ZARK BEDALOV

PRACTICAL POWER PLANT ENGINEERING

A GUIDE FOR EARLY CAREER ENGINEERS

WILEY

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A Guide for Early Career Engineers

Zark Bedalov
Vancouver
BC, CA

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Contents

Preface – Why This Book?

This book is a result of 50 years of practical experience from working in a number of industries with ever-changing technologies and by associating with many experienced engineers; electrical and other engineering backgrounds.

Starting as an engineer is not easy. You are facing a big transition. I'm certain this book will help get you through the most critical phase of your development as an electrical engineer and make you the confident and knowledgeable professional that you wanted to be when you decided to be an engineer.

There are a lot of books on the market explaining the theory of electrical engineering, but there are no books on practical engineering and experience. There used to be the old Westinghouse (now ABB) TD (blue) Book and Donald Beeman, General Electric Co. 1955: Industrial Power Systems Handbook, both of which I have proudly used as a young engineer. Both books now seem to be largely outdated. Computers have taken over much of the handmade calculations.

The information contained in this book is by no means all encompassing. An attempt to present the entire subject of practical electrical engineering would be impractical. However, this book does present guidelines to provide the reader with a fundamental knowledge sufficient to understand the concepts and methods of practical design and equipment selection and operations.

The first hint of a book came in Venezuela. After three years on a job with a local engineering company heading the engineering department, I decided to move on. The boss called me with a special request, saying: "Please stay on for another 3 months and write a book on how to do electrical engineering. You seem to do this work with a lot of common sense. I thank you for your help in leading and teaching our younger engineers. So, stay on, please."

The above dialog happened three years after seeing the movie Papillion (1978) filmed in Venezuela with Steve McQueen. The day after the movie, I fell into a snowy ditch somewhere north of Toronto. I had to leave the car and walk alone in the snow for a couple of hours in a total whiteout. A day later I spoke to my wife, we were going to Venezuela. Both of us loved the tropics and had it enough of Canadian winters.

Einstein: Theory is when everything is known but nothing works.

Experience is when everything works but no one knows why.

When we join theory and experience nothing works and no one knows why.

We quit our jobs, sold everything, and went to Caracas. "How smart was that," I heard it many times? Once in Caracas, I left my resume with six major engineering companies and then we went to a beach. Two weeks later, we returned to the Hotel Sabana Grande in Caracas. The owner said that I had many calls. I had five job interviews and took a job with a company that had a contract to build a 4 × 400 MW power plant. They badly needed an experienced electrical engineer. At that time, I had about 10 years of experience with a great company called Shawinigan Engineering from Montreal, Canada. That company was later taken over by SNC-Lavalin, Inc., my last employer.

Three years later, after the plant was built, I told my Venezuelan boss that I enjoyed it greatly, but I gotta be moving on. I moved on to Riyadh, Saudi Arabia. It was 1981. It seemed I was at the right place at the right time. There was so much going on in Saudia. At that time, some large generation existed in the Eastern province for oil production and barely in the cities of Riyadh and Jeddah. We began the electrification of the country in a major way. After Saudia, I went to several other international posts with companies like Fluor and Bechtel. Finally, I ended up with SNC-Lavalin for the past 17 years as a commissioning engineer. That makes it a total of 50 years as a lead design and commissioning engineer for power plants, heavy industrial plants, and power systems. Of that, 10 years were as an independent engineer on my own.

In the years after Venezuela, I often lectured younger engineers on many engineering issues and had discussions with companies to create a manual that would help their electrical engineers to follow and practice good engineering. It took a while. Finally, in 2015, I agreed to do a book. It took me one and half years to complete a draft copy. Now, it is here in your hands.

As an experienced electrical engineer I have noted huge obstacles young engineers were facing to become experienced engineers. I'm not talking about civil or mechanical, but electrical engineers. Let me explain. For mechanical engineers, everything is visible. Here's a pump, pipe, valve, filter, and strainer. All of it, recognizable objects. What's on the drawing is what you see in the real life. Open a valve and water or oil flows. You see it, hear it. If it leaks, you see it and you replace a gasket or clean a clogged filter.

Electrical engineers, however, in the same environment face an invisible world. Some call it "The mystery world". You may be able to recognize a few pieces of equipment from the drawings, but this is not what matters. In the electrical engineering, it is what you don't see that matters. If something goes wrong, you don't know which way to look. There are no electrons anywhere to be seen? Where do you start? Well, the first several years will be difficult, but with some experience and guidance, you start seeing the invisible. One young engineer told me that he came to his first job interview ready to solve a bunch of differential equations, but all that school teaching didn't seem to matter.

It is clear that mechanical engineers have a head start in the plants and the plant designs. Right off the bat, they are confident about themselves, of what they are seeing, doing, and learning. They will eventually become project managers and will boss the electrical engineers. I have seen this over and over again, anywhere in the world. Young mechanical engineers talk job immediately with confidence and are liked by the bosses because they talk the same language. Meanwhile electrical engineers are fearful to ask questions or suggest anything. They struggle for years. The bosses seem don't know how to talk to them.

So, while our mechanical engineering colleagues confidently talk about the things they do, and advance in their experience and carriers, we the electrical engineers appear shy and aimless, struggling in the world that has no resemblance to what we studied so diligently for many years.

Even the language is different. Here come buzzwords. Everyone uses buzzwords and most of them you don't understand. If that is bad enough, it gets even worse. Young mechanical engineers appear to be smarter. They seem to be learning faster every day in their *visual* world. As they say, a picture is worth 1000 words. On the other hand, a young electrical engineer gets very little visual information and thus retains less. Mechanical engineers are immediately immersed into the overall (big) picture of the plant, while the electrical engineers are pinned down to look at details.

Without an experienced engineer to explain things and to guide him, a young electrical engineer is lost. It would help if he only knew the questions. Not even that. He goes home after work and wonders: What is the reason for having me there? Will I ever be useful?

Let me give you an idea what happens on your first day on the job. You graduated from a difficult faculty of electrical engineering. It was tough and struggle, but you studied hard and endured, and felt you were on the top of the world. The world is yours. What a great feeling of accomplishment and exuberation that you can do anything.

Then you start looking for a job, and soon realize that the world is not all yours. The employers are not looking at your grades but at your experience, of which you have not much to show for. You cannot choose your job and will be happy to take anything that comes along. Finally, after three months of job searching, an engineering company was willing to give you a try.

You will be working on a new project. On the first day, you are introduced to your colleagues from all the disciplines and given a lot of drawings and reports to read. The material is mostly process and mechanical, to give you an orientation of what the project is all about. You were also told to talk to everyone and ask any questions you might have regarding the material you were reading as well as to acquaint yourself with the things the others were doing.

Then after a month of "doing nothing" your lead electrical engineer gives you for instance a couple of tender documents for a 10 MVA transformer just received from the bidders. One is for a transformer with 8% impedance and the other with 9.5%. The first one is more expensive than the other. The Lead tells you to evaluate the cost benefit of one over the other and if you have any questions feel free to ask. Since you were a junior engineer and need a bit of a help, he reminds you that the larger impedance causes more Watt and Var losses and higher voltage drop, while the lower impedance allows for higher fault level on the downstream bus, which may force the project to use more expensive equipment.

Wow, what now? That day back at home you look through your text books and find nothing relevant to help you out. Well, of course not. The text books tell you about the transformers and the transformation in general, but nothing specific for a particular application. That may be the last time you looked at your school books.

This actually is your first day at work. Remember that exuberating feeling when you graduated? You could do anything? Well, your Lead lowered you down to the real world. Now you feel hopeless and lacking confidence. You start asking questions all around and gradually acquire some knowledge but you are still far away from being able to decide which transformer to recommend. Fortunately, your Lead had already made that decision. Of course, he wouldn't let his junior engineer to decide on such an important matter. He just wanted to test you on how you think, how you formulate your questions, and how you deal with the engineers around you.

Welcome to the job. It'll be tough and it'll take time. All of us have started like this. You'll be doing fine if you immerse yourself into the project and start building up your practical experience over several years of working with experienced engineers on a variety of projects. This also includes those of other disciplines to learn what is important to them and how to select the electrical equipment to drive and automate their equipment. This real world book will help you get there.

This book is a result of 50 years of design and field engineering by experienced engineers and teaching others to do the same. As an experienced engineer with acquired practical knowledge, I'm ready to share it with the new coming engineers and lead them through a transition for which there is no blueprint or book, until now. This book provides useful information as a reference guide for all the electrical engineers. It fills the gap between the Academia and being an experienced engineer. If you read this book, you will learn a half of it you need to know and all the proper questions you should ask.

Hopefully this book will spawn others to write books. Your first job is a step into the open, away from your school. As soon as you start reading it, you realize this is a different world and it won't be easy. I agree, it won't be easy, but this unique book in your hands will give you a kick start, help you interact with other engineers and understand what is going on in the design office and in the field around you.

Why not searching on Google? Yes, there is plenty of this stuff and hundreds of answers on the internet. Well, if you only knew what you were looking for and had knowledge to properly assess it for your application? Without proper feedback, you don't know what is right and what is wrong and how to resolve doubts. "The Internet often seems to be a source of befuddlement rather than enlightenment," as Gregg Easterbrook eloquently put it in his outstanding book "Sonic Boom." This book gets straight to the point of what you need to know.

It's not an easy task to cover all the electrical engineering activities into a single readable 500+ page book. Many chapters would require a book by itself. The goal was to summarize the engineering activities and to direct the reader onto the right path and base from which he (she) can build experience needed to make proper engineering decisions. Everything in it, this author has experienced and then confirmed through commissioning and discussions with other engineers.

The theory is essential. It forms your basic knowledge fundamentals. The fact is this; our professors teach us to become professors. That's fair enough. The best students in our class became professors. An engineer you become with practical experience by associating with other engineers, facing multiple engineering applications and problems, making mistakes and reaching accomplishments.

Recently, I spoke to a professor about Variable frequency drives (VFDs), Chapter 15. I was telling him how I use them to regulate the plant flows on demand so I can employ smaller storage tanks, etc., while he was talking about flux vectors inside the rectifiers. "I'm not trying to make rectifiers. I'm just applying them for various useful plant applications," I told him? That's the difference. Because of this issue, many engineering schools are changing. Nowadays, students are forced to work between the semesters. Students are telling me that it's a hard go, as it is not easy to land summer jobs as unfinished engineers.

If you happen to get a job with a manufacturer, your life may be a bit easier. You will be trained for a specific job to work on some electrical equipment, such as improving a lightning arrester, rectifier, or a grounding switch. Soon, you will notice that designing a piece of electrical equipment is mostly of making it smaller, cooler, and with different materials. Then, you also realize that the job is 10% electrical and 90% mechanical engineering, and start wondering: "Is that it?" Well, maybe you'll like it. I didn't.

I graduated with a diploma on power transformers. My first job for two years was mostly how to make better cooling for transformers. I worked on hollow conductors for cooling water passing through them. There was nothing electrical about that. Why didn't they hire a mechanical engineer to do that, I wondered? On the other hand, if you get a job to design power systems for various plants it's a different story. It's an electrical story.

So, between you and me, I had enough of mechanical engineering and them taking advantage of us and bossing us around by saying; "I was not smart enough, so I went into mechanical engineering." I heard that line a lot. With this book, I want to even out the playing field and help you young electrical engineers stand your ground, be productive, and contribute almost immediately.

One of my first job interviews was at Toronto Hydro. An engineer showed me a picture and asked me if I knew what it was? I saw six bushings and said that it was a transformer. I was wrong. It was a high voltage oil circuit breaker. I failed that job interview. I should have known that a breaker had six identical insulators. Transformer has 3 + 3 unequal bushings.

