J.J. DAI

INDUSTRIAL AND COMMERCIAL POWER SYSTEM ANALYSIS FUNDAMENTALS AND PRACTICE

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About the Author

J. J. Dai (Senior Member, IEEE) holds BS, MS, and PhD degrees in electrical engineering. He spent 21 years at ETAP, advancing through various roles to eventually become senior vice president. He then joined Eaton Corporation, where he served as director of renewable applications and country manager of engineering services for APAC for 5 years, followed by a 3-year tenure as global account manager for the Oil, Gas & Chemical Group in the United States. His last full-time affiliation was with the U.S. Department of Energy as a physical scientist, focusing on technology management with an emphasis on solar technology integration into the power grid. He is retired and currently works part time as a research associate at the University of Tennessee, Knoxville, where he supports renewable energy projects funded by the National Science Foundation and the U.S. Department of Energy.

J.J. is actively involved in IEEE, contributing to several societies and subcommittees, including IAS, I&CPS, and PCIC. He previously served as the chair of I&CPS Power System Analysis Subcommittee and co-chair of the IEEE 3002.8 Standard Working Group. He currently holds the position of secretary for the IEEE P3002.9 Standard Development Working Group, focusing on power system transient stability analysis in I&C power systems, and chairs the Codes & Standards Committee of IEEE IAS I&CPS. J.J. is also a registered professional engineer in the state of California, USA.

Preface and Acknowledgments

Power system analysis is essential for new system design, expansion, and operation. This necessity extends to industrial and commercial (I&C) power systems, which have become increasingly complex in terms of voltage level, size, network configuration, distribution framework, generation sources, and load profiles. The industry has evolved from spreadsheet-based calculations to comprehensive computer software modeling and simulation, with various commercial software packages now available for load flow, short-circuit, protection coordination, motor starting, harmonic, transient stability analyses, and others.

Despite the availability of IEEE standards for recommended practices, a gap exists between industrial standards and college education. Industrial standards do not fully explain detailed modeling and simulation procedures for I&C power system analysis. Meanwhile, college education often lacks sufficient coverage of I&C power systems, with textbooks not adequately addressing fundamentals such as computer modeling, simulation of operating conditions, and study scenario selection.

Having worked for 22 years developing commercial computer software for power system analysis, 8 years leading engineering service teams in the power industry, and actively participating in IEEE standards development for 30 years, I envisioned writing a book to bridge this gap. This book provides essential knowledge from system modeling to computer solutions for I&C power systems, referencing relevant IEEE standards and offering rich analysis examples and illustrations.

The book focuses on:

1) Computer modeling
2) Mathematical solutions
3) Numerical simulations
4) Industrial and commercial power system analysis
5) Industrial standards
6) Computer software applications

It serves as a valuable reference for:

1) College and university students studying power system engineering
2) Engineers engaged in I&C power system analysis
3) College/university teachers
4) Power engineers, certified engineering consultants, and other professionals
5) Trainers and educators in power system engineering

Readers will gain a deeper understanding of system characteristics, modeling and simulation techniques, data requirements and preparation, and modeling tuning and validation. Practical examples from industrial plants and commercial facilities will help readers understand how to build accurate computer models, why simulation studies provide reliable results, and which best practices are recommended by industrial standards. This book aims to prepare college graduates for industry roles and help new or junior engineers become proficient in I&C power system analysis, enabling them to assume greater job responsibilities. By bridging the gap between industrial standards and college education, this book will advance both academic and professional expertise in power system analysis.

This book is organized as follows:

Chapter 1 provides an introduction to I&C power systems. It begins with an overview of single-line diagrams, which form the foundation for system analysis. Key components and equipment in I&C power systems are described, including power supplies from utilities, on-site power generation, power distribution network, and various loads. The chapter also covers power quality conditioning equipment and essential auxiliary systems.

Chapter 2 outlines the objectives and procedures for analyzing I&C power systems at different stages of development and operation. This includes conceptual, preliminary, and detailed design for new and expanding systems, as well as diagnosis and validation for systems in operation. The chapter discusses the required input data, system description data, study scenarios, and the expected analysis outputs for computer modeling and from simulation.

