. Material should be presented that will make the designer's task easier and speedier.
2. The information should be presented in the order of requirement as a design progresses.

This is why power-factor correction, short-circuit studies, and checking occur toward the middle or end of Part I rather than as fundamentals at the beginning.

It was decided to place the reference mathematics as Part 2 of the book. This decision was made because it is basically an electrical book, not a mathematics book. It is essential, however, that the mathematics part be perused *first*. Unless the reader is familiar with classical logic, trigonometry, and vectors, his understanding of the electrical portion will be limited.

Project engineers from other fields such as civil, mechanical, and chemical engineering should have no difficulty in understanding matters of electrical design after reading this book or a specific chapter of it.

Because the designer seems to be the forgotten individual as far as practical textbooks are concerned, the author would welcome any suggestions as to future material to include. As revisions are introduced the designers can eventually have their own design standard.

Thanks to Charles J. Helin, P.E., Past President, Board of Registration for Professional Engineers, State of California, for his review of the manuscript and his helpful suggestions.

Illustrations are by John Smets, of Huntington Park, California.

L. B. Roe

Chapter Two

The Basic Electric System

2.1 The System and Primary Components

Electricity is simply another form of energy. It is only useful, however, when it can be controlled and transmitted. There are three basic requirements for the electric system: production, transmission, and utilization. The production of electricity requires a source of energy, such as water, steam, gas, fossil fuels, atomic energy, etc. These are then used to provide a "prime mover" with power. Attached to the "prime mover" is a generator. The generator produces electricity at a relatively low voltage. To prepare the electricity for transmission over long distances, it is fed into a device known as a transformer. The voltage is then raised by transformer action to approximately 1,000 volts for every mile of transmission. For 150 miles the voltage would probably be a standard 169 kv (169 kilovolts). When the fringe of the local area is reached, the electricity is once more fed into a transformer, which then reverses the process and lowers the voltage for local distribution.

2.2 Measurement and Control

The quantity of electricity used is measured by meters and other instruments. The amount delivered and the stability of the system are controlled by regulating devices, protective relays, and circuit breakers.

2.3 Equipment

Generally, all "transmitting" electric equipment will fall into one of the preceding categories. The actual size of the equipment will vary with the amount of voltage and power it is required to handle. For example, a circuit breaker can be as small as a cigarette package, or it can be large enough to walk around in. In either case, it serves the same basic function. To ensure a comprehensive understanding of the function of a particular piece of equipment, we will introduce the basic system. No attempt will be made to explain the design of a specific piece of equipment or the limits of its use. This will be covered in a later chapter. We will explain the general function of the equipment and introduce the correct terminology. Some terms tend to be ambiguous. Therefore, for the purpose of this text, we will establish the generic name and the specific duty of the equipment.

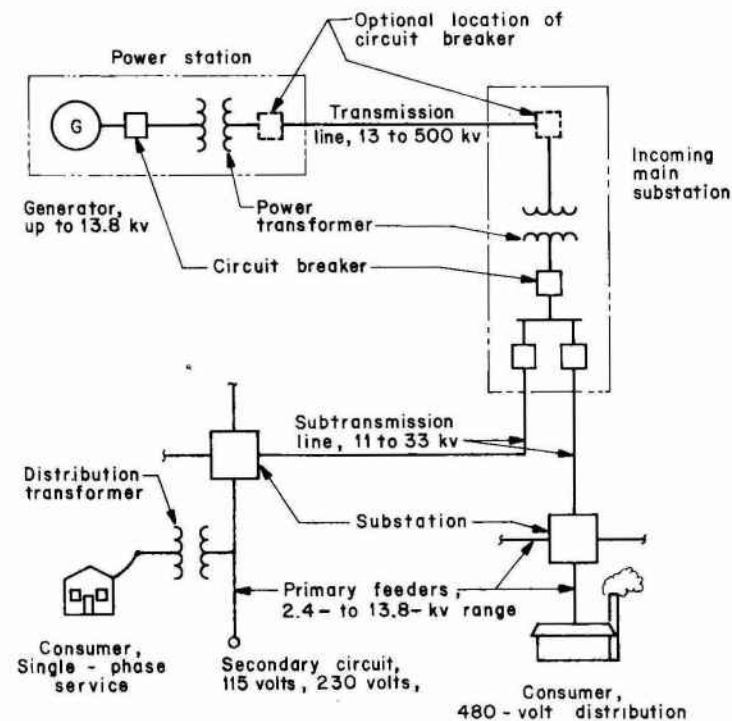


Fig. 2.1 Basic electric system.

