Electricity and New Energy

Smart Grid

Course Sample

8107696

Order no.: 8107696 (Printed version) 8107697 (Electronic version)
First Edition
Revision level: 09/2019

By the staff of Festo Didactic

Internet: www.festo-didactic.com
e-mail: services.didactic@festo.com

Printed in Canada

ISBN 978-2-89789-409-2 (Printed version)
ISBN 978-2-89789-410-8 (Electronic version)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2019
Legal Deposit – Library and Archives Canada, 2019

Safety and Common Symbols

The following safety and common symbols may be used in this course and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign , indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, risk of electric shock
	Caution, lifting hazard
	Caution, hot surface
	Caution, risk of fire
	Caution, risk of explosion
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation

Safety and Common Symbols

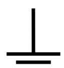
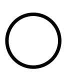
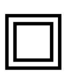
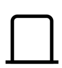
Symbol	Description
	Consult the relevant user documentation.
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

Table of Contents

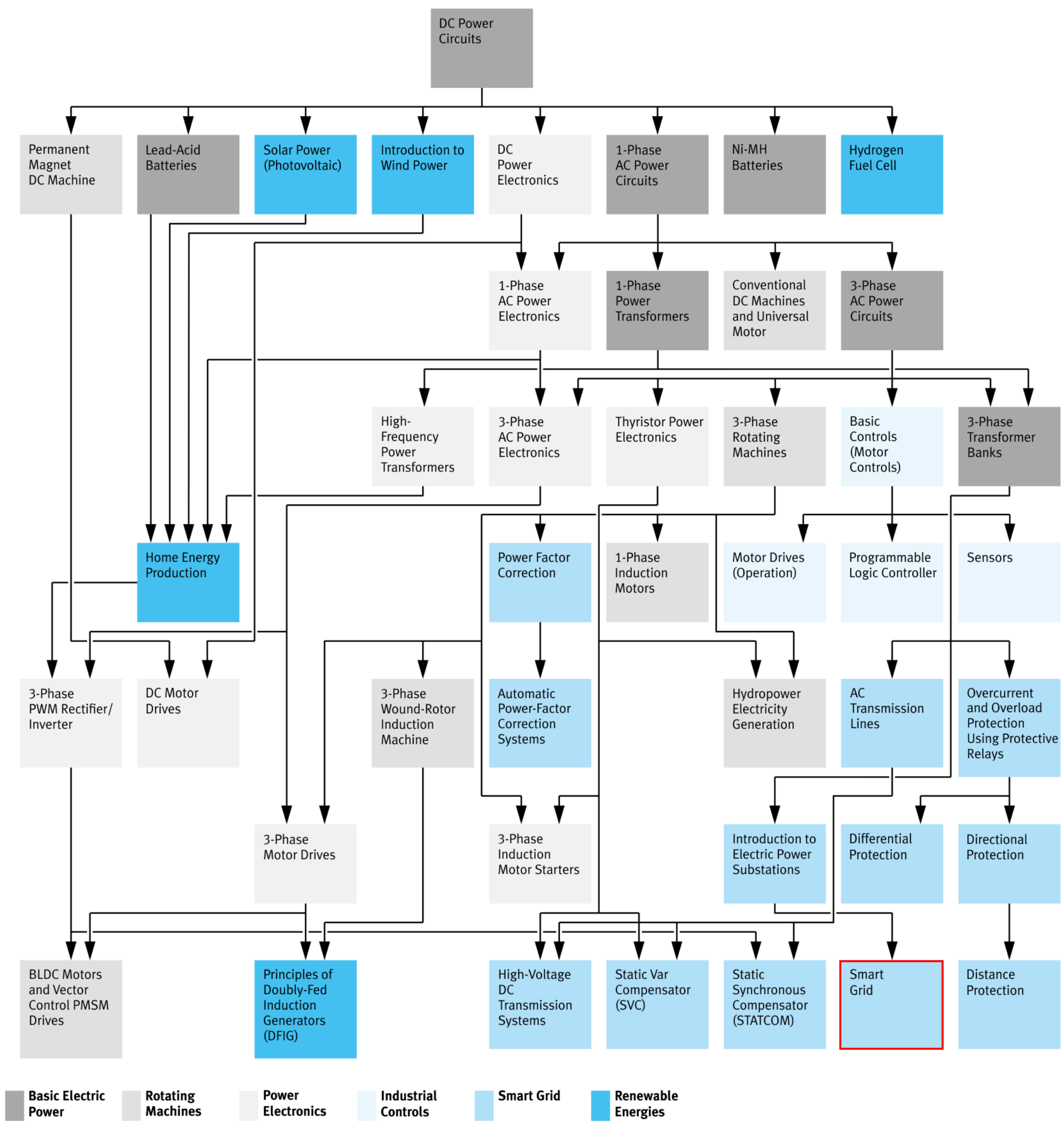
Table of Contents

Table of Contents

Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as motor starters and drives, storage of electrical energy in batteries, home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, protective relaying, and smart-grid technologies (SVC, STATCOM, HVDC transmission systems, etc.).

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to services.didactic@festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

The electric power grid, also familiarly referred to as the grid, is the infrastructure through which power utilities supply electricity to consumers. The increasing demand for electricity observed worldwide forces power utilities in more and more countries to make a transition toward the smart grid to help keep up with demand.

The present course starts with a brief presentation of the electric power grid. It then explains what the smart grid is, as concretely as possible. This is no easy task, because the definition of the smart grid differs slightly from one country to another. The course continues by presenting several different ways of improving the infrastructure of the grid to make it smart. To demonstrate this in a concrete way, the course shows how an aging distribution substation can be upgraded to improve its reliability, maintainability, flexibility of operation, and power efficiency, i.e., to make it ready for operation in the smart grid and to help meet objectives of the smart grid. The course terminates by showing that proper control of the operations in electric power substations is as important as upgrading the infrastructure of substations to achieve objectives of the smart grid.

Making the grid smart is a priority in more and more countries to help keep up with the increasing demand for electricity.

Safety considerations

Safety symbols that may be used in this course and on the equipment are listed in the Safety and Common Symbols table at the beginning of this document.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

About This Course

Prerequisite

As a prerequisite to this course, you should have completed the courses listed below.

- DC Power Circuits
- Single-Phase AC Power Circuits
- Single-Phase Power Transformers
- Three-Phase AC Power Circuits
- Three-Phase Transformer Banks
- Introduction to Electric Power Substations

Systems of units

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Sample

Extracted from

Instructor Guide

Upgrading a Substation for Operation in the Smart Grid

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with some means of upgrading an electric power substation to make it ready for operation in the smart grid and to help meet the objectives of the smart grid.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction
- Initial configuration of an aging distribution substation that needs to be upgraded
- Upgrading the distribution substation for operation in the smart grid
- Automated control of the distribution substation operation

DISCUSSION

Introduction

This discussion presents the case of an aging distribution substation that needs to be upgraded to help meet the objectives of the smart grid. The discussion begins by presenting the initial configuration of the distribution substation and identifying major limitations in terms of reliability, maintainability, and flexibility of operation. The discussion then presents improvements that significantly improve the substation's reliability, maintainability, and flexibility of operation, thereby making the substation ready for operation in the smart grid.

Initial configuration of an aging distribution substation that needs to be upgraded

Figure 14 is a single-line diagram that shows the configuration of an aging distribution substation. The substation uses the basic single bus scheme.

This distribution substation has the following major limitations:

1. A fault on either power transformer T1 or incoming line A of the substation results in a prolonged interruption in the supply of power to all consumers served by the substation.

2. A fault on the substation bus results in a prolonged interruption in the supply of power to all consumers served by the substation.