Chapter 3 delves into the detailed computer modeling of I&C power systems necessary for simulation analysis. It examines key components, equipment, control systems, and networks, offering appropriate modeling approaches, such as circuit models, transfer function models, differential equation models, differential and algebra equation models, and Y-Bus and Z-Bus models. The chapter also describes the integration of these models into an overall system model and addresses special operation modes like parallel and isolated operations, along with their associated models.

Chapter 4 focuses on mathematical simulation solutions for major types of I&C power system analyses, including load flow, short-circuit, motor starting, harmonics, and transient stability. Depending on the requirements for accuracy and applicability, some analyses may have multiple solution methods.

Chapter 5 provides fundamental knowledge of numerical techniques used to solve various types of I&C power system analyses. These techniques address algebraic equations, differential equations, integral equations, and mixed linear algebraic and differential equations as formulated in Chapter 4.

Chapter 6 illustrates common and basic I&C power system analysis cases using computer modeling and simulation tools. The cases include analysis and study for voltage drop, power factor correction, circuit breaker overcurrent, reactive power inrush, harmonic distortion, rotor angle stability, and frequency decay and load shedding protection. Some of these cases are based on real-world systems and include description of system configurations, problem formulations, and simulation studies, along with mitigation or protection recommendations.

Appendix A lists the latest IEEE industrial standards for conducting load flow, short-circuit, motor starting, and harmonic analyses and studies of I&C power systems. As the IEEE standard on transient stability analysis is still under development, the appendix includes the latest IEEE paper on this subject, offering a rich and important resource. The analysis scopes, procedures, methodologies, and other key content of each reference are extensively covered.

Finally, I express my sincere gratitude for the understanding and support of my wife, Wen, and my family during the course of working on this book.

August 2024

J. J. Dai
Irvine, California

1

Industrial and Commercial (I&C) Power System

1.1 General Background

Industrial and commercial (I&C) power systems are intricate electrical networks specially designed and operated to deliver reliable electrical power to industrial plants and facilities, as well as for commercial enterprises and buildings. A typical I&C electrical power system comprises several key components or subsystems, including:

1) electric power equipment and controls.
2) lighting systems.
3) power supply for instrument and control systems.
4) air conditioning system.
5) indicating and alarm equipment.
6) receptacles for electrical devices.
7) bonding and grounding systems.
8) emergency, essential, and miscellaneous power systems.
9) Uninterruptible power supply (UPS) systems.
10) Electrical vehicle (EV) chargers.

These systems are composed of various electrical equipment and components, including loads, drives, transformers, lines, cables, reactors, capacitors, switches and protective devices, etc. The systems are powered by either local or regional power utilities or installed on-site generators, or renewable power generations, or a mixture of various energy resources. I&C power systems could be configured in mash or radial, depending on the power supply availability and reliability requirements. Most systems have the capability to reconfigure the network topology to meet different operation scenarios.

The complexity and scale of I&C power systems have grown extensively in recent decades. Some oil and gas fields and facilities could have a total of load amount in gigawatts (GW) level with the voltage rating going up to as high

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as 220 kV. Three-phase power distribution is commonly employed for high voltage (line-to-line voltage ≥1 kV) systems, while three-phase, two-phase, and single-phase power distributions can be used for lower voltage systems. In normal cases, I&C power systems are connected to power grids, and both are in parallel operation, except in special situations such as on an island, in the desert, or in other remote areas. However, it is not unusual for an I&C power system to temperately separate from the grids and operate in islanding conditions in either planned or unplanned scenarios. For such an operating condition, special design, analysis, and control will be required.

1.2 I&C Power System Single-Line Presentation

For system design, study, and maintenance purposes, I&C power systems are represented by single-line diagrams. A single-line diagram is a schematic that shows the electrical connections of an I&C power system with major equipment and components, including sources, branches, and loads. It is a simplified presentation of a three-phase system due to the symmetry in a balanced three-phase electrical system. Figure 1.1 shows a sample I&C power system single-line diagram that includes a utility connection, two on-site generators, an in-plant distribution system with lines and cables, circuit breakers and switches, transformers, and loads.

1.3 Components and Equipment in I&C Power Systems

Key components and equipment that are needed for successful power supply, distribution, and conversion in I&C power systems are described in the following five categories.