2.4 The Generator

The *generator* is a device used to transform mechanical energy into electrical energy. The electricity may be in the form of *direct current*,

alternating single-phase current, or *alternating polyphase current*. The selected frequency of the alternating current can be optional. The standard frequency in the United States and Canada is 60 cycles per second (cps) for normal utility systems. In aircraft and missile systems, varying frequencies are used. For example, 400 cps is used in some aircraft systems. This high frequency allows a reduction in the weight of components. The rating of ac generators is given in kva output at rated voltage and power factor. The dc generators are rated in kw output at rated voltage. kva is simply an abbreviation for kilovolt-amperes or va 10^{-3} (kilo meaning a thousand). The same applies to kw (this is an abbreviation for kilowatts). The standard generator used for conventional utility electric systems is always a three-phase unit.

2.5 The Circuit Breaker

The conductors leaving the generator terminate in a *circuit breaker*. The function of this piece of equipment is to prevent excessive currents in the system beyond the generator. At the same time, it can be made to serve as a protective device to prevent overloading of the generator. Circuit breakers come in many forms, shapes, and sizes. There are air circuit breakers, vacuum circuit breakers, oil circuit breakers, power circuit breakers, and plastic case circuit breakers. These are varied in current rating, voltage rating, short-circuit rating, and shock rating (mechanical shock). The methods of tripping the circuit breakers are also quite varied. Each manufacturer has particular features in his design which he feels may make it better than another manufacturer's design. Sometimes these features become standard and are common to all circuit breakers. With all these differences, all circuit breakers have one thing in common: They disconnect a circuit from the supply when the current in the system exceeds predetermined limits. The circuit breaker may also serve double duty as a disconnect device or switch, being operated manually instead of automatically.

2.6 The Stepup Transformer

We now begin our sequence of transmitting power from one location to another. We have, up to now—beginning with the generator—terminated in a circuit breaker. From here, we feed into a transformer. The purpose of the transformer is to raise the voltage from the rated voltage of the generator to a new voltage level, suitable for transmitting over long distances. This new voltage level is determined by evaluating a number of conditions. The voltage selected is dependent on installa-

tion cost, distance, operating expense, and also present and future voltages of other systems in the vicinity.

The types of transformers used for feeding transmission lines are usually custom built to meet the utility-company requirements. They may be three-phase autotransformers¹ with approximately a 2:1 ratio of transformation, or three-phase two-winding transformers with higher ratios of transformation. In some cases, three single-phase transformers are used and connected in star or delta to provide a three-phase system of transformation.

2.7 The Circuit-breaker Location

We will again introduce the circuit breaker at this point. As we are considering a logical sequence of major equipment, we must point out that apparent power is the product of voltage and current. For a given quantity of apparent power, we can consider low voltage and high current or high voltage and low current. Depending on the particular values in each case, selection of a circuit breaker must be made. The current values in the low-voltage system may be excessive for a circuit breaker, whereas in the high-voltage system, the current and voltage levels may be well within normal limits for standard circuit breakers. Therefore, we may find it necessary to locate the circuit breaker on the high-voltage side of the transformer. In either case, the same protection is offered to the system. There may also be other factors (such as the type of system the generator and transformer are being connected to) which will govern the location of the circuit breaker. The main point to consider is that there is a choice of locations between the secondary and primary sides of the transformer for location of the circuit breaker.