3. A fault on any one of the outgoing lines of the substation results in a prolonged interruption in the supply of power to the consumers served by the faulty outgoing line.

4. Maintenance of either power transformer T1 or the circuit breaker and disconnecting switches of incoming line A results in a prolonged interruption in the supply of power to all consumers served by the substation.

5. Maintenance of the substation bus results in a prolonged interruption in the supply of power to all consumers served by the substation.

6. Maintenance of the circuit breaker and disconnecting switches of any one of the outgoing lines of the substation results in a prolonged interruption in the supply of power to the consumers served by this outgoing line.

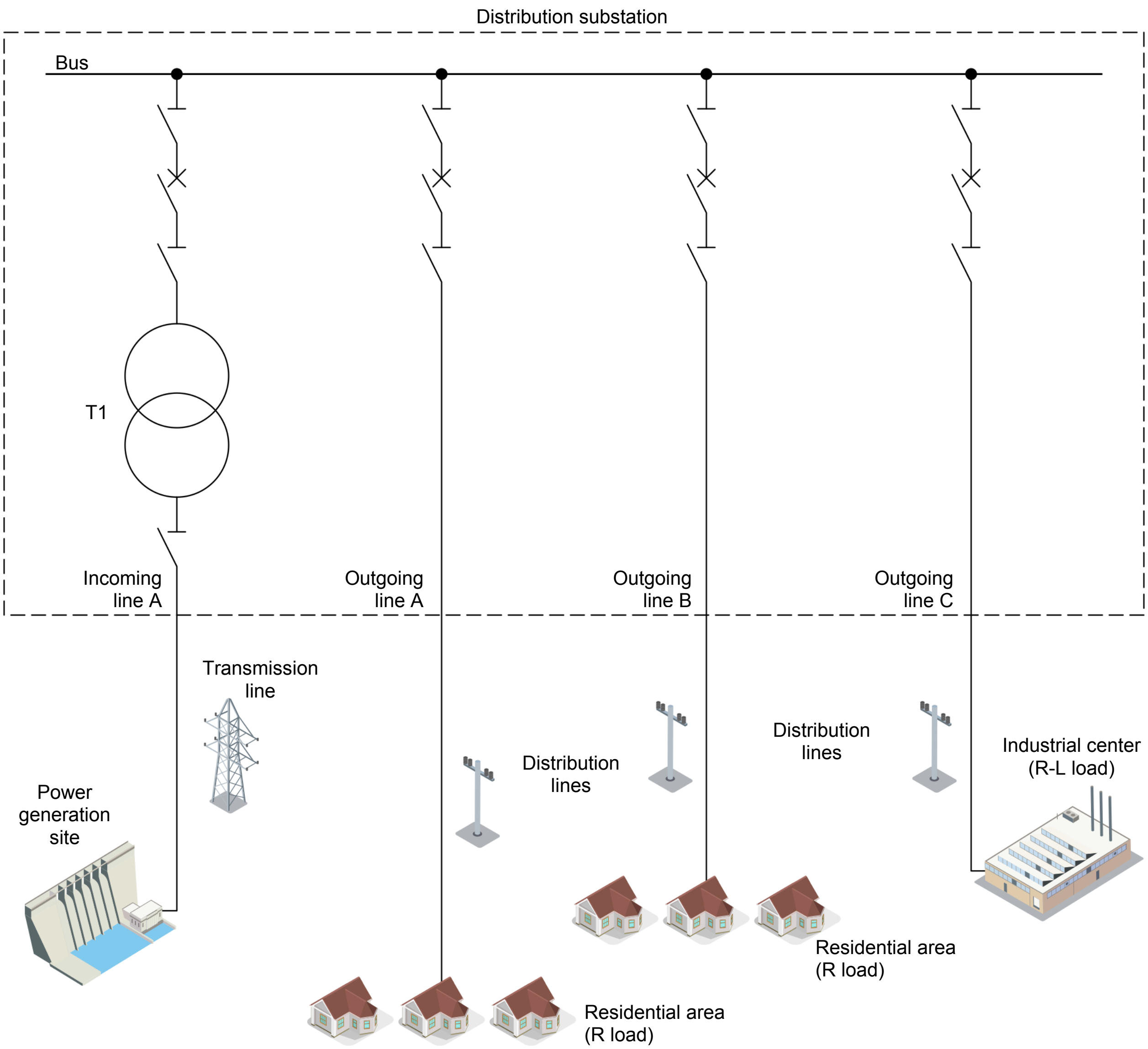


Figure 14. Single-line diagram of an aging distribution substation that uses the basic single bus scheme.

In short, the distribution substation shown in Figure 14 has poor reliability and maintainability. It also has no flexibility of operation. These aspects must be improved significantly to make the substation ready for operation in the smart grid and to help meet the objectives of the smart grid.

Upgrading the distribution substation for operation in the smart grid

Figure 15 is a single-line diagram that shows the new configuration designed to upgrade the distribution substation presented in the previous section. Once implemented, the new configuration makes the distribution substation ready for operation in the smart grid, as is explained and demonstrated in the remainder of this course.