I moved on, looking for my first job in Canada and ended up at Pinkerton Glass for a job interview. A secretary gave me a test sheet to fill in before meeting an engineer. The sheet said “Practical test for electricians.” I filled it up as best as I could, guessing on a half of it. I failed that one too. None of those famous differential equations could have helped me. It was so bad; the Engineer didn’t even waste his time to see me.

Many years later I was already an experienced engineer. Our company, Fluor, had a project with the Xerox Corp. in NY State. As a lead electrical engineer I was invited to visit the plant and scope the work for adding a new ink toner line to the existing plant. We started touring this large plant. As an electrical engineer I prefer to look first at the plant overall one line diagram. This is the Chapter 2 in this book. Having acquired the big picture, then I visit the plant and observe it from my electrical perspective. Well, anyway, we started touring as soon as I got there. The mechanical engineer, my tour guide, looked at me and said: “You are an electrical engineer, right?”

“Yes, any problem with that,” I answered jokingly?

“No nothing, but, let me pass one by you. Here we have a problem,” he started talking. “We’ve been struggling for 2 years now with it. Occasionally, we have light flickers in the plant. It happens suddenly and then nothing for a few days and then again. The whole plant flickers and then everything is back to normal. Do you have any suggestion what that might be,” he asked?

“I really don’t know. It can be anything,” I answered. “Does it happen at night or day, high load, low load,” I inquired? Suddenly, I realized I was in an invisible world of electrical engineering.

“Well, I agree,” the plant engineer said. “It’s unpredictable; anytime. We checked it with the local utility. They said that it must be something internal within our plant as they don’t experience flickers on their system.”

“If I were you I would look at the main transformer since the whole plant is flickering. It may be coming from there,” I said. “Otherwise, you may have to shut down the plant and megger all the major electrical equipment, starting from the incoming transformer.”

“Hmm, I’ll mention it to my electrician,” he answered.

So much for that, I thought. We continued touring and got into a rather noisy room. My guide pointed to their 2000 HP, 5 kV compressor, the biggest drive in the plant. I came closer to the compressor and spotted a drop of oil below its big cabinet on which it read: "Surge Pack." I told him that there was no reason for the oil to be on the floor here and suggested that if he wouldn't mind we open the cabinet.

"Don't worry about the oil, I'll call our cleaning staff to clean it up," my tour guide mentioned it somewhat embarrassed. I insisted and we opened the cabinet. Inside it I saw more oil, obviously leaking from the surge capacitor. I turned to him and said: "This may be your source of flicker. The capacitor is leaking and occasionally breaks down and creates a brief short circuit to discharge itself."

Weeks later, he called me and thanked me for the discovery. They replaced the capacitor and, thank goodness, resolved the issue. I wrote back to him, "We were lucky to be in the room before the cleaning lady had a chance to remove the oil drop. Please don't fire that lady."

In the invisible electrical world, you often have to be lucky.

Read this book and practice it. If you have read it and understood 80% of it, you don't need more schooling, though it would help. Not even calculus. I have nothing against math. I was pretty good at it. Nowadays, since the use of computers for power system studies, the highest level of math I have used was $\sqrt{3}$ and cos ϕ on my calculator. True, I have been using "per unit" a lot in my conservative short circuit fault calculations, though. Most of all, I needed know how to prepare estimates for various project options and calculate percentage power losses or voltage drops in power lines. And, of course, it was always important to be able to answer questions right on the spot during the project meetings with the project owners.

This book will not make you an expert on any of these subjects. For that you will need a lot of experience and hopefully some good mentoring. But it will give you a good start and capability to discuss the subject with some confidence and ask good questions during your job interviews. With this knowledge, you can start your job from a solid base, rather than starting from nothing.

Hopefully, this book will point to you the path on how engineers think in planning and resolving the problems and the basic elements of the engineering considerations; scope of work – big picture, engineering tasks, economics (cost of equipment and production), reliability, and automation requirements.

A few more notes.

As a junior engineer, I grasped from other engineers the concept of looking at the big picture, and what matters, while leaving other things for later. These are likely to change anyway, so why bother thinking of them now. Looking at a big picture means developing a design criteria for all parts of the project right at the start, such as, determining the short circuit levels (by computer) at various plant busses, allowable voltage drops, outage contingencies, big motor start, etc. Then, I develop overall key one line diagram. Once I have done that and have it on paper, I have my base and reference and talking points for everything that fits inside. It's not frozen in concrete. I can adapt it as I go along. If you do this once, you can replicate it again and again on other projects, based on the clients' requirements and new requests, capacity of production and levels of automation and security demanded.

Most employers do look for individuals who talk in terms of looking forward and grasping the whole concept of the project. One day at SNC-Lavalin, I had a chance to see my file they made after my job interview and it read, "Impressive view of looking at big picture."

Also, as a beginner engineer, I was once interviewed by an American company. In their books of potential candidates, next to my name was written: "Capable of looking and seeing a bigger picture. Hire him, when opportunity comes up." I heard that little jewel from a head hunter who called me up and offered me other positions. Head hunters dig out their information from their contacts in the HR (Human Resources) of the companies they deal with. I was not born with it. I looked up to and learned it from other engineers who had impressed me.

When you do your work, share it with others. Be a team worker to be able to succeed in this type of work. There are other disciplines involved on the project and often you will find out something that will help you make a proper decision or make a modification you didn't notice before. So, be a team player. Then, when you are done with an assignment, tell your boss that you are done. He loves to hear that. If you are holding it back, soon it will be noticed. Bosses like to hold onto their best producers and keep them busy.

When you are finished with your assignment, tell your lead engineer to give you feedback. Don't be afraid of his review. Don't work in isolation. Share the ownership of your assignment with him. Involve him as you work on it. He will appreciate that. Besides, he is likely far more experienced than you are and experience is what counts in electrical engineering. He may have a different approach for certain parts. Broaden your thinking, evaluate his input and implement it if beneficial and more economical.

Always show interest. I was always curious. As a kid I wanted to be an engineer. Being a medical doctor also crossed my mind. Later on I realized that being a doctor would have been a mistake. I was not made for it. I function by logical thinking. I don't want to learn anything by heart. I learn and gain experience through logical interaction. Most of it was by observing and listening to others. Being interested puts you in front of the events. Many a time I was sent to investigate a situation about which I had not a clue. Nobody else on the project had a clue either. So, others rejected it and declined to be involved. I always went for it, tried my best and most of the time I found solutions.

Enjoy engineering. This has been your biggest investment so far. Go for it.

Vancouver, BC, Canada
16 June 2019 *Zark Bedalov*

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The first three I knew as experienced electrical engineers who readily shared their valuable experience on me and other young engineers. The forth one was a junior engineer just like me when we worked on some power projects. He took great interest in the grounding issues on the projects. Then he wrote the first computer program to calculate the substation grounding requirements. If one searches on the net anything to do with grounding, his name will appear as one of the greatest authorities in this area, including on so many IEEE papers.

About the Author

Zark Bedalov explains that as a kid he was always intrigued by electricity. He would turn a light switch on and off for hours and observed the light to come on. If the switch sparked, that intrigued him even more. There was no one there to explain to him what was going on in the wires. In his early school days, he was punished for smashing a capacitor to pieces for trying to see what was inside. A lot of greasy paper was inside.

He graduated at University of Electrical Engineering, Zagreb, Croatia, in 1965. Also, attended some master degree studies at the University of Toronto.

His first job was in a factory for power transformers. Soon he realized that making a transformer is 90% mechanical and 10% electrical. That was not what he was expecting. So he skipped over the border to Wiena, Austria, and arranged for immigration to Canada. Finding a job in Canada was not easy, in particular if you are an engineer. Being an engineer comes with responsibility and that requires "Canadian Experience." It took him about six months to start as a draftsman on mining projects. Had a lot of support from many senior engineers and three years later was certified a "Professional Engineer."

From thereon, Zark was in his domain and in demand. Early on, he changed companies every three to four years to learn more. He worked for almost 50 years on large projects, power plants, and heavy industries, all around the world, employed by major international engineering companies, such as Bechtel, Fluor, Atomic Energy of Canada, SNC Lavalin, and often independent, teaching along the way and enjoying the work and life. Now retired, he writes on electricity and teaches young engineers on how the electricity makes the factories and power plants function.

1

Plant from Design to Commissioning

CHAPTER MENU

1.1 Planning

The electrical power distribution systems have to be designed to fit the plant electrical requirements. The power systems must be well planned, considering the technological process, cost, reliability, maintenance, control, operating flexibility, and future growth. Furthermore, the undertaking must take into account

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the safety of people and equipment, continuity of power supply, installation, and operating costs.

Electrical engineers' responsibility is to prepare design criteria and single-line diagrams, power system studies, calculate fault currents, locate load centers within the plant, estimate load diversity, select the grounding system, define the routes of overhead lines, prepare plant layouts, and develop the electrical protection system, all of it to suit the plant location and the prevailing standards. Furthermore, he/she must procure the equipment and participate in the plant construction and commissioning.

The basic concept for a single-line diagram representing the *power plant* power distribution is generally established by the utilities. The main engineering effort is on implementing the power system around the generating units. Depending on the generator unit MW size, a decision will be made on having generator breakers next to the generators or employing high voltage (HV) breakers instead, in the switchyard to serve as the unit breakers for the generator/transformer groups. That is one of the most significant factors that define the overall concept of the diagram. The power plant station service generally uses less than 5% of power of the generator MW rating, thus, the one-line diagram for a power plant is relatively simple in comparison to the industrial plants (see Chapter 18 for more details).

One-line diagrams for industrial plants vary significantly from industry to industry. The load is fully distributed around the various operating activities, such as crushing, grinding, mixing, drying, pumping, batching, each of which requires a considerable engineering effort and decision making process to arrive at an optimal economic diagram that can be scaled and readily expanded in the future.

This book is written in 26 chapters to cover all the technical aspects of electrical engineering and to transfer practical experience onto young electrical engineers. In order to present it in a meaningful way, the book explains the technical details around a fictitious, though realistic power plant and industrial projects. An industrial project offers a greater variety of requirements and lends itself better for practical analysis.

This analysis can be applied to other plants that use similar electrical equipment, such as transformers, motors, generators, variable frequency drives (VFDs), cables, switchgear, overhead lines, fire protection, control systems, grounding, lighting, etc.

The project is commenced by an investor (company) who have decided to build a power or an industrial plant (cement factory, steel manufacturing, oil refinery, wood mill, plastic cups, fruit canning, etc.) on a particular location for a particular operating capacity (produced MW, tons of cement, tons of steel, tons of paper, tons fruit, etc.).

The investor company had already prepared a rough estimate proposal for a project with a simple budget estimate of ±40% accuracy and had received

Project development steps

Owner	Initial feasibility study → 40% Estimate → Bank
Engineer/ owner	Conceptual design → 20% Estimate for bank loan Review of process alternatives Eng. drawings: flow, P&ID, one lines, based on projections procurement of major long lead equipment
Engineer	Detailed design based on actual procurement engineering specifications and drawings procurement: mechanical, electrical and control site construction of infrastructure
Engineer/ contractor/ engineer	Project construction Civil → mechanical, Electrical, controls Precommissioning: individual equipment commissioning: system by system
Contractor/ owner	Release to production ownership and production

Figure 1.1 Project development.

positive indications of financing from a bank to develop a feasibility study and a more detailed cost estimate. Figure 1.1 shows the steps of the project development.

From the electrical power system perspective, the first step is to review the project flow diagrams produced by mechanical engineers and on that basis prepare electrical design criteria and develop a **key one-line diagram** (see Chapter 2). The key one-line diagram will envelop all the process facilities within the plant starting from the power source down to the individual equipment users and services. This is followed by preparing a (±20%) budget cost estimate as part of the conceptual design inclusive of the cost for engineering and construction and then present it to the bank to secure a loan.