2.8 The Transmission Line

The transmission line may be considered the part of the system bridging the gap between one remote area and another remote area. Its sole purpose is to span long distances. This is accomplished by a system of towers carrying high-voltage conductors. The towers are usually steel and are a familiar sight across the country. The high-voltage systems are as high as 450 kv (450,000 volts). We then get into what is known as the EHV system (extra high voltage). This is in the range of around 700 kv (700,000 volts). The transmission line may be sectionalized for convenience purposes. Also, there may be interlinkages with other transmission systems requiring switching connections. This does

¹ See Chap. 6.

not make it a *distribution system*. It is still a transmission system, with the primary function of spanning long distances.

2.9 The Stepdown Transformer

When the transmission line reaches its approximate area of distribution, the voltage must be reduced to a lower level to permit distribution within populated areas. Here, then, we reverse the procedure. The transmission line terminates in a stepdown transformer. The specifications for the transformer are similar to the requirements for the transformer at the generating end. The circuit-breaker requirements also apply; i.e., we may locate a circuit breaker on either the primary or the secondary side.

2.10 The Distribution System

After lowering the voltage at the consumer's end of the transmission system, the power must still be routed to various places of utilization. The *distribution system* is designed to cover a specific area such as a town rather than long distances. The method of distribution is usually by the use of wooden poles. The height of these varies but is usually between 30 and 50 ft. Using poles of this height requires reduced spacing between conductors. Therefore, the voltage is reduced to levels limiting the spacing between conductors to 2 or 3 ft. This allows crossarms of 6 to 10 ft to be utilized. Subtransmission lines are used to connect the transmission system to the distribution system. The voltage on these lines is approximately between 138 and 33 kv. From these main subtransmission lines, a further system of feeders is routed to other specific areas. Again, shorter distances are covered, and therefore the voltage may be reduced. This part of the distribution system is known as the *primary circuits*. From these, we connect further lines known as subfeeders and laterals. The voltages on the feeder part of the system are usually between 13 kv and 4.16 kv. The subfeeders may be three-phase or single-phase, depending on the exact requirements of the load density in that particular area. The single-phase voltages would be the three-phase voltage divided by 1.73 or $\sqrt{3}$. And so the electrical system approximates the shape of a tree, with the transmission line as the trunk and the distribution system as the branches, gradually reducing in voltage.

2.11 The Distribution Transformer

The last link between the distribution feeder and the consumer is the distribution transformer. This transformer is a standard stock item, de-

signed with standard voltages and output ratings. Minor extras are available in the form of *taps* to allow a small percent of adjustment in voltage. Optional impedances are available to permit paralleling with other transformers, and also to limit short-circuit availability to some extent. The transformers are available in single-phase and three-phase; however, the single-phase transformer is more adaptable to general use and provides more flexibility. To obtain three-phase power, it is only necessary to use three single-phase transformers. This also provides a safety margin, in that the failure of one transformer will still allow operation by connecting the remaining two in delta or open wye, providing a service with 58% of the original three-transformer bank output. The voltages, of course, are reduced by the distribution transformer to the standard consumer levels, which could be 115, 230, 277, 480, or 550 volts, depending on local requirements.

2.12 Protection and Control

To prevent failure of power supplies and also to provide protection against excessive overloads, numerous types of devices are used. Basically, all these devices monitor the line variables in one form or other. They eventually result in the operation of a circuit breaker or instrumentation and metering. Some devices operate on current alone, others measure the angle between the current and voltage, and others measure voltage or voltage and current giving apparent power. The different types are too numerous to mention here; however, as we introduce various design procedures, we will also introduce the necessary metering and protective devices required.

2.13 The Substation

The *substation* is the part of an electric system containing one or more power transformers, switchgear, bus-bar distribution, regulating equipment, and (sometimes) a control building. These substations can be a large complex of buildings, steel structures for bus-bar distribution, huge transformers and banks of power-switching circuit breakers, or they may be smaller, individual packaged unit substations supplying a small factory. The designation of substation, then, is dependent on function rather than size.