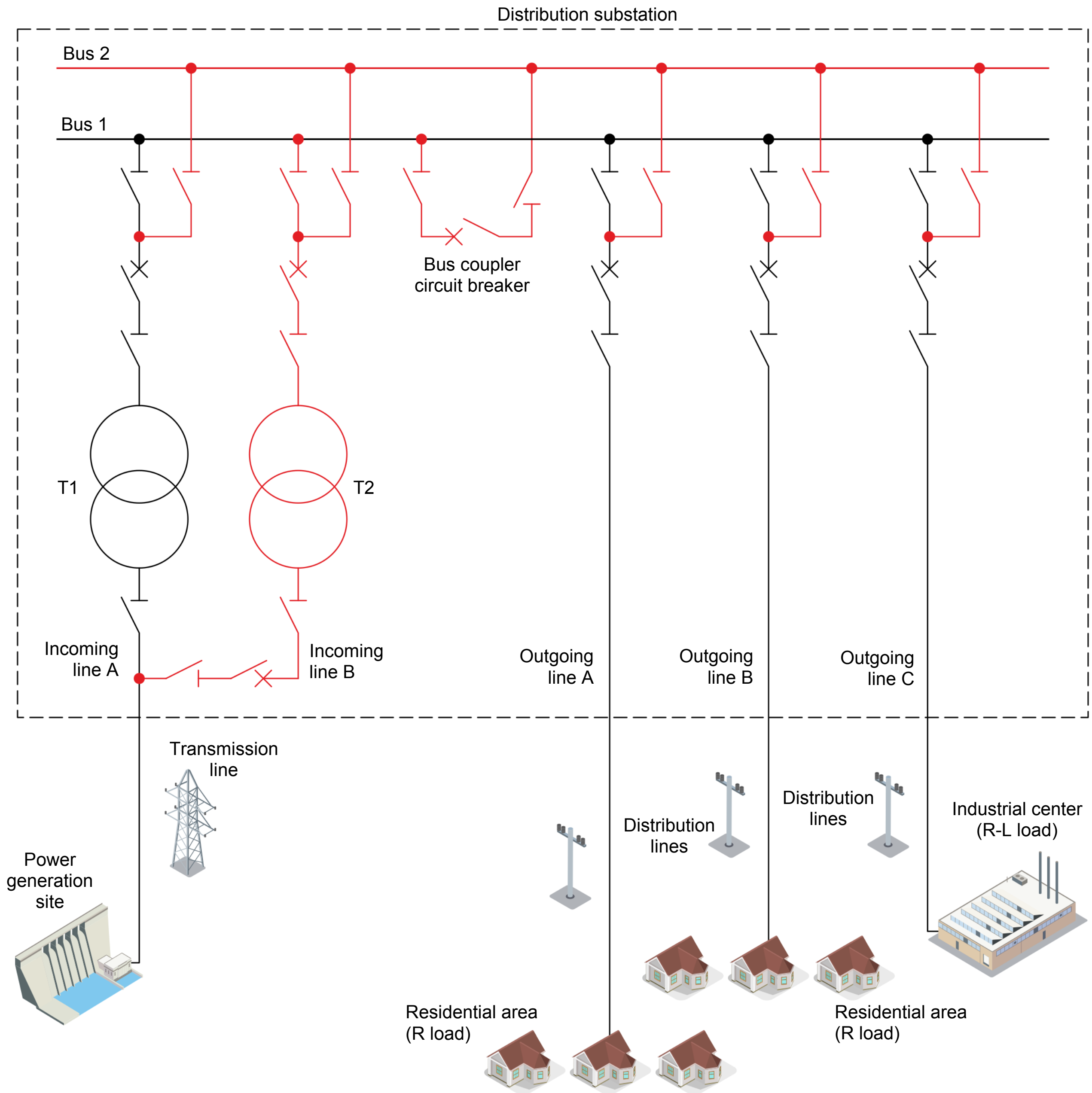


Figure 15. Single-line diagram showing the configuration of the distribution substation once upgraded for operation in a smart grid.

The new configuration of the distribution substation includes the following two major improvements (shown in red in Figure 15):

1. Some equipment redundancy is provided, i.e., a second incoming line (B) and a second power transformer (T2) are added to the substation. The second power transformer has the same rating as the first power transformer (T1). Notice that a circuit breaker and two disconnecting switches are also added to tie the second incoming line with the first incoming line (A). This allows both incoming lines, and consequently both power transformers, to be fed by the transmission line reaching the substation.

2. The switching scheme of the substation is upgraded to the double bus, single breaker configuration. This provides further equipment redundancy (i.e., a second bus in the substation) as well as some flexibility of operation.

These two major improvements have the following benefits:

1. They ensure electric power is still available in the distribution substation after a fault on either one of the power transformers or either one of the incoming lines. Consequently, this prevents a prolonged interruption in the supply of power to the consumers served by the substation in case of a transformer fault or an incoming line fault, thereby solving limitation 1 identified in the previous section.

2. They ensure that electric power can still be delivered to the customers served by the distribution substation after a fault on either one of the busses. This greatly diminishes the duration of the interruption in the supply of power to the consumers served by the substation in case of a bus fault, thereby providing a solution to limitation 2 identified in the previous section.

3. They allow either one of the power transformers and the corresponding incoming-line circuit breaker and disconnecting switch to be isolated for maintenance purposes, without any interruption in the supply of power to the consumers served by the substation. This solves limitation 4 identified in the previous section.

4. They allow any one of the busses of the distribution substation to be isolated for maintenance purposes, without any interruption in the supply of power to the consumers served by the substation. This solves limitation 5 identified in the previous section.

To summarize, the above improvements solve several limitations of the distribution substation identified in the previous section of this discussion. In fact, this makes the distribution substation ready for operation in the smart grid and helps in meeting the objectives of the smart grid. The only limitations that remain are related to a fault on any one of the outgoing lines or the maintenance of any one of the outgoing lines. Solving these two limitations would require an upgrade of the switching scheme of the distribution substation to either the breaker-and-half configuration or the double bus, double breaker configuration. These two switching schemes, however, are more expensive than the double bus, single breaker scheme. In the present case, the double bus, single breaker scheme is deemed acceptable.

Automated control of the distribution substation operation

To fully take advantage of the improvements above, the control of the distribution substation operation should be automated. In other words, the substation should be equipped with a substation automation system (SAS). The SAS ensures proper sequencing of the operations (basically the opening and closure of circuit breakers and disconnecting switches) required to perform actions in the distribution substation (e.g., the on-load transfer of an outgoing line to the other bus of the substation). This virtually eliminates the occurrence of operating errors when performing actions in the substation, thereby further contributing to the reliability of the grid. Furthermore, the SAS allows remote control of the distribution substation, which helps reduce operational costs and improve grid management coordination. The operation of the distribution substation is further discussed in the next exercise of this course.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Familiarization with the SCADA window of the dual-transformer distribution substation
- Starting up the dual-transformer distribution substation
- Maintenance of one of the two power transformers and the switchgear of the corresponding incoming line
- Fast restoration of power to loads after a bus fault in the distribution substation

PROCEDURE

⚠ WARNING

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connection with the power on unless otherwise specified.

Set up and connections

In this section, you will set up a distribution substation that is virtually identical to the dual-transformer distribution substation shown in Figure 15 of the discussion.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

   Install the required equipment in the Workstations. Figure 16 shows the suggested equipment installation.

⚠ WARNING

Before coupling rotating machines, make absolutely sure that the power is turned off to prevent any machine from starting inadvertently.

   Mechanically couple the Four-Pole Squirrel-Cage Induction Motor to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

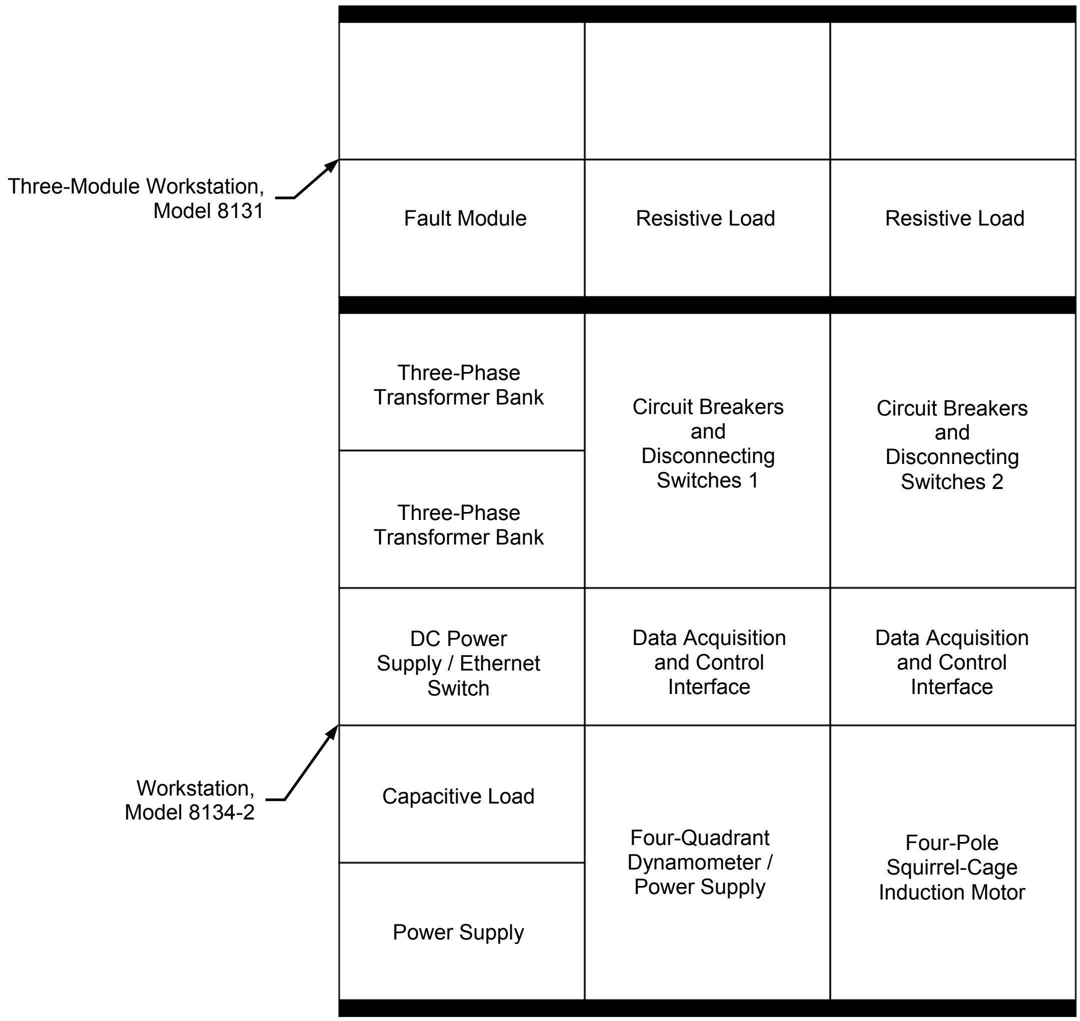


Figure 16. Suggested equipment installation.