1.3.1 Power Supply and Generation

Power supply and generation units are responsible for electricity to energize and operate local loads. Normally, they include utility or grid supply, on-site generation by conventional generators, and renewable resources and energy storages.

Utility power supply. This is the main source of electrical power supply by local power utility companies through transmission lines or distribution networks. For increasing reliability, multiple lines or even multiple sources can be interconnected to the I&C facility from utilities or grids. Each point of the interconnection is regarded as the point of common coupling (PCC), which usually is on the high-voltage side of the main transformer.

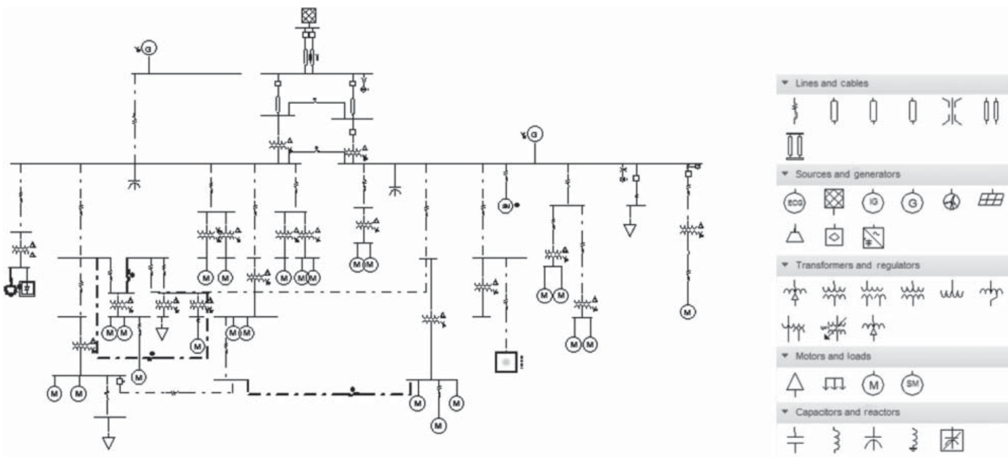


Figure 1.1 A sample I&C power system single-line diagram with symbols for typical components.

On-site power generation. Due to system reliability requirements or economic considerations, large I&C power systems or systems with critical loads often have on-site installed generators. For example, in industrial plants, combined heat and power (CHP) generation set can be installed to simultaneously generate electricity and heat for processing applications, which can bring more efficiency, cost savings, and enhanced reliability to the operation. With renewable resource technology development, solar photovoltaic (PV) and wind turbine systems are also deployed inside I&C power systems to convert energies from sunlight and wind into electricity using solar panels and wind turbines, respectively, which increase the system cost savings and sustainability and create environmental benefits. As backup and optional power sources, diesel and natural gas generation units sometimes are also deployed to the I&C power system.

Energy storage. Energy storage devices such as batteries, flywheels, pumped water, compressed air, thermal or heat pumps, supercapacitors, and others in bio, chemical, or mechanical forms can also be installed and integrated to become a part of critical components at I&C power systems. These devices provide energy and power for power backup, islanding operation, black start, and similar purposes and can improve system efficiency, reliability and resiliency, and green energy support. It needs to be pointed out that the electrical characteristics and controls of these devices are very different from conventional power generation equipment.

The size and configurations of the on-site power generation can be designed and tailored to satisfy the specific needs of the facility. Figure 1.2 shows a typical I&C power system with two utility connections at 46 and 69 kV and two on-site synchronous generators at 5 and 25 MVA, respectively.

1.3.2 Power Distribution

Power distribution networks in I&C power systems are an infrastructure that ensures the electric powers are delivered from the power sources discussed above to loads connected throughout the system efficiently, safely, and reliability. The main electrical components and apparatus in the I&C power system distribution network are described below.

Substation. Substations play an important role in transforming voltage to different levels in I&C power systems to meet equipment ratings and provide various essential operation and protection functions. Substations consist of lines, cables, transformers, switchgears, breakers, protection devices, meters, etc. Figure 1.3 is a sample substation schematic.