1.1.1 Plant Design Procedure

Plant design is a joint effort by multiple engineering disciplines: process, mechanical, civil, electrical, architectural, structural, estimating, scheduling, procurement, document controls, and project management. Every department is doing its work in strict coordination with others to insure everyone is "on the same page" and that nothing falls "between the cracks." Lead engineers of all the disciplines are on the email circulation of everything that is happening on the project to insure all the design decisions and project changes are being communicated and implemented, both "vertically and horizontally" through the project organization chart. Regular meetings are held on a weekly basis to assess the progress, critical path schedule, any design changes, manpower shortfalls, and any delays in design, procurement, fabrication, and installation and their impact on the project schedule. Design options and temporary measures are being reviewed to overcome the delays in the equipment deliveries and/or equipment failures.

1.1.2 Codes and Standards

The publications listed below form a part of this book. Each publication shall be the latest revision and addendum in effect at the time of issue of contract and design specifications, unless noted otherwise.

ANSI	American National Standards Institute
CSA	Canadian Standards Association
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electro-technical Commission
ISA	Instrument Society of USA
ISO	International Standards Organization
NACE	The Worldwide Corrosion Authority
NEMA	National Electrical Manufacturer's Association
NEC	National Electrical Code
NFPA	National Fire Protection Association
UL	Underwriters Laboratories of USA

Standards, codes, and guidelines listed above and referenced in every chapter of this book are widely used by the engineers in the industry, both as directives and guides. When working in another country, the local standards must also be applicable. This book refers to and often presents data courtesy of these engineering standards, which are considered one of the major sources of guidelines and good engineering practices for engineers.

The standards and codes are extremely important. Actually, there are three parts to your success as an experienced engineer:

(1) Understanding the applicable standards and knowing how and where to apply them.
(2) Referring to the suppliers' equipment catalogs and reviewing the graphs and performance data sheets to determine the proper equipment ratings and supplies for your specific applications.
(3) Building experience by field reviews of the equipment performance and its related hardware.

1.2 Project Development

1.2.1 Type of Project

A typical project referred to in this book is an ore-bearing property, owned by an investor, which according to the exploration figures contains a large ore body of Cu/Zn ore. This can equally be a mining property of coal, silver, and gold, or it may be a brewery batch plant or a large harbor development.

On the power industry side, this may be a hydro development project, for which a catchment area is defined and dammed to create a head and estimate the flow of water that can be controlled from the area. The electrical part of the project, though large, is relatively small in comparison with the huge civil infrastructure required to be built. Utilities typically take ownership of these large projects.

1.2.2 Conceptual Design for Feasibility Study

If the project gets a go ahead by the investment partners, the investors or their bank will provide initial funding to engage an engineering company to investigate the project a bit closer. There are a number of different engagements possible between the owner and the engineer that can be employed. That may be a subject of another book.

The project team with all the engineering disciplines has been given an assignment to develop conceptual drawings and budget estimate. The conceptual design includes plant layouts, load flow diagrams, electrical design criteria for all the electrical activities and equipment, a key one-line diagram, and a reasonable accurate capital cost estimate to be presented as a "bankable feasibility study." This document will also serve as a basis for the future detail engineering design to build the project, should the project proceed further.

The design calculations in this conceptual study will use the system and equipment characteristics from previous projects similar to this one to generate the design parameters for the new project. The budget estimate is obtained from the various budget quotations, previous projects, and earlier work done in the country of the project with their labor rates.

During this three to six months of engineering phase, some major long lead mechanical and electrical equipment may be ordered on the basis of a possibility of cancelling the orders if things don't "pan out." The electrical lead equipment may include the main transformers and HV switching equipment.

The flow diagrams show the flow of the ore, through the various plant processes, including additions of other ingredients: water, heat, and fuel to process it and take it to the final product. In this case, the final products are bars of

Cu and Zn. Where there is Cu, there is a chance of minor percentage of gold, while silver is never far off from a deposit of Zn.

From the electrical design perspective, design criteria, major cable routing, and one-line diagrams will define the shape of the plant power distribution and other aspects of the electrical equipment and plant operation.

1.2.3 Detailed Design

Detail design will follow the conceptual phase. This "detailed" phase may last anywhere from 9 to 18 months for an industrial plant or two to four years for a power plant, depending on the type of plant. The conceptual drawings will be reworked and expanded. Procurement phase will commence by preparing the purchase specifications to specify equipment performance requirements and also to make the interface diagrams to tie up with the related mechanical equipment. Often, the electrical design may have to wait a while for the mechanical design to near its completion and their suppliers' drawings are in hands to determine the electrical ratings and the interfacing connections needed.

The first effort will be to update the electrical plant design criteria and the key one-line diagram from the conceptual design phase. These two items are your two big pictures, and the foundations for everything else you plan to build on.

System studies: The detailed design will present final one-line diagrams with the actual impedances and equipment characteristics. It will use the data based on the results from power system studies: load flows, motor start, voltage drops, phase and ground short circuits, arc flash, insulation coordination, and step and touch potential. The studies will determine more precise and factual system characteristics and prove that the selected equipment ratings conform to the requirements set out in the design criteria. For these calculations, we will use the software from various system houses, such as Easy Power, ETAP, Cyme, and others. The plant data will be laid out on a computer and let the computer do the math. Not only that, the computer teaches you the power system functioning. One can introduce changes and alternatives and then observe the impact of the changes on the power system performance. It allows you to select the optimal solutions.

Interfaces: At this time, schematic and wiring diagrams for all the motors and valves, cable lists, and plant layouts will be prepared.

One of my bosses once told me: "Project usually fails at the interfaces." He was right. The projects require a huge effort by many personnel working on the project, ranging from secretaries to the managers. Possibilities of errors are ever-present. The interface changes may be due to a late design modification initiated by other engineering departments. If not well communicated and reconfirmed, the changes may not get on the drawings. This applies also for the communications between the engineering departments, the suppliers, and fabricators. If the equipment arrives to site with incorrect connections, it will lead to a lot of confusion on site, "throwing blame around of who said what, and so on." This is where the experience comes in from working on large projects and by recognizing how the equipment is supposed to work and how it relates to the other equipment. Experienced engineers would notice problems if incorrect drawings cross their desks.

Every discipline can use approximations, add (+) or delete (−) a few inches or feet here and there on the drawings. The electrical engineers have no such a benefit. We have to produce drawings that match the equipment perfectly. Electrical drawings show several hundreds of thousands of wires, power, and controls interfacing between the various electrical and mechanical equipment. The only grace we get is that we can bend the plant cables around in the cable trays.

You may have done your job to perfection, but unfortunately, when you come to the construction site, you may face some disappointments. You will notice the supplier's actual equipment does not match the drawings you received to prepare your diagrams from. The suppliers have just got confused and sent you drawings they had engineered for a previous customer, or they had made changes but failed to inform you.

Do not panic now. This is something to get used to. It happens. Once the wires are connected, you may notice different problems stemming from errors, suppliers' incorrect designs, and of course, the wiring errors. This is where pre-commissioning and commissioning comes into play to make sure everything is properly tested and made to work as intended.

Everyone can make mistakes. Let us be honest about it. Even mechanical engineers can make a mistake here and there. But there is nothing like what the electrical engineers face. Thousands and thousands of wires are laid out in the field, and each one must find its proper place or it may turn out to be a major mistake and error, which will have to be troubleshooted later during the plant commissioning. Fortunately, with the advances in technology, a half of wiring in the modern plant is now replaced by communication cables, coax, a pair of wires, etc., carrying thousands of signals which can be shaped and configured as part of the plant control system. But that is another story. That certainly is a wiring relief, but our problems will now likely resurface in the software during commissioning (see Chapter 17).

You as an electrical engineer will prepare or work on the following drawings and documents:

- Equipment and installation specifications.
- *System studies*: Load flow for voltage drops, short circuits for the equipment ratings, large motor starts, and relay coordination.
- One-line diagrams.
- Design criteria.

- Layouts for electrical equipment, lighting, cable trays, load Lists, cable schedules and terminations, embedded grounding, equipment grounding, lightning, and power corridors.
- Prepare schematic and wiring diagrams for each motor, valve, and feeder,
- Review of civil, mechanical, and instrumentation drawings.
- Review of suppliers' drawings, and more.

That is a lot. A project of this magnitude may require thousands of electrical drawings and hundreds of documents.

1.2.3.1 Cost of Change

At the project meetings, you will note that the design is still open to changes. With the design criteria and key single-line diagram in hand, you will be discussing with your civil, process, and mechanical counterparts on what is possible and reasonable and what is not, and what will cost "an arm and a leg" and what may be a more reasonable option. The developer may suddenly decide to add another process line in the plant, which may stretch your "almost finished" power distribution system or completely change it. Remember, a plant change on paper is 10 times less costly than doing it during construction (Figure 1.2).

1.2.4 Engineering Documents

During the plant design, an electrical engineer with his team of designers must prepare the following documents:

Drawings: Drawings are being prepared for the specific electrical equipment and as layouts for the equipment installations. The former are included with corresponding equipment specifications, while the latter are part of the construction (installation) specifications. The drawings are to be prepared by experienced designers with a help and under the supervision of a lead engineer.

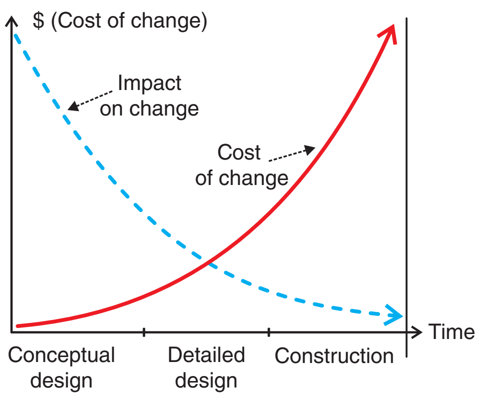

Figure 1.2 Cost of change.

Initially, the drawings are prepared as preliminary and issued to various suppliers for tendering purposes. Once a winning bidder is selected, the preliminary drawings are updated and finalized based on the fabrication drawings received from the selected supplier and finally issued for construction. The drawings must be marked with appropriate revisions as they are being revised and issued.

There are different methods of marking the drawing revisions. Here's one. The preliminary issues of the drawings are labeled with revisions, Rev. A, B, C, … or PA, PB, PC, …. The final drawings for construction are marked as Rev. 0, 1, 2, 3. Minor changes not affecting the contents or performance may be modified without raising the revision number.

Reports: During the project, many situations are encountered where the engineer is required to prepare official reports to evaluate various options and make recommendations of possible changes and improvements to the project. The changes may be due to the project cost reductions, technological changes, or changes to the site or operating conditions.

Coordination with other engineering disciplines: The electrical engineer must also review the mechanical, process, and civil engineering drawings to familiarize themselves with the buildings and mechanical equipment, as well as to insure the mechanical equipment includes appropriate electrical parameters specific for the project.

1.2.5 Equipment Specifications and Data Sheets

These documents will be prepared by the lead engineers for the electrical equipment, such as transformers, motor control centers (MCCs), VFDs, switchgear, etc. Revisions to these documents may follow the same procedures as identified for the drawings. Following a receipt of the tenders from the suppliers, the engineer prepares technical tender evaluations with appropriate conclusions, recommendations, and specific conditions for purchasing the equipment. As part of the award of contract, the specifications and data sheets are updated to match that of what was agreed on "as purchased" (see Chapter 24 for some specification details and data sheets).

A typical small or big project requires a number of specifications with data sheets to be written. The specifications define the equipment performance requirements and workmanship. The data sheets cover the specific equipment rating requirements. The specification for a particular piece of equipment can be updated from project to project with some minor changes. It is the data sheet that changes in a big way as the application and ratings may be completely different from project to project.

Hopefully, the new specifications will be similar to those of your previous projects. Often, one can change the project name and the spec number and then revise the data sheet to suit the equipment you need for your new project.