The options available in electric system design are innumerable. Transmission line design, substation design, distribution system design, equipment application, system stability are all individual fields of study, each with its associated pitfalls, shortcuts, dos and don'ts that only experience will give. This does not imply that design cannot be done in all these fields by the competent designer. All the information is avail-

able in design procedures, and usually the specifications are outlined either by the customer or by the utility companies in the area. This, then, leaves only the conventional calculations and selection of equipment.

Thus when we consider design procedures, we will assume that the standard practice has already been formulated by the experts and chosen as the normal procedure for all probable conditions. We will encounter unusual conditions where possibly another alternative might be better. However, for reasons not obvious to the nonexpert, it is better to stay with the conventional approach. Again, we do not recommend that original thinking not be used. But it should be pointed out that before deviating from the conventional approach, one should evaluate very carefully the contemplated change and consider all the aspects, from problems of obtaining equipment which may be nonstandard to consideration of the electrician who may have to troubleshoot during a thunderstorm. Sometimes the cost and convenience advantages acquired in straying from the standard are lost many times over in the down time or equipment-replacement costs.

operate, it will open the circuit. To do this, it must be able to handle the momentary stresses existing at that time without damage. This, then, is termed the *interrupting rating*.

9.17 Impedance Diagram

The short-circuit study is relatively simple, once the impedance diagram is established. The important step, then, is setting up the impedance diagram.¹ We begin with the single line, as previously mentioned. Next we draw a similar single line, replacing all equipment symbols with a resistor symbol. The impedances will then eventually be reduced to a single impedance. This serves as the master plan for the short-circuit study. We must now decide where to locate the fault, and whether we require interrupting or momentary rating. We combine reactances with the same rules as resistors.

Series resistors $R_T = R_1 + R_2 + R_3 + \dots + R_n$

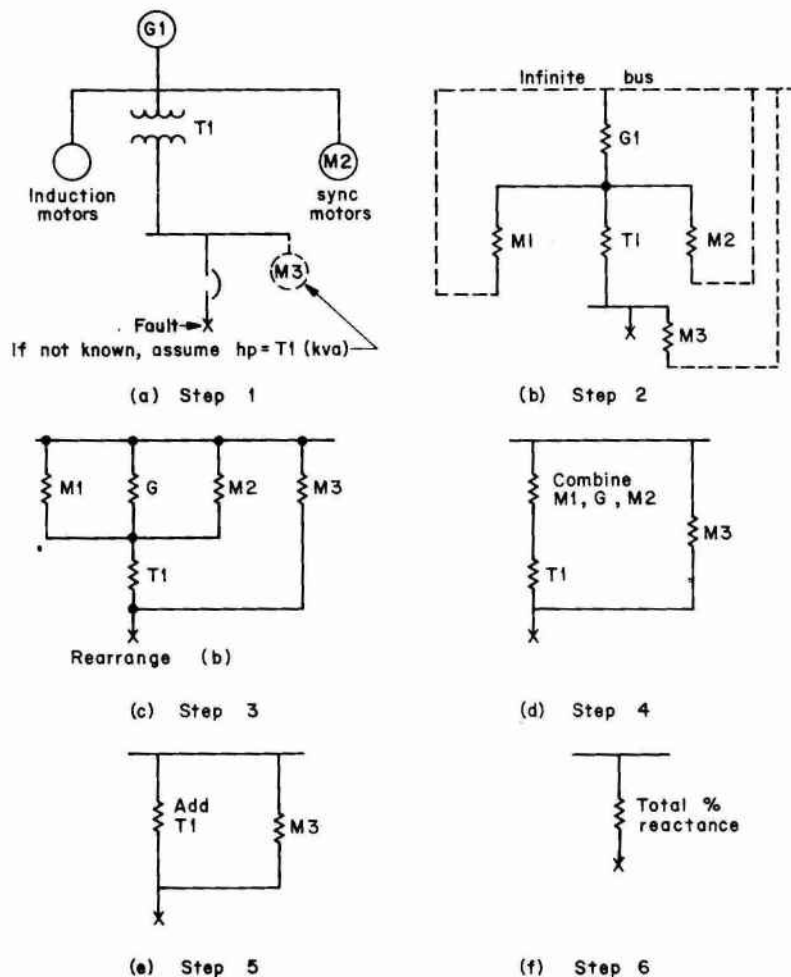
Parallel resistors $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_n}$