2. Make sure that the ac and dc power switches on the Power Supply are set to the *O* (off) position, then connect the Power Supply module to a three-phase ac power outlet.

   Make sure that the main power switch on the Four-Quadrant Dynamometer/Power Supply is set to the *O* (off) position, then connect the Power Input to an ac power outlet.

   Make sure that the power switch on the DC Power Supply / Ethernet Switch is set to the *O* (off) position, then connect the *Power Input* to an ac power outlet.

3. Make sure that the *Software Development Kit (SDK)* is available in each of the two Data Acquisition and Control Interface (DACI) modules. A label affixed to each DACI module lists the functions that are available in the module.

Connect the *Power Input* of each of the two DACI modules to a 24 V ac power supply. Turn the 24 V ac power supply on.

Connect the USB port of each of the two DACI modules to a USB port of the host computer.

4. Connect the *Power Input* of each of the two Circuit Breakers and Disconnecting Switches modules to the 120 V output of the DC Power Supply / Ethernet Switch.

5. Connect the Ethernet port of each of the two Circuit Breakers and Disconnecting Switches modules to one of the ports on the DC Power Supply / Ethernet Switch.

6. Connect a USB port of the host computer to one of the ports on the DC Power Supply / Ethernet Switch via the USB-to-Ethernet adapter (included with the DC Power Supply / Ethernet Switch).

7. Figure 17 shows the single-line diagram of the dual-transformer distribution substation that you will set up and use in this exercise. This distribution substation uses the double bus, single breaker scheme and is identical to the one shown in Figure 15 of the discussion, except for the following minor differences:

   - Power transformer T1 is connected directly to the three-phase ac power source which emulates the power generation site, without passing through a transmission line and a disconnecting switch. The transmission line is omitted to limit the amount of equipment required to perform the exercise. The disconnecting switch is omitted due to the limited number of disconnecting switches available to set up the substation.

   - The two incoming lines are interconnected via a single disconnecting switch instead of a circuit breaker and two disconnecting switches. This is due to the limited number of circuit breakers and disconnecting switches available to set up the substation.

   - Voltage and current inputs of two DACI modules (referred to as DACI modules #1 and #2 in Figure 17) are used to measure electric parameters at the incoming lines, outgoing lines, and the two busses of the substation. Notice that the voltage and current inputs of DACI module #2 are shown in red in Figure 17.

   Also, three-phase resistive loads R_1 and R_2 emulate two residential areas served by the distribution substation. On the other hand, the three-phase induction motor (a resistive-inductive load) emulates an industrial center served by the distribution substation. The induction motor is mechanically coupled to a brake. This allows the mechanical load applied to the induction motor to be adjusted. A capacitor is connected in parallel with the induction motor. This capacitor corrects the power factor of the induction motor.

8. The equipment required to implement the various components of the dual-transformer distribution substation shown in the single-line diagram of Figure 17 is indicated below.

- Circuit Breakers and Disconnecting Switches 1 and Circuit Breakers and Disconnecting Switches 2 are required to implement the distribution substation.
- A Three-Phase Transformer Bank module is required to implement each of the two three-phase power transformers (T1 and T2). The nominal power of each transformer is 433 VA.
- Two Data Acquisition and Control Interface (DACI) modules are required to implement the various voltage (E) and current (I) inputs necessary to measure voltage and current at various points in the distribution substation.
- A Resistive Load module is required to implement each of the two three-phase resistive loads (R_1 and R_2). For now, set all switches on the two Resistive Load modules to the *O* (open) position. This makes the resistance of each three-phase resistive load infinite.
- The Four-Pole Squirrel-Cage Induction Motor is required to implement the three-phase induction motor.
- A Capacitive Load module is required to implement the power-factor correction capacitor (delta-connected, three-phase capacitor bank) of the three-phase induction motor. For now, set all switches on the Capacitive Load module to the *O* (open) position.
- A Four-Quadrant Dynamometer/Power Supply is required to implement the brake coupled to the three-phase induction motor.