Try not to repeat yourself in the documents. Sooner than you think, someone will call and ask you: "What do you want: 1000 A breaker written in the specification or 1200 A breaker listed in the Data Sheet." If you want to talk about the breaker in the specification, just note: "For the ratings, refer to the Data Sheet."

From project to project, try to maintain the same ID number for the same design product, if the project permits it. For instance:

Specification and data sheet, respectively, for MCCs on project ABC: ABC – xxx – TS31 – DS31
Specification and data sheet, respectively, for MCCs on project XYZ: XYZ – xxx – TS31 – DS31

Try to group the documents for the type of equipment and services. Leave some gaps as there are differences in scope from project to project. When you are dealing with equipment like MCCs located in various different parts of a plant, write a common spec with several data sheets added to it for different areas.

Here is a list of specifications from a recent project in Minnesota on a 55 MW power plant using turkey litter as fuel:

(1) Electrical contribution to mechanical engineers' specifications.

TS01	Electrical requirements for mechanical equipment
TS02	Electrical requirements for 480 V motors up to 200 kW
TS03	Electrical requirements for medium voltage (MV) motors over 200 kW

(2) Main power distribution

TS11	Switchyard equipment and hardware
TS13	Large transformers
TS14	Standby diesel generator
TS15	Relay protection panels
TS17	13.8 kV transformers
TS21	13.8 kV switchgear

(3) Plant equipment

TS23	MV motor controllers
TS24	MV VFDs

TS31	480 V MCCs
TS32	480 V VFDs
TS33	Unit substations and low voltage (LV) switchgear
TS35	Station battery and chargers
TS36	Uninterruptible power supply (UPS) equipment and panels
TS37	Rigid bus ducts
TS38	Cable bus ducts
TS39	Lighting and distribution panels
TS40	Power and control cables
TS41	Plant heat tracing panels and hardware

(4) Services and plant installation

TS43	Plant CCTV
TS44	Plant public address
TS45	Plant telephones and data
TS51	Plant fire detection and suppression system
TS52	Plant heat tracing
TS54	Overhead distribution lines
TS55	Switchyard installation
TS57	Plant installation

1.2.6 Equipment Numbering

There are a number of methods on how to number the equipment. Some clients may have their own numbering system for all of their projects. The numbering is generally done by the mechanical department, except for the purely electrical equipment, which is numbered by the electrical group. The most popular numbering systems are the intuitive systems, as follows:

Example: **20 PU 007**; Area 20; **PUmp** sequence number: 007. The pump number is also given to the associated motor.

The plant process areas may be given the specific area designations:

00: For a general site, including the main substation
10: Crushing
20: Conveying
30: Milling
40: Flotation, etc.

For the equipment, assign intuitive designations as follows:

PU, pump; SP, sump pump; TK, tank; CR, crane; AG, agitator; VF, vent fan; RF, roof fan; LP, lighting panel; HR, heater; CV, conveyor; TR, transformer; CY, cyclone; etc.

The sequence is from 001 to 999. The sequence numbering may restart from 001 for each area.

The numbers do not have to be consecutive. The sequence number 001 may start from the basement, 101 on the first level, etc., to better describe the equipment location.

Be consistent and make sure the pumps are sequenced in pairs: 001/002, 103/104, the odd number is, for instance, on the left side approaching the motors.

Cables are generally numbered and defined by the loads and not the MCC sources. Some companies insist that cable numbers include indications of the source (the MCC bucket) and the destination (load). Standardize control cables for the common hardware such as pushbuttons by using consistent cable C suffixes, programmable logic controller (PLC) connections. For instance, the cables for the pump 40 PU 003 are labeled:

40 PU 003 P: For the motor power cable.
40 PU 003 C1: For the control cable to PLC equipment.
40 PU 003 C2: For the control cable to the Push Button station.
40 PU 003 C3: For the control cable to the field level switch or other sensor.

Make sure the numbering is consistent for all plant motors. This will allow for easier understanding of the plant cabling and purposes. For instance, establish that cable C1 for all the plant motors is always the cable from the motor starter going to PLC. If that cable is not used, that number is skipped for that particular drive. Push button station always occupies cable C2, etc. This consistent method of numbering will help you computerize the cable lists and to sort the lists to specific equipment.

The equipment numbers are needed to create load lists, which will later be expanded to create the list of schematics and cable lists. For instance by adding to the list of loads: the load names, voltage, kW rating, MCC, and bucket, a computer program can create a list of cables, select the cable sizes, and assign "From – To" destinations without any manual input.

If you add a typical schematic diagram type for each drive or feeder to the load list, the computer program will assign and fill in the cables and cable details on the drawings for each particular drive/feeder without any human input.

1.2.7 Load List

Based on the data given in the load list (Table 1.1), the computer calculates the cable size, type, length, and routing (see Table 1.2).

Adopt minimum cable sizes: #12 American wire gauge (AWG) for power and #16 AWG for controls.

Should the kW rating change and a new kW rating be entered into the list, the cable size will be computer-updated automatically when the cable list is regenerated.

The same computer program generates and prints the schematic and wiring diagrams automatically adding to the drawing of all the specific data including the cable data, input/output (I/O) data, and wiring terminations.

1.2.8 Generated Cable List

Table 1.1 Load list (simplified).

ID	Name	Volt	kW	MCC	In service	Type
40 PU 003	Feed Pump, Water Tank 1	460	15	MCC11	1	T1
40 PU 004	Feed Pump, Water Tank 1	460	15	MCC11	SB	T1
30 AG 006	Agitator, Tank 6	460	10	MCC03	1	T1
30 CR 001	Crane, 60 Tone, Main Hall	460	100	MCC03	1	F1
10 RF 003	Crusher Roof Fan	460	1	MCC 01	1	T3

In service: 1 = operating, SB = on standby.
Type: this is the designation of the type of operating circuit to be implemented.

Table 1.2 Cable list (simplified).

Cable ID	Cable size	kW	Type/class	From	To	Length
40 PU 003 P	1-3/c #10 AWG,	20	Teck 600V	MCC11	PU Motor	120
40 PU 003 C1	1-5/c #16 AWG,		Teck 300V	MCC11	PLC 2	15
40 PU 003 C2	1-3/c #14 AWG,		Teck 300V	MCC11	PB Stn	120
40 PU 004 P	1-3/c #10AWG,	20	Teck 600V	MCC11	PU Motor	120
40 PU 004 C1	1-5/c #16 AWG,		Teck 300V	MCC11	PLC 2	15
40 PU 004 C2	1-3/c #14 AWG,		Teck 300V	MCC11	PBStn	120
40 PU 004 C3	1-2/c #14 AWG,		Teck 300V	MCC11	TH1	130
30 AG 005 P	1-3/c #12AWG,	15	Teck 600V	MCC05	PU Motor	85
30 AG 005 C1	1-5/c #16 AWG,		Teck 300V	MCC05	PLC 3	20
30 AG 005 C2	1-3/c #14 AWG,		Teck 300V	MCC05	PB Stn	85
10 SP 003 P	1-3/c # 12 AWG,	5	Teck 600V	MCC01	PU Motor	60
10 SP 003 C2	1-3/c #14 AWG,		Teck 300V	MCC01	PB Stn	60

1.2.9 Schematic/Wiring Diagrams

In the last 20 years, the schematic and wiring diagrams have changed in the following ways. This author has participated on all three of them:

(1) Relay logic diagram. That is past. We will not dwell on this wiring approach any more.
(2) Connection to PLC I/O (see Figure 1.3)
(3) Connection to distributed control system (DCS) communication modules (see Figure 1.4).

It is not known whether there is a forth step around the corner, but it could be said that each advance has brought us considerable progress and simplification to the design of the schematic/wiring diagrams.

Specific operating logic for each motor and valve is no longer needed to be shown in the diagrams as it used to be with the relay logic diagrams. The circuits (Figure 1.3) were drawn and wired uniformly into DCS or PLC I/O cards, while the specific logic to each drive is developed as software. Though this method

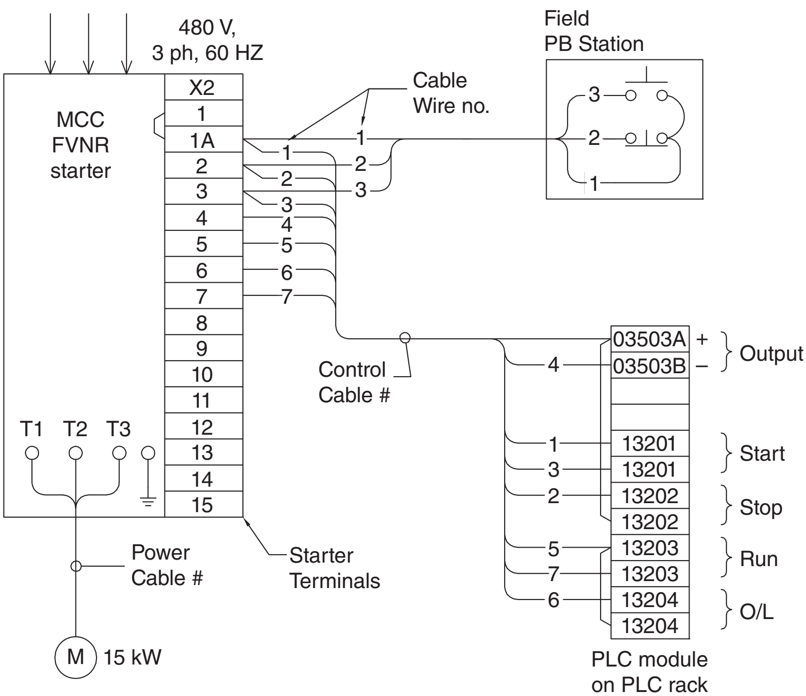

Figure 1.3 Motor wiring diagram with PLC module.

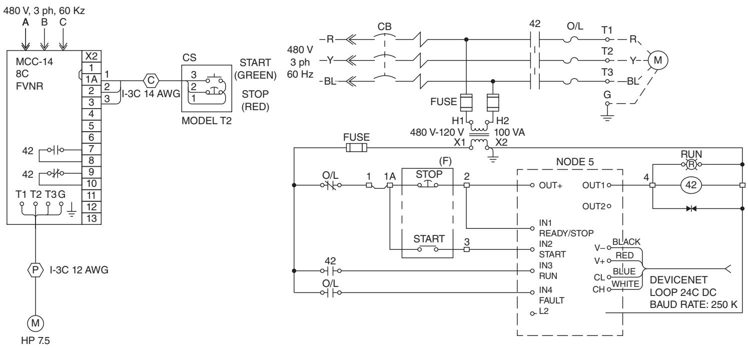

Figure 1.4 Motor wiring diagram to DeviceNet communication module.

needs less wiring and it is made to be uniform, there is still plenty of wiring to be done.

Figure 1.4 illustrates the latest wiring method with a DeviceNet communication loop clearly indicating that most of the external wiring has disappeared. For DeviceNet and other means of communications (see Chapter 17).

Evidently, this motor needs a cable for its pushbutton station and a DeviceNet loop to a DN module. The loop loops from one starter bucket to the other. That is it. The rest is software.

The specific logic for each drive is now written as software into the processors to receive status from the drives and to feed the decisions of the software logic back to the inputs to start/stop/sequence the drives in accordance with the flow requirements of the conveyors, pumps, etc.

Or if the drive is a VFD-operated motor, software provides a set point to the drive to increase/decrease its speed to match the plant output at any particular moment. Therefore, the VFDs are not only needed to help the motor to start softly but to also continuously adjust the plant production of a certain product in the plant operation. This could never have been done with relay logic.

What is the difference between a wiring and schematic diagram?

A wiring diagram of a motor is shown in Figure 1.3, complete with all the cabinet terminations. A schematic diagram is the stretched version of the wiring diagram (Figure 1.4a) and is shown in Figure 1.4b.