Transformers. Transformers are primarily installed to change voltage levels between different clusters of I&C power systems. The utility power imported

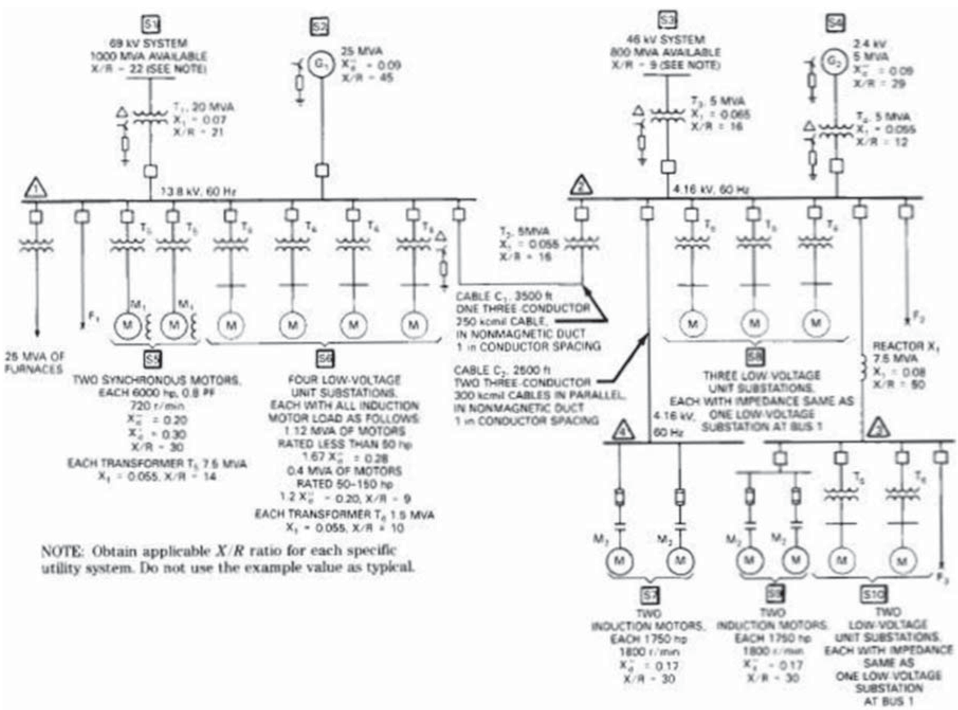


Figure 1.2 Typical I&C power system with utility power supply and on-site generation. Source: Figure 4-10 of [1]. Reprinted with permission from IEEE.

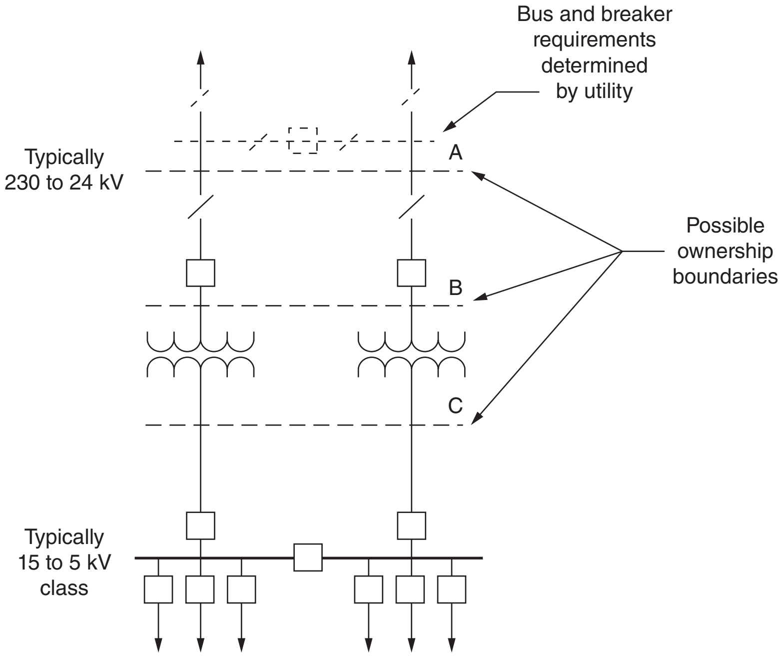


Figure 1.3 A sample substation schematic. Source: Figure 15-2 of [1]. Reprinted with permission from IEEE.