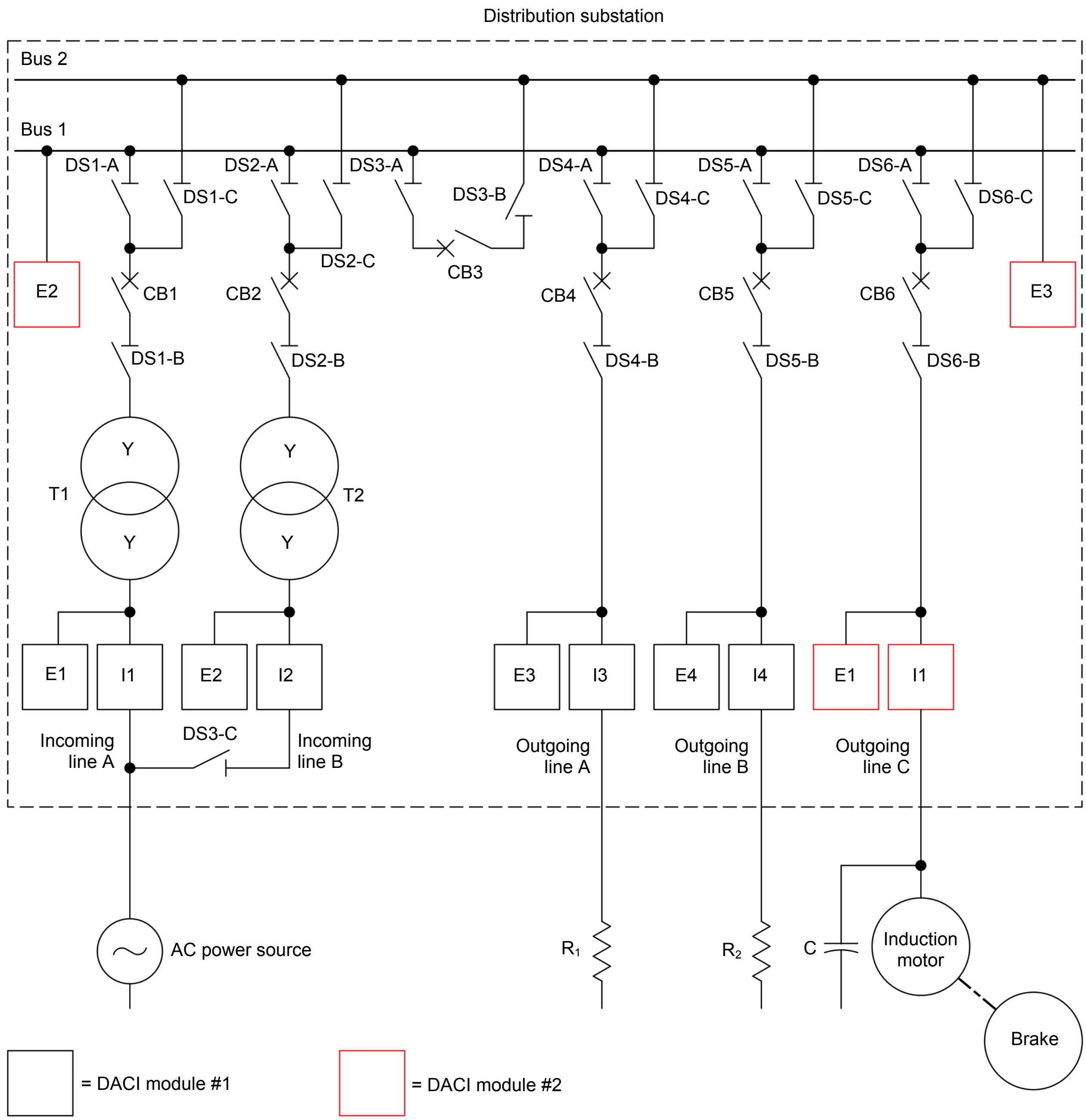


Figure 17. Single-line diagram of a dual-transformer distribution substation using the double bus, single breaker switching scheme.

9. On one of the two DACI modules, connect *Analog Output 1* to *Analog Input 1*. This connection identifies this DACI module as DACI module #1 shown in Figure 17.

   On the other DACI module, connect *Analog Output 1* to *Analog Input 2*. This connection identifies this DACI module as DACI module #2 shown in Figure 17.

10. Connect the equipment as shown in the single-line diagram of Figure 17 to set up the dual-transformer distribution substation. Use three-phase connections to set up the substation. When doing the connections, refer to Figures 18 through 23 which provide detailed connection diagrams of the voltage and current inputs of the two DACI modules as well as of the three-phase ac power source, power transformers, resistive loads, and induction motor with power-factor correction capacitor.

Making the connections required to set up the dual-transformer distribution substation takes significant time. If you are missing time to complete the connections or to continue the exercise procedure, keep the equipment setup as it is. This will allow you to continue the present exercise procedure at the next lab session.

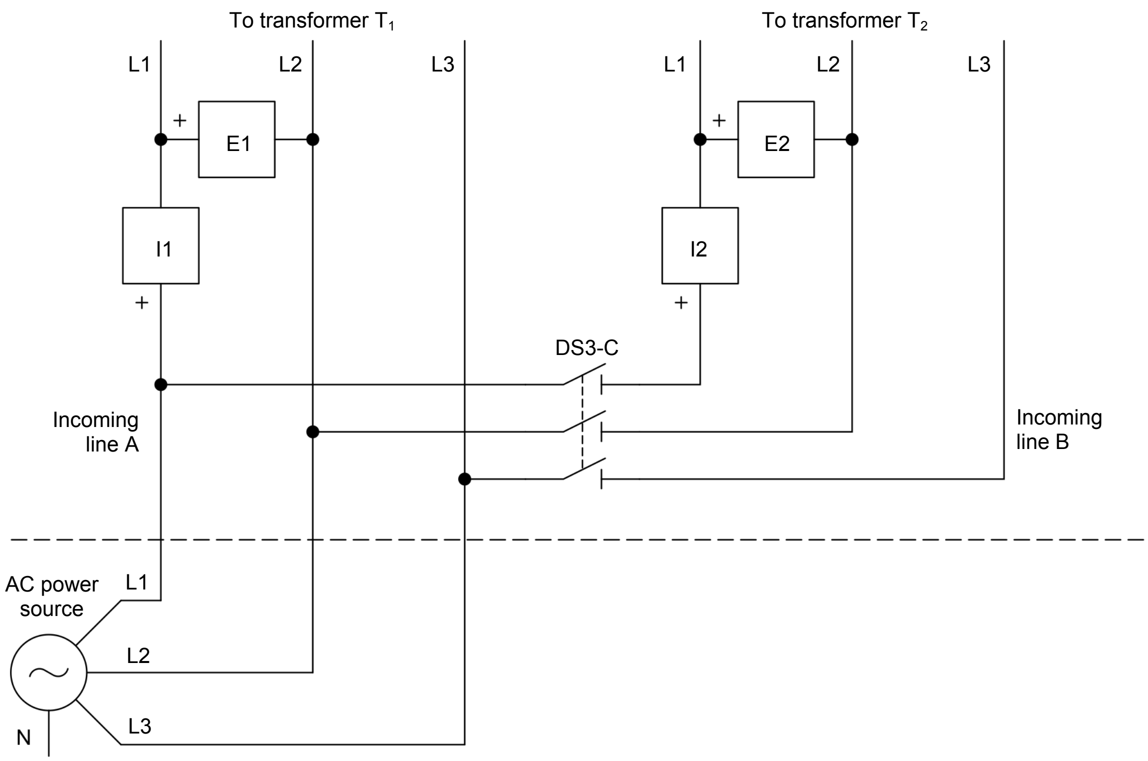


Figure 18. Diagram of the connections between the three-phase ac power source and power transformers T1 and T2 in the distribution substation.

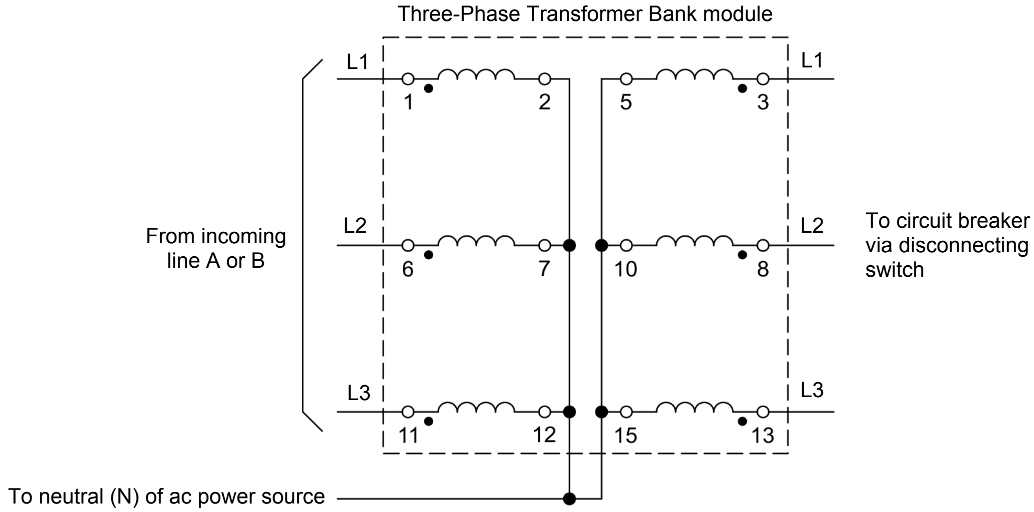


Figure 19. Connection diagram for each of the two power transformers (T1 and T2) in the distribution substation.

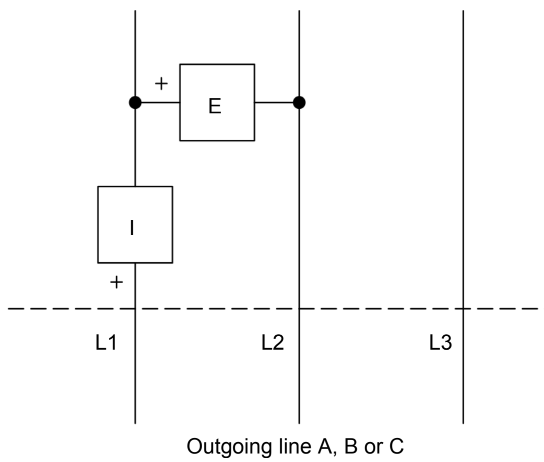


Figure 20. Connection diagram of the voltage and current inputs at each outgoing line of the distribution substation.