The approach to laying out the impedance diagram is relatively simple. It is necessary to remember some basic rules:

1. Show all sources of fault current, i.e., induction motors, generators, and synchronous motors.
2. Replace all components having resistance and/or reactance with a resistor symbol.
3. Identify these components with letters.
4. Show all power-transformer secondaries feeding an induction-motor load whether motors are indicated or not (unless all load is accounted for).
5. Join all components by an "infinite bus."
6. The *source* is not the "infinite bus,"² but is shown as a separate reactance.
7. Rearrange reactances carefully into parallel and series groups.
8. When considering momentary rating, include all induction motors and use subtransient $X''d$ reactances.
9. When considering interrupting rating, neglect all branches feeding pure induction motors and use only transient reactance $X'd$ except below 600 volts.

¹ Even though we are using reactances, the accepted term is *impedance diagram*.

² The "infinite bus" can be considered a conductor connecting all the machine's neutral points together.



Note: Refer to Table 9.3 for interrupting duty and which reactances to include or omit.
 Short-circuit kva = base kva $\times 100 / \text{Total \% reactance}$
 SC amp, symmetrical = SC kva / kv $\times 1.73$
 For asymmetrical, see Table 9.3 for multiplier

Fig. 9.3 Impedance diagram, Example 1. Neglect cables for example only. Calculation is for momentary rating.

We notice in Example 1, Step 2, that we have reactances connected at only one end. The general procedure to follow here is to connect the unconnected ends to the source (infinite) bus, except for the reactance(s) terminating in the fault.

Now we will consider a more involved system in the Example 2, Fig. 9.4. Notice the two following points: The motor loads $m1$, $m2$,