via the transmission system is normally at high voltage and needs to be stepped down inside I&C power systems. Step-up transformers are also used in I&C power systems when on-site generation is at lower voltages. Transformers come with different structures and designs, some are with three-cores, and some are with single core. There are also special-purpose transformers such as ground transformers, zig-zag transformers, transformers with a dedicated phase shift between two sides, open-delta (three-phase windings are in delta connection with open-circuit), etc. From the cooling method point of view, both dry-type and oil-immersed-type transformers are widely used in I&C power systems. Voltage transformer/potential transformer (VT/PT) and current transformer (CT) are also extensively used in I&C power systems, mainly for measuring and protection applications. Figure 1.4 illustrates several typical transformer symbols used in single-line diagrams.

Switchgear. Switchgear is a set of equipment assemblies, including breakers, switches, sensors, inductors and capacitors, and protection devices that are used for controlling and protecting electrical circuits, providing isolation, and safeguarding against overloads and faults. Figure 1.5 is a schematic of a

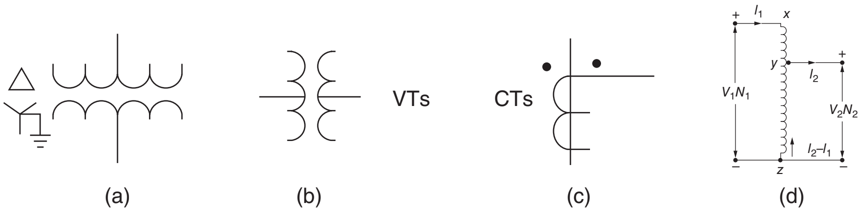
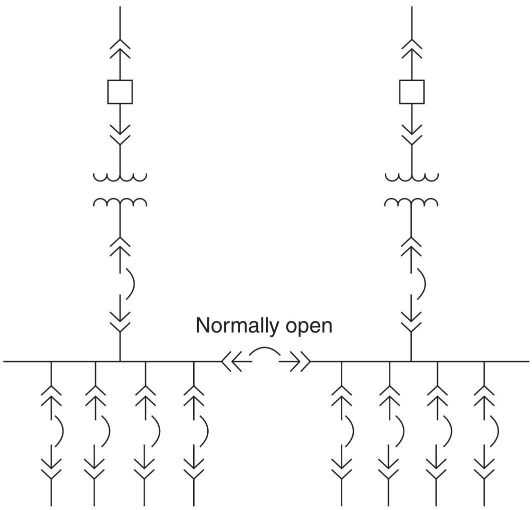


Figure 1.4 Transformer schematic. (a) Power transformer, (b) voltage transformer, (c) current transformer, and (d) auto transformer.Source: Figures 10-1 and 11-3 of [1]. Reprinted with permission from IEEE.

Figure 1.5 A sample switchgear schematic. Source: Figure 2-5 of [1]. Reprinted with permission from IEEE.



switchgear showing only the breakers at both medium voltage (upstream of the transformer) and low voltage (downstream of the transformer) levels.

Distribution lines/cables. Lines and cables form distribution networks in I&C power systems. They connect the power sources to loads through substations, transformers, switchgears and busbars, panels, switchboards. Lines have different structures and installations, including single-circuit or multicircuit; cables have three-phase and single-phase configurations. In general, they are represented as an equipment Pi circuit, as shown in Figure 1.6.

Busbars. A busbar or busduct serves as a common connection point for electrical circuits which form a distribution network within I&C power systems. They are represented as a short bus or a node in a single-line presentation.

Load feeders. Load feeders are directly connected to loads, usually over short distances.

Busbar and load feeder representations are found in Figure 1.7.

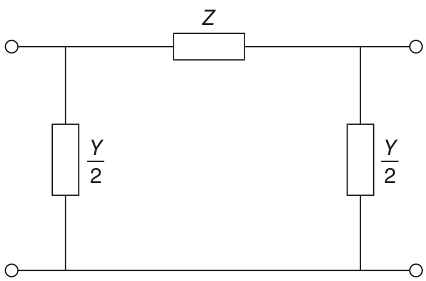


Figure 1.6 Distribution line and cable. Source: Figure 4-8 of [2]. Reprinted with permission from IEEE.