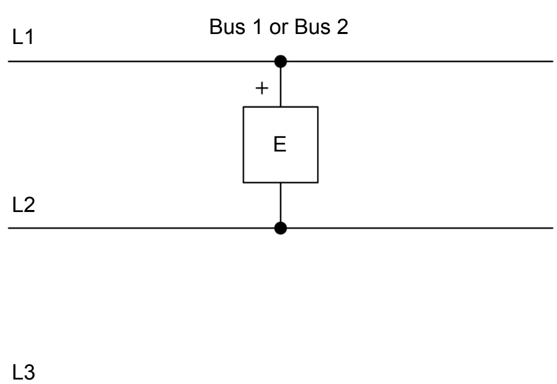


Figure 21. Connection diagram of a voltage input used to measure the line-to-line voltage across one of the busses of the distribution substation.

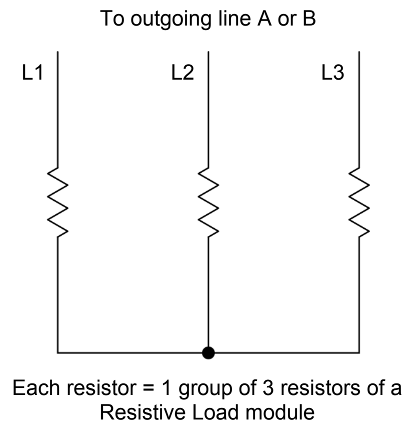


Figure 22. Connection diagram for each of the two three-phase resistive loads (R_1 and R_2).

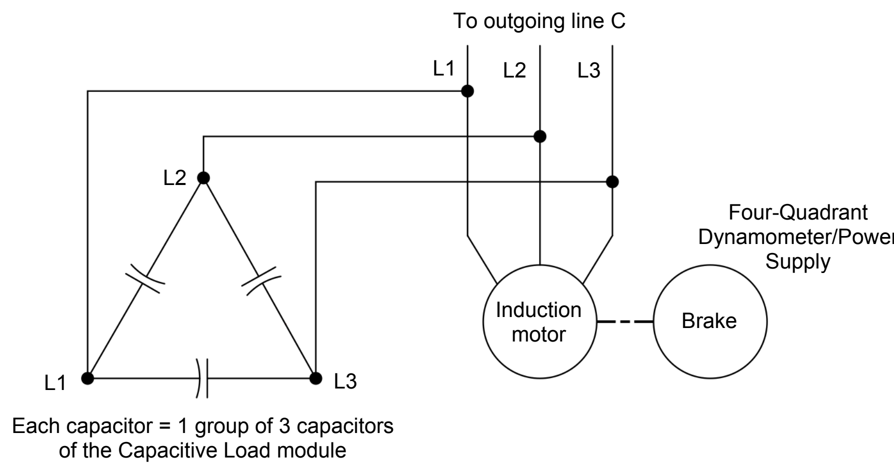


Figure 23. Connection diagram of the three-phase induction motor with power-factor correction capacitor (delta-connected, three-phase capacitor bank).

Familiarization with the SCADA window of the dual-transformer distribution substation

In this section, you will familiarize yourself with the SCADA window of the dual-transformer distribution substation.

11. Turn the DC Power Supply / Ethernet Switch on.

Wait a few seconds, then notice that all open (*O*) LEDs on the front panels of the two Circuit Breakers and Disconnecting Switches modules are lit. This indicates that all circuit breakers and disconnecting switches in the dual-transformer distribution substation are open.

12. Turn the host computer on, then start the Electric Power Substation SCADA Application by performing the following two steps.

- Start the Electric Power Substation SCADA Application Launcher by double-clicking the corresponding icon on the host computer desktop.

- Launch the Electric Power Substation SCADA Application by clicking the *Launch Application* button in the Electric Power Substation SCADA Application Launcher. The Electric Power Substation SCADA Application Launcher should disappear (in fact, the corresponding window is minimized) and the Electric Power Substation SCADA Application window should appear.

13. In the Electric Power Substation SCADA Application window, click the *Dual Transformer Substation* button to select this substation configuration. The single-line diagram of the corresponding electric power substation should appear on the host computer screen.

For the remainder of this exercise procedure, the Electric Power Substation SCADA Application window is simply referred to as the SCADA window.

Observe that the single-line diagram of the electric power substation displayed in the SCADA window corresponds to the single-line diagram (see diagram in Figure 17) of the dual-transformer distribution substation that you set up.

Observe that each circuit breaker symbol in the SCADA window indicates the current state (open) of the corresponding circuit breaker in the distribution substation. Similarly, each disconnecting switch symbol in the SCADA window indicates the current state (open) of the corresponding disconnecting switch in the distribution substation.

Observe that the letter “R” appears next to each circuit breaker symbol in the SCADA window to indicate that the corresponding circuit breaker in the distribution substation is ready to close.

Finally, observe that displays in the SCADA window indicate the values of voltage at bus 1 and bus 2 as well as the values of current and active power at each of the incoming and outgoing lines of the distribution substation.

Starting up the dual-transformer distribution substation

In this section, you will perform the operations required to start up the dual-transformer distribution substation. You will adjust the amount of power that each three-phase resistive load consumes. You will set the power factor of the three-phase induction motor as close as possible to unity by adjusting the reactance of the power-factor correction capacitor bank. You will set the amount of active power that the three-phase induction motor consumes by adjusting the braking torque. You will make the bus coupler circuit breaker ready for on-load transfers.

14. On the Power Supply, turn the three-phase ac power source on.

15. Successively close disconnecting switches DS1-A and DS1-B in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box.

Close circuit breaker CB1 in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This connects incoming line A and power transformer T1 to bus 1. Observe that bus 1 is now energized by transformer T1. The value of the voltage at bus 1 is indicated in the SCADA window.

Parasitic voltage may appear across bus 2 even if it is not yet energized, due to some capacitive coupling in the distribution substation. Ignore this voltage for now.

16. Successively close disconnecting switches DS4-A and DS4-B in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box.

Close circuit breaker CB4 in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This connects outgoing line A to bus 1, thereby energizing three-phase resistive load R_1. The values of the current and active power at outgoing line A are indicated in the SCADA window. These values should currently be zero because the resistance of three-phase resistive load R_1 is infinite.

17. Set the resistance of three-phase resistive load R_1 so that the amount of active power it consumes (i.e., the power demand) is about 165 W. For the moment, neglect the fact that the polarity of the active power value at outgoing line A displayed in the SCADA window is negative.

Three-phase resistive load R_1 must remain balanced when setting the power demand. When changing the switch settings on the corresponding Resistive Load module, make sure that each one of the three resistor sections is set to the same value of resistance.

Power is now routed to three-phase resistive load R_1 via incoming line A, power transformer T1, bus 1, and outgoing line A.

Observe that the active power value at incoming line A is positive because power enters the distribution substation. Conversely, observe that the active power value at outgoing line A is negative because power leaves the distribution substation.

Observe that the active power value at incoming line A is a little higher than the active power value at outgoing line A (neglect the polarity of the power values). This is mainly due to power losses in transformer T1.

18. Close disconnecting switch DS3-C in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This interconnects incoming lines A and B of the distribution substation.

19. Successively close disconnecting switches DS2-B and DS2-C in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box.