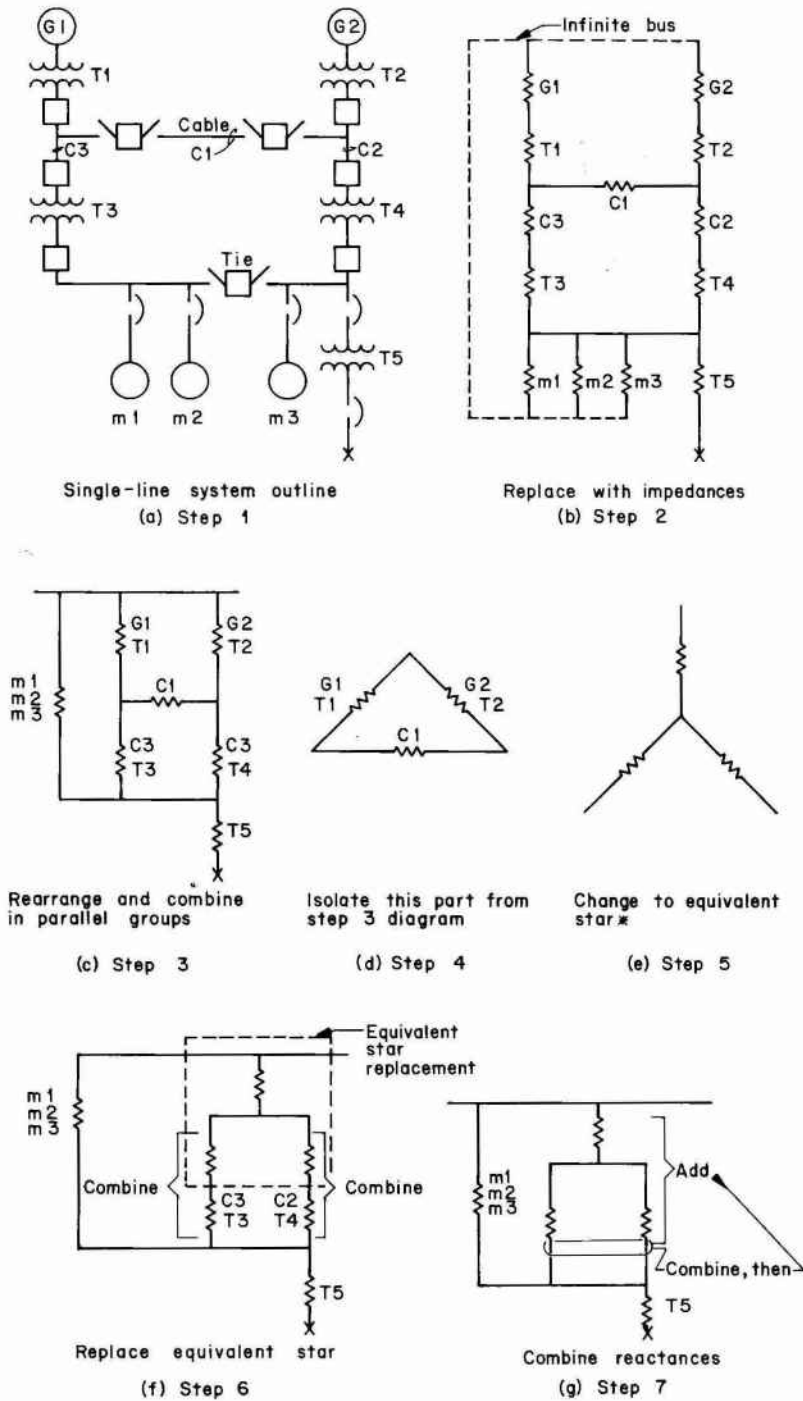
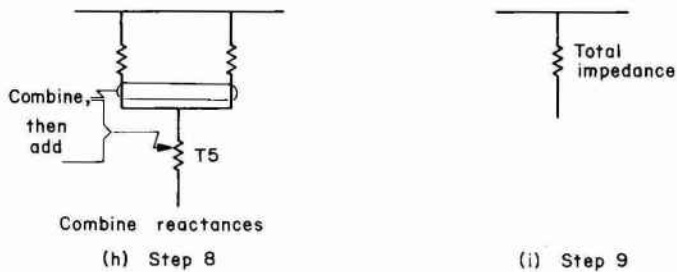


Fig. 9.4 Impedance diagram, Example 2; example with tie breaker closed.



* See sec. 9.18 for star - delta conversion

Fig. 9.4 (continued) Impedance diagram, Example 2; example with tie breaker closed.

$m3$ in Step 2 were connected to the "infinite" bus. The second important point was the star/delta conversion. It should be recognizable that the reactances $G1$, $T1 - C1$, $-T2$, $G2$ form a closed delta in Steps 2 and 3. By changing this to an equivalent star connection, we have a simple series parallel equivalent.

9.18 Star/Delta Conversion

The star/delta conversion is accomplished by the use of the following formulas:

$$\begin{aligned}
 B &= \frac{ab + ac + bc}{b} & b &= \frac{CA}{A + B + C} \\
 C &= \frac{ab + ac + bc}{c} & c &= \frac{AB}{A + B + C} \\
 A &= \frac{ab + ac + bc}{a} & a &= \frac{BC}{A + B + C}
 \end{aligned}$$

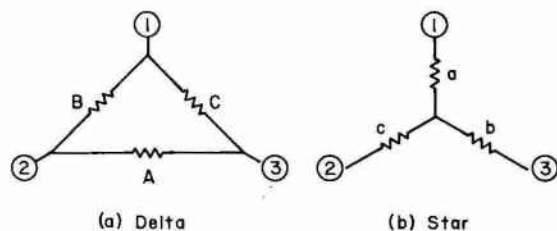


Fig. 9.5 Star/delta conversion numbering method.

We see then that if we assign the numbers 1, 2, and 3 to the corners of a delta, we can solve for a , b , and c . This produces the star connection with corresponding 1, 2, and 3 connections.