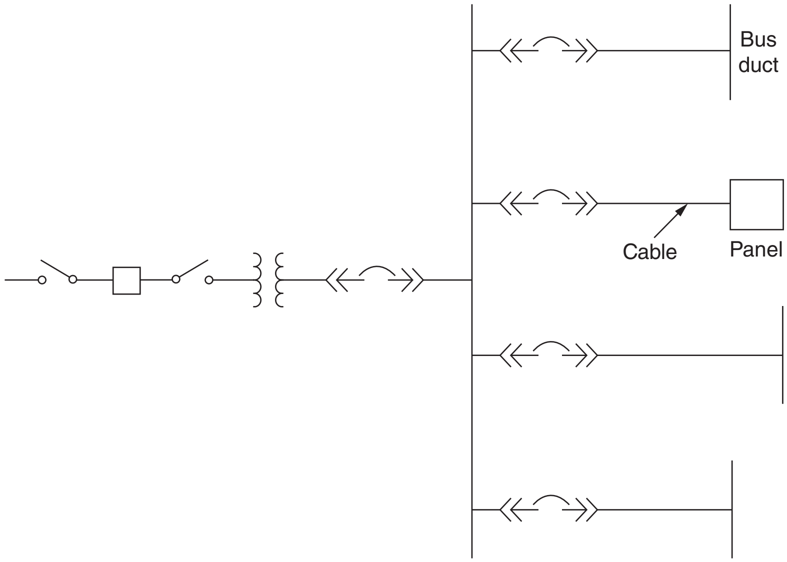


Figure 1.7 Busbar and load feeder. Source: Figure 2-1 of [1]. Reprinted with permission from IEEE.

1.3.3 Loads

Electrical loads in I&C power systems vary widely based on the types of facilities. The primary types of electrical loads are described below.

Motors and drives. Motors make the majority of loads in industrial power systems. They convert electric power into mechanical power to serve numerous processes. There are different types of motors based on the operation principles, including inductor motors, synchronous motors, and DC motors. Motor loads could have very different characteristics, such as a fan, a compressor, a pump, and a conveyor, just to name a few. Modern I&C power systems use motor drives extensively to provide controlled inputs to motors to achieve smoother, more reliable, and efficient operation. Drives are electronic devices with power converters and control circuits.

HVDC. Heating, ventilation, and air conditioning (HVDC) systems are the major loads in both I&C power systems for buildings and special working environments. They employ motors and drives to optimize efficiency.

Lighting. Lighting is found in every I&C power system. There are different designs and technologies for lighting, such as fluorescent lights and light emitting diode (LED) lightings. Their electrical characteristics are also very different.

Other Loads. There are many other electrical loads existing in general I&C power systems with different functions, applications, and characteristics, such as arc furnaces, welding machines, computers, control devices, and communication equipment. Loads can be aggregated into electrical load centers within a specific area and provide a centralized point for power distribution and conversion. Load centers may include electrical panels, subpanels, and branch circuits.

The variety of loads in a general industrial system is illustrated in Figure 1.8.

1.3.4 Power Conditioning

Power conditioning devices are used to mitigate power quality issues and restore sinusoidal waveform for voltage and current. Commonly used devices in this category in I&C power systems include the following described.

Reactors. Reactors are basically used to limit fault currents. They can also be connected in line with the circuits to attenuate harmonic currents or installed inside harmonic filters to work with capacitors to form serious resonant circuits for harmonic filtering. Figure 1.9 shows reactors that are installed in series with generators to limit fault current contribution from the generators into the system.

Capacitors. Capacitors have multiple applications in I&C power systems. The majority of capacitors are installed in shunt with the network to provide reactive power injections into the system to compensate for inductive power consumptions and losses and are called power factor correction capacitors. By the same principle, capacitors provide local reactive power support to reduce voltage drop along the distribution circuits so system voltage profile can be improved. In both power factor correction and voltage drop reduction cases, the capacitor bank can be adjusted in settings either manually or automatically to achieve a regulated control. Capacitors can also be configured with reactors to form harmonic filters with the capacitance turned to specific harmonic frequencies. Figure 1.10 shows an example of various locations to install capacitors with different performance considerations.