As a result of the innovations, the site labor for installing the field control wiring has substantially been reduced. Please do not make a sigh of relief, as yet. Though the operating logic is no longer visible on the above diagrams, you will now have to understand the PLC logic and program the ladder diagrams to make the plant motors function like an orchestra.

Computer program: It is desirable that the engineering company develops a software program that will create schematic/wiring diagrams and cable lists directly from the project load list database by using attributes that automatically get filled on the typical model drawings with the data sourced from the load list. Manual entry to these documents is the biggest source of errors on the project. A small project change must permeate through all the documents. Let the computer enter it for you.

The schematic/wiring diagrams and cable lists are the products of the load list. The diagrams can then be printed for the whole project or for a specific area or MCC.

Some third-party software programs are available for this purpose. Unfortunately, these were written for the wide market audience to be saleable to every company as one unadjustable product. This third-party approach unfortunately tends to require a massive manual input, and for that reason, defeats the purpose. In discussions with some users, I was told that the input is overwhelmingly manual and leads to erroneous inputs. It was not efficient, and the software was abandoned.

This author has developed its own program on FoxBASE for that purpose. It is updated for every new project to be project-specific resulting in minimal manual entry, mostly for cable lengths.

1.3 Precommissioning and Commissioning

Commissioning of an industrial plant is a bit simpler. The plant operating system can be broken down into smaller subsystems, such as crushing, milling, which could be precommissioned and commissioned totally independently.

In the power plants, the generating units are large operating blocks, which are tested one at a time along with the water or fuel paths (input) and the electricity path to HV switchyard (output), as well as the unit services and operating controls all at the same time. Station services are commissioned separately.

1.3.1 Precommissioning

Precommissioning and commissioning of an industrial plant or a power plant are different activities. They must be approached differently in particular if the plants are fully automated. Precommissioning is testing of the equipment such as switchgear, MCC, VFD, or transformers on an individual basis in an energized state, but totally disconnected from the other operating equipment.

Secondary injection: First, the switchgear is meggered and high-pot tested. Then, the protective relays are tested by secondary injection (simulation) to trip the breakers due to overloads or undervoltages according to the protective relay setting sheets for each breaker. Protective current transformers (CTs) and potential transformers (PTs) circuits are fed to the tester to simulate the operating state. The secondary injection is performed by a three-phase tester, shown in Figure 1.5.

Circuit breakers: Each breaker in the switchgear can be tested for functioning in its drawn-in (connected), test and withdrawn position. The switchgear is

Figure 1.5 Three-phase tester.

not energized, but the circuit breakers can be operated because the 125 V_{dc} control circuits are energized to allow the breakers to function. Furthermore, there may be an additional control circuit at 24 V_{ac} or V_{dc} used for remote operation and signaling to and from the plant control system.

In each of the three positions, the switchgear and the circuit breaker leave its mark.

In the withdrawn position, one can test the breaker to charge the activating spring and to open/close without affecting the other breakers in the assembly.

The breaker test position is a half-drawn-out position. In this position, one can fully test breaker in all aspects of control and interlocks, but without affecting the other parts of switchgear assembly.

In the connected position, the breaker can be fully tested provided the incoming and the tie breakers are locked and held in a withdrawn position. This test position is very useful in the commissioning (energized) phase of the plant testing that follows the precommissioning.

Similar precommissioning activities are carried out on MCCs for each motor or feeder circuit to enable the assembly to be energized and to power motors and feeders for further tests. Each motor is being bumped for its rotation to match that of the pumps or conveyor travels, etc. For this activity, the motors are decoupled from the pumps.

Furthermore, the motor branch circuit breakers are also pretested to establish their minimum instantaneous protection settings to suit the motor inrush currents (see Chapter 3 for details).

Wiring: During the precommissioning, a lot of simulation will be required to be performed to test the equipment and cable wiring. This includes jumpering the contacts and injecting volts or currents from other sources to command the operation of the switchgear breakers or MCC starters. All the wiring and schematics of the field devices and hard wired safety interlocks must be verified.

Wiring diagrams used to be checked during the precommissioning stage too, but these diagrams are now becoming a rarity and often obsolete. As mentioned earlier, wiring diagrams have been greatly simplified by using the communication links, such as Ethernet, DeviceNet, Modbus. The present schematics have all the terminals marked just the same as the wiring diagrams used earlier. It seems to be a trend now. Perhaps not in the industrial projects yet, but, certainly, it is a trend in the large power plants.

You may then ask, how do you make cable terminations if you do not have wiring diagrams? That is a very good question. Well, what many contractors now use are the cable tabulation lists showing the terminations from the terminals shown on the equipment A to the terminals on equipment B, but without giving any significance to each wire. The wiremen can swiftly terminate the wires as listed and let someone else think if the list was right or wrong. As a result, not all the signaling is being precommissioned. Some parts of it may be rung out, but not precommissioned to verify the interlocks. It is left to the commissioning group to test it and prove it on the equipment performance basis. Again here, this approach refers to the large power plants and not industrial projects.

Transformer oil: Transformers oil is tested for its dielectric strength several days prior to energizing. New oil should have a strength of >65 kV/cm, while older oils must demonstrate the insulating strength of >60 kV/cm. If the strength is lower than those desired, the transformer oil must be purified by the heating and filtering equipment to exhaust the moisture before energizing. Oil samples will be taken from the transformer during installation a week before energizing.

Figure 1.6 presents an actual handover chart of a power plant from construction, through precommissioning, commissioning, and reliability run (RR) to operation and ownership transfer.

The precommissioning checks on a larger piece of equipment, for instance, a large hydroelectric generator, is a relatively complex endeavor. A large number of interlocks must be simulated, much of them from the software. Some precommissioning can be done and must be done, such as unit trip logic and emergency stops and safety trips. In order to make the simulations more manageable, control functions are usually broken down into a number of sequential steps. These critical offline tests are performed before the online tests are attempted in order to minimize any unforeseen inadvertent operation. During this process, the unit is tested through a restricted logic to allow the checks on part of the logic and then proceed to the next ever larger step. The rest is left for commissioning. Since there are too many interlocks to be dealt with, there is also a fear that some of the simulation jumpers may be forgotten and left behind. Jumpered contacts left behind hide unreal bypassed conditions.

1.3.2 Commissioning

Commissioning is often called wet commissioning. It is an engineering activity that follows the precommissioning phase, often called dry commissioning. Commissioning is an engineering activity dedicated to testing the plant or part of the plant, in a fully energized state of applied electricity, pressure, heat, steam, and water with all the auxiliary systems in service.

During the days of relay logic and manual plant control, the commissioning was not that extensive. Nowadays, the plants have become fully automated and generally unmanned, having inputs from numerous field devices, start, stop, overload, ready, local/remote (Loc/Rem), breaker position, trip, analogs, etc. To diagnose the plant directly on the operator's screen rather than by pulling, simulating, and jumpering, the wires in the panels takes a lot of coordinated effort in many parts of the plant at the same time.

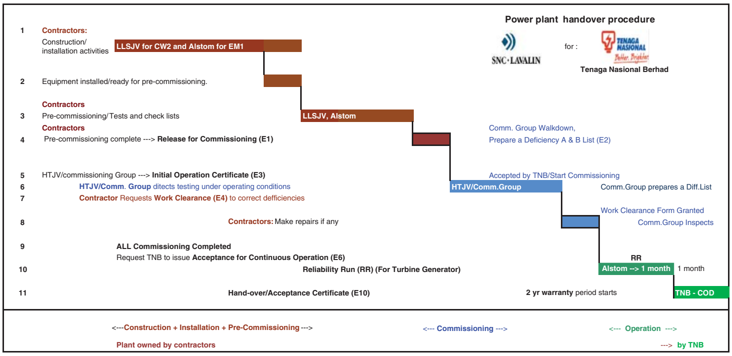

Figure 1.6 Plant handover procedure. Source: Courtesy of SNC-Lavalin.

Only a fully energized condition offers a controlled testing environment that allows all the logic elements to be properly commissioned and proven. This work in a noisy environment requires good communications between all the parties. Often, the cell phones do not work due to the noise interference. On the last project, the proper communication was only achieved after the house telephones operating on fiber optic cables were installed.

Primary injection: Commissioning of large power plants carries considerable risks and safety issues. This is because commissioning is mostly performed under the primary injection when the equipment is fully energized. The operating voltage is applied, and the currents are flowing through the cables and breakers. This flow can now be monitored on the real front panel instruments and/or relays. The flow of current (power) can be changed by loading the feeders and circuit breakers.

While most of the precommissioning and troubleshooting is performed from the schematic diagrams, just like always has been, the commissioning is performed based on the operational requirements. Commissioning as mentioned above is energizing and testing of the groups of equipment working together under active pressure of oil, water, steam, air, or electricity, with a minimum of simulation. This is the first time the equipment and the control system will face fuel, water, air, oil, and electricity. Believe me, this makes a lot of difference in the equipment behavior, particularly the instrumentation. The instrumentation finally gets to be checked for flow, speed, voltage, pressure, etc. Some of the instruments will now prove to be faulty, poorly calibrated, or incorrectly selected, or perhaps incorrectly wired or leaking.

The precommissioning of the power plant control system is mostly skipped in favor of the commissioning as mentioned earlier when the generator is energized in a controlled manner and tested.

Most of the wiring or control logic (95%) is expected to be correct, but a small part (5%) may be incorrect. The operator's screen may not indicate an error, but it will show what is not functioning or functioning incorrectly. It is not an easy task to comprehend as multiple malfunctions may be a result of a single wrong input. But which? Where to start? The logic interlock strings have to be investigated by observing the schematics, by removing the wired and software interlocks, one interlock at a time to zoom in on the possible targets or "usual suspects."

What are the interlocks? These are the "permissives" that enable or disable another drive. This may be a case of set of pumps of which one only is allowed to run at any time. Safety Interlocks are hard wired into the electrical circuits as in Figure 1.7. Process interlocks are entered into software as shown on the right.

Sometimes, missing wiring must be added, wires reversed, corrected, removed, and jumpered to make it correct according to the schematics.

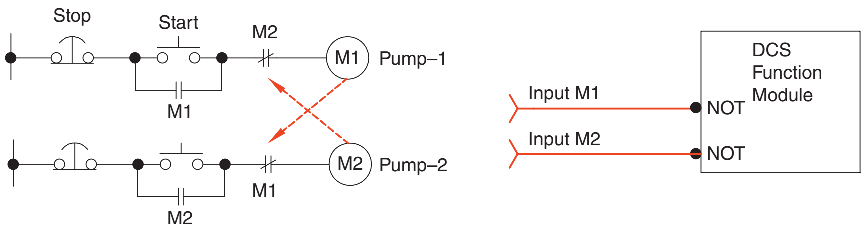

Figure 1.7 Plant interlocks, hard wired and software.

And if it still does not work, then the schematic must be corrected and the circuit rewired. Often, an interposing relay may not be seating properly. There are so many ways to fail?

The wiring tabulations, mentioned earlier, are generally not being updated. The schematics are updated in red and issued “As Built.” The commissioning approach, though relatively cumbersome, avoids all the simulations to be done and saves the time as the work is concentrated on fixing faulty wiring and wrong logic lines only, and not on all the wiring and all the logic. This approach may work providing the unit was being fully tested under all the operating conditions of loading, ramping, and stopping to expose the functioning of all the instrumentation, the transmitters, and indicating instruments. The transmitters may work correctly for certain loading and operating sequences, but rapid changes in the load may expose their weaknesses.