Close circuit breaker CB2 in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This connects incoming line B and power transformer T2 to bus 2. Observe that bus 2 is now energized by transformer T2. The value of the voltage at bus 2 is indicated in the SCADA window.

20. Successively close disconnecting switches DS5-B and DS5-C in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box.

Close circuit breaker CB5 in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This connects outgoing line B to bus 2, thereby energizing three-phase resistive load R_2. The values of the current and active power at outgoing line B are indicated in the SCADA window. These values should currently be zero because the resistance of three-phase resistive load R_2 is infinite.

21. Set the resistance of three-phase resistive load R_2 so that the amount of active power it consumes (i.e., the power demand) is about 65 W.

Three-phase resistive load R_2 must remain balanced when setting the power demand. When changing the switch settings on the corresponding Resistive Load module, make sure that each one of the three resistor sections is set to the same value of resistance.

Power is now routed to three-phase resistive load R_2 via incoming line B, power transformer T2, bus 2, and outgoing line B.

22. Successively close disconnecting switches DS6-B and DS6-C in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box.

Close circuit breaker CB6 in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This connects outgoing line C to bus 2, thereby energizing the three-phase induction motor which starts to rotate. The values of the current and active power at outgoing line C are indicated in the SCADA window.

23. Adjust the reactance of the power-factor correction capacitor bank so as to lower the value of the induction motor current (i.e., the value of the current at outgoing line C) as much as possible. This ensures that the power factor of the three-phase induction motor is close to unity.

The power-factor correction capacitor bank must remain balanced when adjusting the power factor. When changing the switch settings on the Capacitive Load module, make sure that each one of the three capacitor sections is set to the same value of reactance.

24. Turn the Four-Quadrant Dynamometer/Power Supply on, then set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

On the Four-Quadrant Dynamometer/Power Supply, use the *Function* button to select the *2Q CT Brake* (two-quadrant, constant-torque brake) function, then use the *Command* knob to set the torque command of the brake to 0.40 N·m (3.5 lbf·in).

The selected function and the torque command of the brake are indicated on the front panel display of the Four-Quadrant Dynamometer/Power Supply.

On the Four-Quadrant Dynamometer/Power Supply, depress the *Start/Stop* button briefly to start the brake, then adjust the torque command of the brake so that the amount of active power the three-phase induction motor consumes (i.e., the active power at outgoing line C) is about 115 W.

The status (started or stopped) of the brake is indicated on the front panel display of the Four-Quadrant Dynamometer/Power Supply.

Power is now routed to the three-phase induction motor via incoming line B, power transformer T2, bus 2, and outgoing line C.

Observe that the active power value at incoming line B is a little higher than the sum of the active power values at outgoing lines B and C (neglect the polarity of the power values). This is mainly due to power losses in transformer T2.

25. Make sure that bus coupler circuit breaker CB3 in the distribution substation is open.

Close disconnecting switches DS3-A and DS3-B in the distribution substation by clicking the corresponding symbol in the SCADA window, then clicking the *Close* button in the switchgear control dialog box. This makes bus coupler circuit breaker CB3 ready for on-load transfers.

Maintenance of one of the two power transformers and the switchgear of the corresponding incoming line

In this section, you will demonstrate that the maintenance of one of the two power transformers in the distribution substation and the switchgear of the corresponding incoming line can be performed without interrupting the supply of power to the loads served by the substation.

26. Power transformer T2 in the distribution substation and the switchgear of the corresponding incoming line (i.e., circuit breaker CB2 and disconnecting switch DS2-B) are scheduled for maintenance. Determine the sequence of operations that is required to isolate power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B for maintenance purposes without interrupting the supply of power to the loads served by the distribution substation.

The following sequence of operations is required to isolate power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B for maintenance purposes without interrupting the supply of power to the loads served by the distribution substation.

- Perform an on-load transfer of outgoing line B to bus 1 (close bus coupler circuit breaker CB3, close disconnecting switch DS5-A, and open disconnecting switch DS5-C).
- Perform an on-load transfer of outgoing line C to bus 1 (with bus coupler circuit breaker CB3 still closed, close disconnecting switch DS6-A then open disconnecting switch DS6-C).
- Once the on-load transfers are completed, open bus coupler circuit breaker CB3.
- Open circuit breaker CB2.
- Open disconnecting switch DS2-C and make sure disconnecting switch DS2-A is open.
- Open disconnecting switch DS3-C.

27. Perform the sequence of operations that you determined in the previous step to isolate power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B. While performing the sequence of operations, monitor the values of current and active power at outgoing lines A, B, and C.

Has the supply of power to the loads served by the distribution substation been interrupted while you performed the sequence of operations required to isolate power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B?

❑ Yes ❑ No

No

Which precautions must be taken before proceeding to the maintenance of power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B?

The following precautions must be taken before proceeding to the maintenance of power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B.

- Check that no voltage is present on both sides of power transformer T2 and circuit breaker CB2.
- Install protective grounding equipment on both sides of power transformer T2 and circuit breaker CB2.

28. Once the maintenance of power transformer T2, circuit breaker CB2, and disconnecting switch DS2-B is complete and the protective grounding equipment has been removed, the distribution substation is ready to return to its initial operating state. Determine the sequence of operations that is required to return to the initial operating state without interrupting the supply of power to the loads served by the distribution substation.

The following sequence of operations is required to return to the initial operating state without interrupting the supply of power to the loads served by the distribution substation.

- Close disconnecting switch DS3-C.
- Make sure disconnecting switch DS2-B is closed.
- Close disconnecting switch DS2-C.
- Close circuit breaker CB2 to re-energize bus 2.
- Perform an on-load transfer of outgoing line B to bus 2 (close bus coupler circuit breaker CB3, close disconnecting switch DS5-C, and open disconnecting switch DS5-A).
- Perform an on-load transfer of outgoing line C to bus 2 (with bus coupler circuit breaker CB3 still closed, close disconnecting switch DS6-C then open disconnecting switch DS6-A).
- Once the on-load transfers are completed, open bus coupler circuit breaker CB3.

29. Perform the sequence of operations that you determined in the previous step to return to the initial operating state without interrupting the supply of power to the loads served by the distribution substation. While performing the sequence of operations, monitor the values of current and active power at outgoing lines A, B, and C.

Has the supply of power to the loads served by the distribution substation been interrupted while you performed the sequence of operations required to return to the initial operating state?

❑ Yes ❑ No

No

Do the observations you made in this section of the exercise demonstrate that maintenance of one of the two power transformers and the switchgear of the corresponding incoming line can be performed without interrupting the supply of power to the loads (consumers) served by the distribution substation?

❑ Yes ❑ No

Yes

Fast restoration of power to loads after a bus fault in the distribution substation

In this section, you will insert a fault on one of the two busses of the distribution substation. You will open circuit breakers in the distribution substation to interrupt the fault current and isolate the faulty bus. You will observe that this interrupts the supply of power to some of the loads served by the distribution substation. You will demonstrate that the supply of power to these loads can be restored rapidly by transferring the outgoing lines affected by the fault to the other bus of the distribution substation.

30. On the Power Supply, turn the three-phase ac power source off.

On the Fault Module, make sure that the *Fault* switch is set to the *O* (open) position, then connect the *Power Input* to the ac power source. Also connect fault contact *K1-A* and the *Current-Limiting Resistor* of the Fault Module as shown in Figure 24.