In my judgment, the following are typical commissioning problems:

(1) *Mechanical*: Rare. They tend to be visible, but take longer (days) to fix and replace with spare parts if available.
(2) *Electrical wiring*: Due to wrong wiring, wrong schematics, inappropriate contact seating. This is diagnosed by going over the schematics and fixed within hours.
(3) Control logic software errors. This is diagnosed and modified within hours. Often, several attempts are tried.
(4) Nonresponsive devices (level switches, analogs, pressure switches, transmitters, etc.). The devices may be faulty or inappropriate for the application. These problems are relatively common and difficult to deal with because of their unpredictable and intermittent behavior. These issues may take several days to be discovered, repaired, and the fix confirmed when repaired.

Here is an example of unpredictable nature of certain field devices. A large hydro generator sometimes fails to transit from the synchronous condenser mode to the generator mode when requested. Having spent days to review the field devices that control this activity, the focus shifts toward three-level switches operating in a tube controlled by an orifice. The switches may work well for days, but then suddenly fail to provide a transition signal. After days of trying and figuring out many situations, it is finally correctly concluded that the water in the tube is too turbulent at certain conditions and water pressures and affects the operation of the switches. Several new orifice sizes were tried and eventually a proper size is selected and placed. The trial period to prove a particular orifice may take weeks. Also, the same orifice size used on Unit 1 may not be the right one for Unit 2, due to varied operating conditions.

Naturally, all the changes implemented on Unit 1 in the wiring, control logic, and unresponsive field devices are immediately updated on the next unit if it is available, thus, insuring faster commissioning and release to operation.

In an industrial plant, the commissioning is based on a system-by-system basis grinding, flotation, conveying, leaching, etc. Switchgear, transformers, MCCs, and motors are tested together under partially energized conditions. Each system is semiautonomous and gradually energized to prove it operates in proper sequence for starting and shutting down under specific conditions. The systems are being commissioned until the whole plant is made operational and ready for starting up from the control room and it is correctly represented on the control system monitors.

Some say that commissioning is the slowest game in town. It is 90% logistics and preparation to position right people to the right places, keep them focused on the task with proper tools, and to prepare the safe environment and operating conditions for the test. The actual test may take only a few minutes to show a change in state on the instruments, or that something had moved or rotated. Conveyors start moving in sequence, grinders start grinding, and pumps start pumping and filling the tanks. Level switches regulate the speed of the drives to prove the set points established by the control system. The automation starts directing the process.

For the commissioning to work well, one has to have a good cooperation of the mechanical, process, and controls engineers and excellent means of communications in the field. Why are the electrical engineers most often assigned to be the commissioning engineers? Well, I think because the electrical engineering is the hardest part of the project to understand. Electricity is the blood flow of the plant. It connects all the pieces in an invisible way that experienced electrical engineers can understand.

1.3.3 Reliability Run

RR is also shown in Figure 1.6. This is a big commissioning event as the unit enters the operation and starts producing electricity. Typically, RR is applied to power plants but not to the industrial plants. RR lasts anywhere from 7 to 30 days. A period of 30 days is the most common RR period. For the plant to enter an RR, it means it has been fully commissioned and proven to be operational, with some minor listed deficiencies that do not affect the production.

These can be fixed during the RR or later. Successful RR leads to ownership transfer and a start of a one to two years warranty period.

During an RR, the owner's operators take over the plant operation in the presence of the suppliers in supervisory role. This is also a phase of practical training for the operators. The operators follow the directives of the dispatch center and load the machines accordingly in terms of MW and MVARs. The intent is to operate and expose the plant to all the operating modes and transitions without restrictions and as often as possible. As more and more automation and supervision is added to the plants the commissioning and RR tests get more and more involved.

Each plant owner may dictate different constraints for RR. The rules may also depend on the unit performance during the commissioning. If the plant has been failing often, owners may impose more stringent conditions. In general, the unit must operate 30 days, 24 hours a day without a major failure that would cause the unit to reduce its capability to carry load. If that happens, the RR is restarted from the beginning. For instance, a failure of a pump with a successful automatic transition to the healthy pump will not be a cause to stop the RR, but considered a successful operating action.

It is much easier to commission a plant if you had followed it through the design and construction into commissioning. Sometimes a commissioning engineer may be invited to do a commissioning on a plant that he/she may not be familiar with. There were a number of cases like this. One of difficult ones was in Lahore, Pakistan, where we were invited to conduct a commissioning and RR test after it has failed in 12 earlier attempts over a period of two years. It was a 5×30 MW thermal plant.

During the RR, the plant was supposed to operate flawlessly for seven days without a single alarm while being tested under all the operating conditions. In addition, there was a specific test during the RR while all the plant units were running, called "Islanded Test." An unexpected three-phase fault is arranged on the HV line, connected to the plant. To pass the test, the plant had to separate itself from the grid, shutting down four units, while one unit was supposed to be left running and maintaining the plant station service load.

Well, this time, it worked well, and the plant passed the test. We knew that this time, we had to take a different approach. We modified the protective relay settings and readjusted the governor transfer functions. Every short circuit is different, and the units are required to conform accordingly. Perhaps we were just plain lucky. It is hard to tell. This time the protective relays operated selectively and the new governor settings acted correctly.

1.3.4 Power Plant Grid Tests

The power plant or a unit connected to a HV grid is often subjected to a number of grid tests that must be completed to confirm its compatibility with the grid and to operate from the dispatch center. Here is a list of some of the grid tests:

- Load dispatch following capability
- Reactive power dispatch follow
- Isochronous capability (droop)
- Dispatch MW ramp rate
- Fast ramp MW response
- Synchronous condenser mode switchovers
- Primary/secondary high-frequency response
- Under-frequency trip setting check (simulation)
- Loss of station service AC supply – switchover to standby power
- Black start, synchronizing on islanded grid dead bus
- House load operation on generator power for two hours

1.3.5 Commissioning Reports

Most commissioning engineers observe the testing in a passive way, and at the end of the test, they ask for the commissioning reports by the contractors. In their preprepared reports, you will never find a hick up or any failure noted. So, why bother having the reports, when everything is 100% perfect. In fact their reports are already done before they even start testing. Everything is Yes, Yes, OK, OK! There are tests that indeed go smoothly. Faults do happen and often due to multiple reasons that can be either fixed quickly or postponed and fixed later. That has to be recorded, as well as all the temporary deviations due to missing components, etc.

We do our own commissioning or precommissioning report for reasons noted below. We do it directly on our PCs as the events evolve. We sit with the test engineers at the end of a large desk in front of the main control panel and observe and write:

- We do not make a story. We write the action.
- The testers pay more attention to their work in our presence. They cannot hide the actual facts.
- As active people, we can ask for repeat tests or test it from a different perspective or condition.
- Our report is chronological and timed as it happens. One never knows what and when something unusual will happen. It does happen and often. One wants to capture the moment and to include all the background details on what was in action before the occurrences of a failure.
- It includes the failures as a record, why and how they were resolved and made to be OK.
- Later on during the operation when something fails, one can look into the commissioning reports and figure out if this is a recurrence of the same fault and likely to be expected to happen again.

1.4 Project Economics

1.4.1 Budget Estimate

A typical project passes through a number of development phases, starting from an initial estimate, conceptual design for feasibility study, detailed design, construction, and start up.

Let us name some typical projects:

- a power plant: hydro, diesel generation, gas combined cycle, etc., and
- an industrial project that may be an ore exploitation process, a factory of detergents, potato chips, and any other similar facility.

Utilities typically take care of the large power projects of this nature. They make a budget estimate of the project cost and evaluate it against the revenue based on the kWh to be sold to the consumers. The projected cost will include the initial capital for the equipment, materials, and labor over the years of construction, cost of money and plant maintenances, and operation (see Section 1.4.2)

The overall cost must include the transmission line from the power plant to the major switchyard. In case of a hydro project, the transmission lines are inevitably long and at higher transmission voltages. Diesel generation plants, on the other hand, are generally built for specific consumers in remote isolated areas. This may be a case of a mine up North needing 10–20 MW of power, for which the cost of building a transmission line would be rather prohibitive, in particular, if one evaluates it on the basis of the cost of km of line per MW delivered.

It is not only the utilities that are involved with power generation. There are small power producers called Independent Power Producers (IPPs) for generating anywhere from 2 to 100 MW. They generally do not get involved with power distribution and readily sell all the power to the local utilities.

The cost of fuel over the years of plant exploitation is always the most prevalent factor in the evaluation of a project development. This is where the hydro facility jumps ahead in spite of its huge cost of civil infrastructure. A gas fired plant will certainly be less costly on the basis of the initial cost of the plant and transmission line, but it is the cost of fuel per kWh produced that matters over the life of the plant. A diesel generation plant up North may be built at a low initial cost, but the cost of fuel is high, due to the additional cost of trucking and barging it to the site and storing it there for a full year. But do not forget that the usage of waste heat from the diesel engines can lift the plant efficiencies and reduce the cost of fuel usage.

An evaluation of a power plant also depends on the daily/weekly operating cycle. For hydro, the idea is to maximize the water usage, in particular during the rainy seasons to avoid spilling. Not many power hydro plants are built with a 100% operating capacity factor. A hydro project operating at 50% capacity factor is common, while I have seen hydro plants built for a projected 12% annual capacity factor. In other words, a plant of 100 MW installed capacity with a projected 12% capacity factor can produce, based on the estimated water availability, only 12 MW on a daily average for the whole year. It produces power when it has enough water drawing it down to the minimum operating level (MOL). Producing power below the MOL would be highly inefficient use of water resources and may make it difficult to recover back to the higher more efficient operating levels. Such plants with low capacity factors may be operating as base load generation during the rainy seasons and also as peaking plants because of their quick start capability when the marginal energy cost is the highest.

On the other hand, a fossil-fuel operating plant costs a lot more to operate and is likely to be used for peaking duties in a daily cycle only. Therefore, the overall economics of building a fossil-fuel operating plant in an area, which includes a mixture of different types of generation, must be estimated on the basis of its low operating hours.

While the power plant projects are built with the highest quality of equipment and redundancy, intended for 40 years of operation, an industrial plant may be built for a shorter duration of, say 10 years.

Levelized Cost Of Electricity (LCOE) is one of the yardsticks the owner's accountants use to compare the energy options for power plants. The formulae of totalizing the lifetime cost of production against the lifetime revenue are quite complex summations, using discount rates, inflation, and present worth accounting. Let the accountant work his figures. You as an engineer should understand the math behind it and offer technical options that may reduce the operating and initial costs to make the project more feasible.

1.4.2 Levelized Cost of Energy (LCOE)

Figure 1.8 [1] shows the relative costs in \$/kWh for a number of generating options over the plant lifetime.

For instance, everything including a large hydro generation costs \$0.04/kWh compared to an offshore wind farm priced at \$0.19/kWh during the lifetime of the plant. The graph also shows the range of the cost for other alternatives. Clearly, the utility may have a hard time selling the wind power in this situation.

$$\text{LCOE} = \sum_{(1-n)} \text{total lifetime cost (\$)} \Big/ \sum_{(1-n)} \text{total lifetime energy production (MWh)} \quad (1.1)$$

The units of LCOE are money/energy (usually \$/MWh or c/kWh[1]).

1 If you want to convert between the two, it is handy to remember that 1c/kWh = 10\$/MWh.

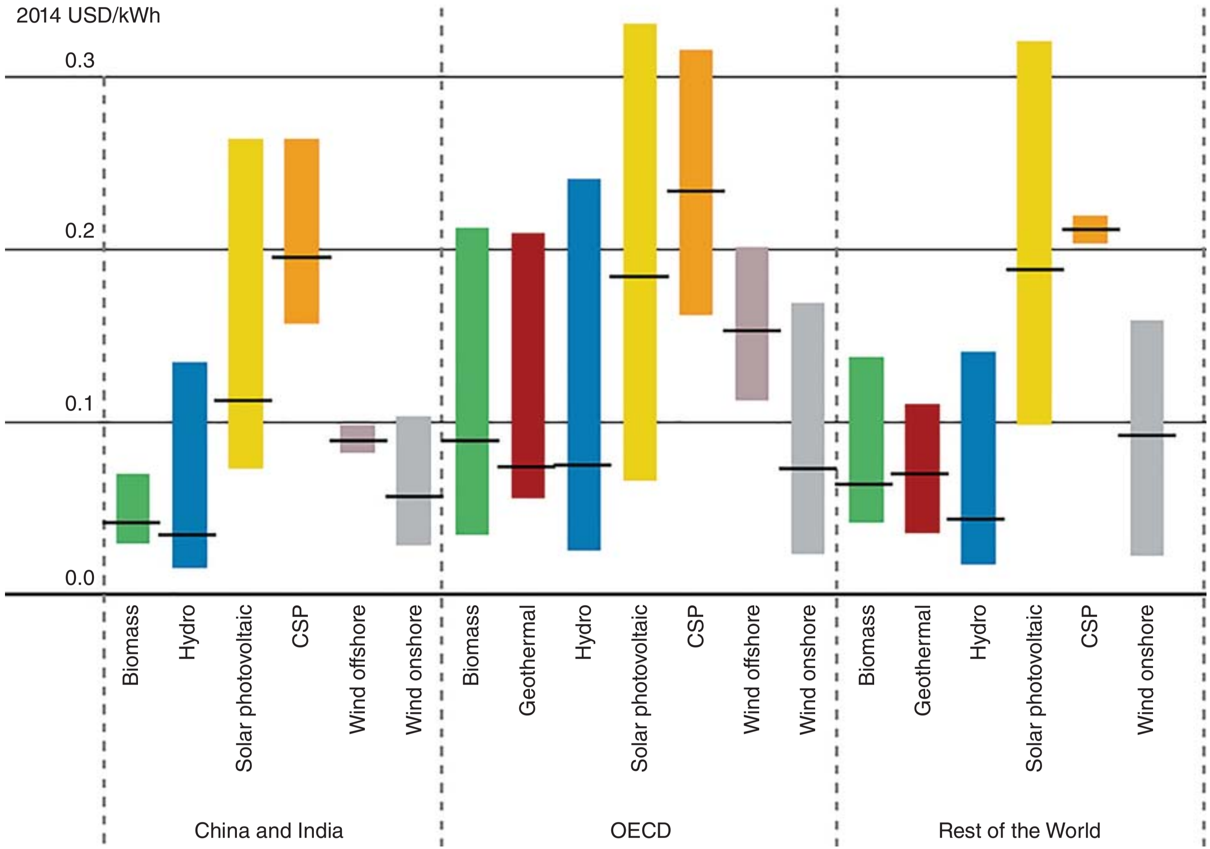

Figure 1.8 Typical LCOE cost ranges and weighted averages for electricity generation. Source: Courtesy of IRENA Publications (2014).

As the name suggests, the "money" part of this equation consists of costs: specifically a summing up of all the costs spent over the whole lifetime (from year 1 to year n) of the project. So this is the money spent building a power plant – at the start, capital expenditure (capex), and a long list of operational expenditure (opex), for example fuel, maintenance and repairs, land lease, insurance, tax, and interest on bank loans. If you can sell your system for something at the end of the project lifetime, you can knock this residual value off your list of costs.

Some projects, such as solar PV and hydro, will involve considerable up-front capex, but followed by years of very low operating cost. Others, such as a gas-fired power plant, will see the majority of spending over the project lifetime during the operating years of burning fuel.

Indeed, levelized cost analysis is all about comparing different energy systems with very different cost structures on a "fairer," long-term basis. Comparing the two examples mentioned earlier, the revenue of the solar PV will depend on how sunny it is and by how much the output of the solar panels degrades over time. On the other hand, the revenue for the gas plant will depend on the capacity factor and how often it runs. The later will be more difficult to predict though, as it will depend on the interplay between electricity sale and gas purchase prices.

1.4.3 Marginal Cost of Energy

The LCOE cost can be considered the average cost of a particular type of generating source. Utilities are interested in the marginal energy cost also. It is the cost experienced by the utilities for the last (peaking) kWh of electricity produced and sold. The marginal cost is highly variable and could vary throughout the day between negative pricing when there is over generation and could increase to hundreds of $/MWh when the demand is high and supply is low. The marginal cost determines the ranking of the type of generating source that will be dispatched. Those with the lowest marginal costs are the first ones to be energized to meet the demand, while the plants with the highest marginal costs are the last to be brought on line.

For example, a wind or solar power plant has no fuel cost and relatively low O&M costs. It yields the lowest marginal energy provided when the sun is shining and the wind is blowing. There is a big difference in production cost whether the plant is generating 1 or 100 MW. Similarly, a gas turbine plant also has low marginal cost if the gas price is low, which it is right now (2017).

1.4.4 Profitability of an Industrial Plant

What is the profitability of an industrial plant? The investor is typically interested in the initial capex and a quick construction schedule to insure a quick loan repayment from the plant operating cost. The investors like to use a simple formula called a "**payback time**." The investor is typically looking at a maximum of five-year payback plan to repay the cost of the initial plant (capex) with the sale of the product, ore, or other merchandize and enjoy a loan and cost-free life thereafter. Naturally, the economics are highly dependent on the commodity prices of the materials produced. Once the project is initiated, the cost estimate follows a more detailed approach.

Reference

1 IRENA: International Renewable Energy Agency (2014). LCOE, Levelized Cost of Energy.

2

Plant Key One-Line Diagram

CHAPTER MENU

Practical Power Plant Engineering: A Guide for Early Career Engineers, First Edition. Zark Bedalov.
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2.1 One-Line Diagrams

Designing a **Key one-line diagram** is the most important task in the development of an electrical system for a power or an industrial plant. This diagram is a result of the key decisions made by the engineers working on the project. This book devotes significant time in explaining the electrical components, which are fundamental in building the functional electrical one-line diagram.

The one-line diagram represents the electrical power distribution formed to suit the technological process for the proposed project (see Chapter 1). The electrical engineers must focus on acquiring information on the type of process, load magnitude, load centers, quality and availability of power, power loss tolerance, and required plant reliability.

The *key* one-line diagram prepared at the initial stage of design will be conceptual in nature. It will encompass the other one-line diagrams for the specific parts of the plant. It will serve for discussions, cost estimates, and to offer the other design team engineers a basis for their equipment selections. Figure 2.1 is not a “key” diagram, but a part of a plant one line diagram.

The design procedure in this chapter is described in light detail to arouse interest of the electrical engineers in the design and operation of electrical systems for industrial manufacturing and power plants. More clarifying details related to the specific equipment specifications, applications, and reasons for their selection can be found in the chapters that follow.

2.1.1 What Is the One-Line Diagram, or Single-Line Diagram?

Mechanical engineers have their “flow diagrams.” Electrical engineers have their single-line diagrams showing the electrical power flows and plant overall integration. As the name implies, it is the principal electrical diagram or our big picture of the plant or specific part of the plant, whereby the three phases are represented in a simplified single-line form. The diagrams show all the

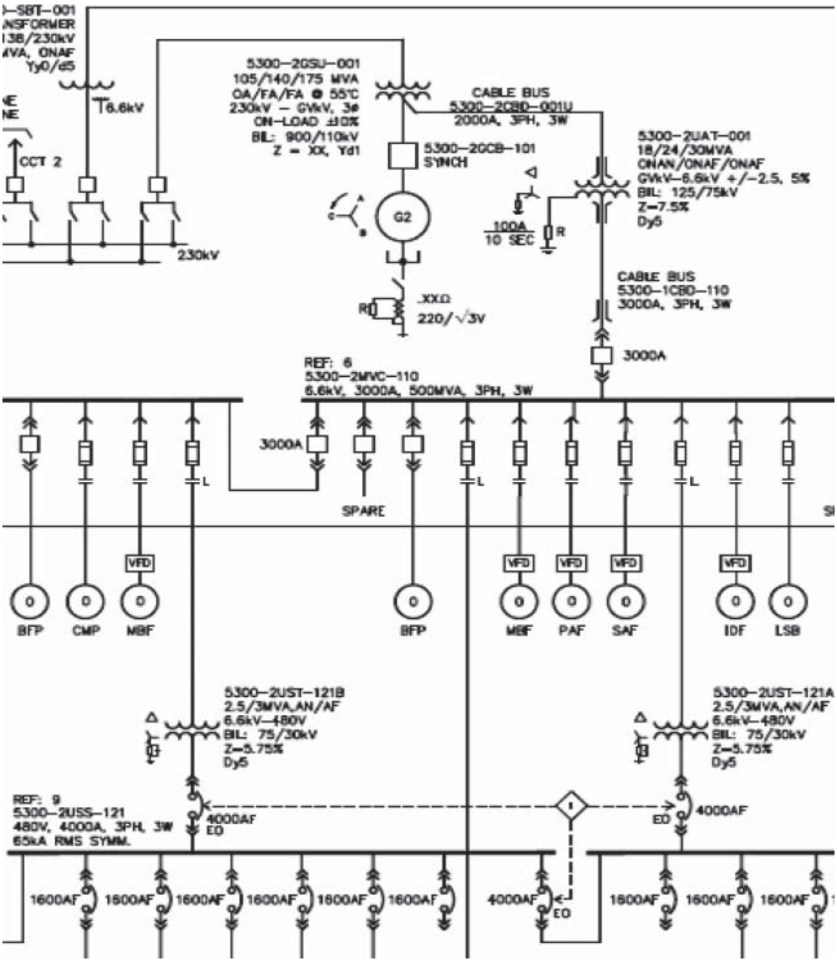

Figure 2.1 Part of a plant one line diagram.

major transformers, loads, circuit breakers, and cables or line connections, including the ratings: kW (HP), MVA, V, A, AWG (mm^2), leading to the major plant equipment. The key diagram includes references to the partial more detailed one-line diagrams for the specific process areas. One medium size industrial plant may have 20 individual one-line diagrams starting from the key one-line diagram down to the individual MCC 480 V (400 V) diagrams.

Decisions must be made on the main switchyard, the number of incoming transformers, and the selection of the plant busbar voltages for distribution of power to the major load centers for large and small loads and primary and secondary power lines to remote plant facilities.

Note: The voltages and frequency applied in this book will be those of the North American standards. The principles of calculations and application used here are equally applicable to the IEC system voltages used in the other parts of the world.

2.2 The Electrical Project

The activities presented in this book, some of it in this chapter as part of the electrical design, include the following:

- Determine the site conditions and discuss the interconnection with local Utility.
- Review of mechanical load flow diagrams, P&D diagrams and establish load (kW) estimates and voltage levels.
- Prepare one-line diagrams and plant design criteria.
- Conduct system studies and determine electrical equipment ratings.

As the starting point, the mechanical engineers will develop 10–20 flow diagrams of the plant process. A small part of the ore handling flow diagram is shown in Figure 2.2. The process (instrumentation) engineers will develop 30–40 process piping and instrumentation diagrams (P&ID) to instrument and automate the plant, as shown on a small P&ID segment in Figure 2.3 for a feed pump. The P&ID gives us the indications on how the plant will be controlled, monitored, and operated.