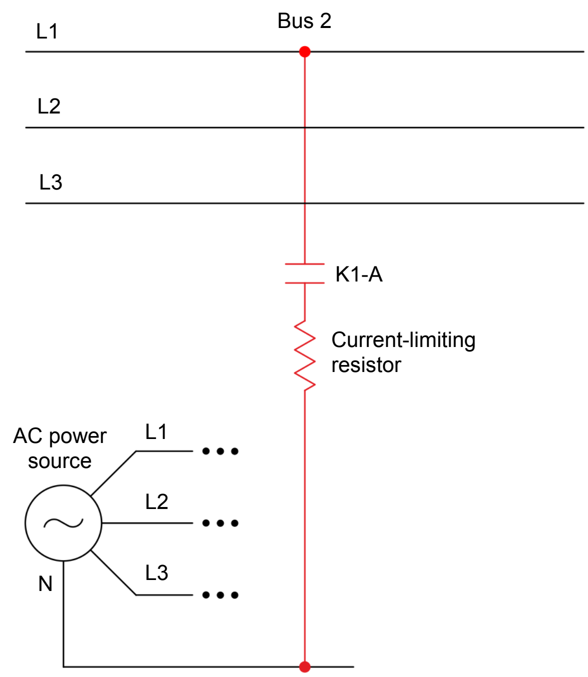


Figure 24. Connection diagram of the Fault Module.

This allows a fault to be inserted on bus 2 of the distribution substation. The *Current-Limiting Resistor* is connected in series with fault contact *K1-A* to limit the value of the fault current.

31. On the Power Supply, turn the three-phase ac power source on.

CAUTION

The nominal current of power transformer T2 is exceeded significantly when a fault is inserted on bus 2 of the distribution substation. Proceed rapidly (within 2 minutes) to perform the next step of the procedure.

32. On the Fault Module, set the *Fault* switch to the *I* (closed) position to close fault contact *K1-A* and insert a fault on bus 2 of the distribution substation.

Observe that the value of the current flowing through incoming line B of the distribution substation increases considerably.

Which circuit breakers in the distribution substation must be opened to interrupt the fault current flowing through incoming line B and isolate bus 2?

Open the circuit breakers that you mentioned above to interrupt the fault current flowing through incoming line B and isolate bus 2.

Circuit breaker CB2 in incoming line A, circuit breaker CB5 in outgoing line B, and circuit breaker CB6 in outgoing line C.

33. Observe that opening the circuit breakers does not only interrupt the fault current, it also interrupts the supply of power to resistive load R_2 (residential area) and the induction motor (industrial center). This is because opening these circuit breakers de-energizes bus 2 and outgoing lines B and C.

How can the supply of power to resistive load R_2 and the induction motor be restored rapidly?

The supply of power to resistive load R_2 and the induction motor can be restored rapidly by transferring outgoing lines B and C to bus 1 which is still operational.

Determine the sequence of operations that must be performed in the distribution substation to rapidly restore the supply of power to resistive load R_2 and the induction motor.

The following sequence of operations must be performed in the distribution substation to rapidly restore the supply of power to resistive load R_2 and the induction motor.

- Open disconnecting switches DS5-C and DS6-C to disconnect outgoing lines B and C, respectively, from bus 2.
- Close disconnecting switches DS5-A and DS6-A to connect outgoing lines B and C, respectively, to bus 1.
- Close circuit breaker CB5 to restore the supply of power to resistive load R_2 (residential area).
- Close circuit breaker CB6 to restore the supply of power to the induction motor (industrial center).

Transformer T2 is not connected to bus 1 to avoid having the two power transformers connected in parallel. The reason is explained in the next exercise of this course.

34. Perform the sequence of operations that you determined in the previous step to rapidly restore the supply of power to resistive load R_2 and the induction motor.

    Has the supply of power to resistive load R_2 and the induction motor effectively been restored?

    ❑ Yes ❑ No

    Yes

    Do the observations you made in this section of the exercise demonstrate that the distribution substation has good reliability in case of a bus fault? Explain briefly.

    Yes, because a bus fault only results in a brief interruption in the supply of power to some of the loads served by the distribution substation.

35. On the Four-Quadrant Dynamometer/Power Supply, depress the *Start/Stop* button briefly to stop the brake.

36. On the Fault Module, set the *Fault* switch to the *O* (open) position to open fault contact *K1-A* and remove the fault from bus 2 of the distribution substation.

    On the Power Supply, turn the three-phase ac power source off.

37. Turn the Four-Quadrant Dynamometer/Power Supply off.

    Close the Electric Power Substation SCADA Application by closing the corresponding window.

    Turn the DC Power Supply / Ethernet Switch off.

    Turn the 24 V ac power supply off.

    Remove all leads that connect the Fault Module to the equipment setup.

    The next exercise in this manual uses the same equipment setup. If possible, leave the equipment setup as it is. This will save you valuable time when performing the next exercise.

CONCLUSION

In this exercise, you became familiar with some means of upgrading an electric power substation to make it ready for operation in the smart grid and help meeting objectives of the smart grid. More specifically, you saw that the reliability, maintainability, and flexibility of operation of an electric power substation can be improved significantly by adding some equipment redundancy and upgrading the switching scheme of the substation. You learned that to fully take advantage of the improvements which the added equipment redundancy and upgraded switching scheme provide, the control of the electric power substation should be automated using a substation automation system (SAS).

Review Questions

1. Consider the distribution substation using the single bus scheme shown in Figure 14. What is the consequence of a failure of the power transformer or a fault on the substation bus? Also, how does the maintenance of the power transformer or the substation bus affect the supply of power to the consumers served by the substation?

   A failure of the power transformer or a fault on the substation bus results in a prolonged interruption in the supply of power to all consumers served by the substation. The maintenance of the power transformer or the substation bus also results in a prolonged interruption in the supply of power to all consumers served by the substation.

2. Give the main reason why electric power substations using the single bus scheme are not well suited for operation in a smart grid.

   Electric power substations using the single bus scheme lack the reliability, maintainability, and flexibility of operation necessary to operate in a smart grid.

3. Consider the dual-transformer distribution substation shown in Figure 15. What is the consequence of a failure of either one of the power transformers or a fault on either one of the substation busses? Also, how does the maintenance of either one of the power transformers or either one of the substation busses affect the supply of power to the consumers served by the substation?

   A failure of either of the power transformers or a fault on either of the substation busses results in a short interruption in the supply of power to consumers served by the substation. On the other hand, the maintenance of either of the power transformers or either one of the substation busses has no effect on the supply of power to the consumers served by the substation.

4. Consider the dual-transformer distribution substation shown in Figure 15. What are the main two features that provide the substation with the reliability, maintainability, and flexibility of operation required for operation in the smart grid?

   The provision of some equipment redundancy (two incoming lines and two power transformers) and the use of the double bus, single breaker scheme are the main two features that provide the distribution substation in Figure 15 with the reliability, maintainability, and flexibility of operation required for operation in the smart grid.

5. State two major advantages of using a substation automation system (SAS) in an electric power substation.

Using a substation automation system (SAS) in an electric power substation virtually eliminates the occurrence of operating errors, thereby further contributing to the reliability of the grid. Furthermore, the SAS allows remote control of the substation which helps reducing the operational costs and improving grid management coordination.

Bibliography

Acha E, Agelidis V.G., Anaya-Lara O., and Miller T.J.E, *Power Electronic Control in Electrical Systems*, 1st ed., Oxford: Newnes, 2002, ISBN 0-7506-5126-1.

McDonald, John D., *Electric Power Substations Engineering*, 3rd ed., Florida, USA: Taylor and Francis Group, 2012, ISBN 978-1-4398-5638-3.

Mehta V.K. and Mehta Rohit, *Principles of Power systems*, 4th ed., New Delhi, India: S. Chand and Company Pvt. Ltd., 2005, ISBN 81-219-2496-0