As a young design electrical engineer you have been assigned to be a part of a multidiscipline engineering team responsible to develop a project estimated to consume about 30 MW of power, or 37.5 MVA at 0.8 power factor (pf). The design team of electrical engineers and draftsmen led by an experienced senior

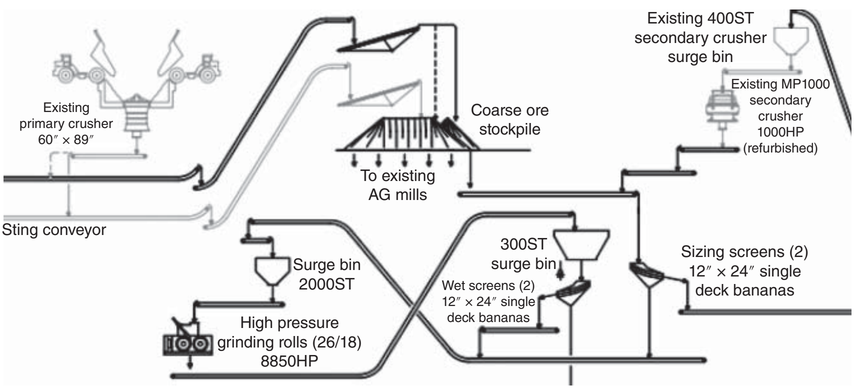

Figure 2.2 Part of plant flow diagram.

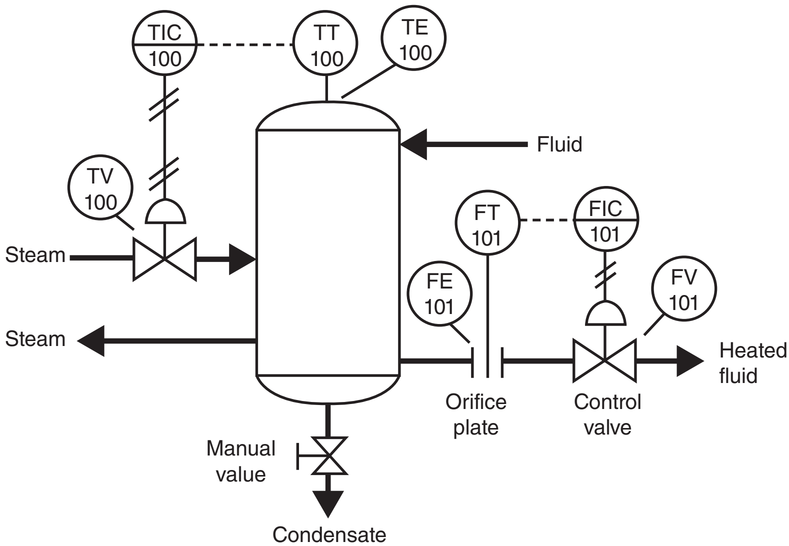

Figure 2.3 A part of a P&ID diagram.

lead electrical engineer is responsible to design the electrical power distribution system and procure the electrical equipment to power up and control the plant equipment. The plant distribution system will follow the national standards and voltages for 60 Hz (50 Hz) frequency as applicable to the location of the project.

The principal operating item in this facility and the biggest electrical load is a large 10 MVA semi autogenous grinding (SAG) mill operated as a variable speed drive cyclo-converter. It receives the ore from the crushers, as 10–20 cm chunks of raw material and reduces it to 1–2 cm large gravel. The mill speed is regulated in accordance with the hardness of the ore, which may vary on a daily basis. This material is then conveyed to ball mills, which pulverize the product to allow it to be mixed with water and pumped around as slurry through the rest of the plant. The slurry will be then subjected to some chemical treatment processes to separate the metal from the ore.

What is the operating basis for this project? The owner will look at operating the plant 24 hours a day to maximize his early output in order to quickly pay off the loan to the financial institution. The only way to do that is to run the facility around the clock in two 12-hour shifts. This operating regime is also favored by the local utility, as it allows them to run more generation around the clock as less costly base load and flatten the load cycle.

A housing complex for 100 people will be built at a site about 3 km away from the main process plant for the workers to build and operate the plant. This is an area away from the plant crushers. Operators are happy to work long shifts seven days a week on a basis of three weeks in and one week out. The housing complex (camp) will be a continuation of a construction camp for 300 people, which will be used for a full year prior to the start of production.

2.3 Site Conditions

2.3.1 Source of Power

Let us assume, the local utility has just built a new power plant on the coast, about 120 km away from the ore deposit and have extended a 230 kV transmission line to a city 50 km away from the deposit. This is the line to which the plant will be connected to. The line passes 20 km by the proposed mining site. To further simplify the matters, we will assume that the utility has sufficient spare capacity and is happy to furnish power to the new facility. This is a fortunate situation as it makes it feasible to import the power instead of generating it on its own.

The plant load will be relatively constant with ±10% variability. Utilities love constant load, which they can supply as a base load. The base load energy is less costly to produce in $/MWh.

The plant's electrical distribution system must operate in a stable manner within the prescribed tolerances of voltage and frequency as stipulated by the standards, in spite of the load variations. The load may be subject to changes, both MW and MVAR, caused by the operating cycle and duty of the plant large motors.

The plant owner must determine, based on the history of operation of the generating plant, if the source of power is reliable enough to meet the plant requirements. The plant process can tolerate short power outages without detrimental effects, but longer outages would be a concern with respect to the economies of the plant production.

Studies will have to be made to find out if a wind farm or a solar plant could be economical and possibly developed in the vicinity to supplement the imported power.

2.3.2 Ambient Derating Factors

The electrical equipment will be operating at an altitude of 1700 m. The equipment shall be derated for the altitude in accordance with the applicable ANSI C57.40 and IEC 282-1.2 standards. The following derating factors are applicable for the 1700 m site altitude:

Voltage: 0.93
Current: 0.99

The voltage derating will be factored by the suppliers of the equipment, such as switchgear, transformer bushings, to ensure the equipment insulation is designed for lower air density at the specified altitude. The current (ampacity factor) derating for the plant cables is not significant, well within our conservative plant selection estimates.

Applicable ANSI or IEC standards for ampacity derating factors will be used for the power cables buried or installed in multiple duct banks, also discussed in Chapter 12.

The other site ambient conditions, such as road conditions, minimum/maximum temperatures, humidity, rainfall, number of lightning days, are normally included in the tender document for the vendors to design the equipment accordingly.

2.3.3 Reliability Criteria

Before we start putting things together, let us clarify the design reliability criteria, discussed in Chapter 21.

In order to ensure adequate availability and continuous plant operation, the power distribution system must be designed to tolerate and override certain failures of the equipment. Generally, the system will be designed for "a single contingency failure" of the principal distribution equipment. This is sometimes called "a single outage contingency." In other words, the design will fully cover for a single failure of one major piece of equipment, such as transformer, pump, motor, but not for a simultaneous failure of two pieces of similar major equipment.

Therefore, each pump system, which is considered a critical primary part of the operating plant shall include $2 \times 100\%$ units. In some cases, for larger pumps, $3 \times 50\%$ pumps could be used. For sump pumps, roof fans, heating, ventilating air conditioning (HVAC), etc., which are considered the plant auxiliary services, there shall be no immediate substitutes. The switchgear busbars from the plant distribution transformers will be bussed together through bus tie breakers to allow for feeding the plant loads from a single transformer, in case of an outage of one transformer. Failure of some smaller distribution transformer may be tolerated by reconnecting the load to alternate sources of power supply.

Recovery from power outages will be either by having spares cable connected or piped, or by switching capability to feed power from alternate sources such as closing the bus tie circuit breaker.

No contingency consideration will be given to the failures of power cables, lines, or pipes, which can be replaced or fixed relatively quickly, except for the high voltage (HV) single conductor cables used in power plants for 138 kV and higher, where one additional spare phase is added and laid out next to the operating cables. Therefore, during the plant design, one may ask: "What if…?" But not: "What if…, and if…?"

2.4 Connection to Power Utility

The investors will likely not be interested in building this industrial facility unless they have spoken to the utility and were assured that there is available generating capacity to power the project.

Let us talk to the Utility to acquire the information we need to build our plant power distribution system. Here are some of the issues to be clarified by the Utility engineers:

- Power agreement: firm or interruptible
- Tariffs, for power demand and time of use
- Line voltage and its daily and weekly profile
- Frequency off-limits
- Power factor tariffs and penalties
- Source impedance, inclusive of the transmission line impedance (conductors)
- Double- or single-circuit incoming transmission line
- Generating capacity, firm power, how many units are available, and their ratings
- Method of line protection
- Lightning level (number of lightning days/yr) in the area

Let us review each of the aforementioned issues:

Power agreement: The plant owner will sign a power agreement with the Utility. If the plant needs power 24 hours a day, every day, the owner will look at signing a power agreement for uninterruptible firm power supply, if available. An interruptible power supply allows the utility to occasionally cut the power supply in a specific amount or in total. Naturally, this contract comes with a lower tariff. The plant owner will likely insist on an uninterruptible power supply (UPS).

Tariffs: In addition to the nominal charge for kilowatt-hour consumed, the utility will likely have additional tariffs as demand charge, peak load, and reactive power hour consumption (MVARh consumption). The demand is the load averaged over a specified time (15 minutes, 30 minutes, or 1 hour) in kW or KVAR. The peak load may be the maximum instantaneous load or a maximum average load over a designated period of time. The reactive energy charge may be applicable for the load operating at <95% power factor at the point of interconnection (POI).

Voltage operating range: For this plant, 69, 138, and 230 kV voltages can be used. In this case, 230 kV is available and preferred. We have to determine the percentage range of voltage oscillations received from the utility and how stable it is. The next thing is to decide if our plant will need an automatic on-load tap changers (OnLTCs) on the main incoming power transformers, or simple off-load tap changers (OffLTCs). See a typical transformer in Figure 2.4.

Figure 2.4 Large oil filled transformer.

Assume a 20% adder to the cost of a transformer with an automatic tap changer. On the other hand, an automatic LTC can, in addition to keeping the plant voltage constant, better regulate the flow of power and save us some money in penalties charged by the utility for the low plant power factor.

If the voltage swings are large, OffLTC changers may not be able to provide a manageable operating solution. They can regulate the plant voltage manually to a preselected percentage tap, while the OnLTCs manage the plant voltage automatically and linearly to the full tap range of ±10% on the primary winding.

If OffLTCs are employed, the operator will have to shut down the plant in order to change the taps, if desired. Naturally, manual tap changes cannot be performed on a regular daily basis. Voltage at night may be higher than during the day. So once you set the taps, that is it. You may be forced to change the tap settings again if the operating conditions alter.

Suppose, you have decided that your incoming transformers are to be rated 230 to 13.8 kV. Also, you were informed that the incoming voltage from the utility varies from 215 to 245 kV, but most likely toward the lower range (see Chapter 24 for more details on transformers).

Let us examine in Table 2.1 the voltage range at the secondary side of the transformers with OffLTCs for the various taps and voltage swings:

Transformer voltage: 230 to 13.8 kV
Taps on primary side range: ±10% in 2.5% steps.

Based on the aforementioned, a choice would be to operate the transformer with OffLTC at −2.5% taps for the primary voltage range of 215–245 kV. Negative taps on the transformer primary winding are the taps of choice used for boosting the plant 13.8 kV voltage. On the other hand, the OnLTC, if used, will maintain voltage relatively steady in smaller tap movements within the full tap range.

Table 2.1 Secondary voltage for primary grid voltage.

Grid voltage	215 kV	230 kV	245 kV
Taps set at:			
−5.0%	13.54	14.48	~~15.42~~
−2.5%	12.98	14.14	15.05
0	12.89	13.8	14.69
+2.5%	12.57	13.45	14.32
+5.0%	~~12.25~~	13.10	13.95

Most of the industrial plants would purchase transformers with OffLTCs. In this case, based on the discussions with the utility and due to the expected significant variations in the day/night voltage profile, we would prefer transformers with automatic OnLTCs to make sure we have a stable voltage in the plant at all times.

The plant voltage profile is not determined solely by the utility but also by the plant motor load. Plant reactive MVAR load will likely have to be partly drawn from the utility, as explained in Chapter 13.

The smaller plant transformers, which distribute power to lower voltages, will generally have (±5%) OffLTC tap changers. Taps for each transformer will have to be set to obtain the most comfortable voltage profile throughout the plant during the normal plant operation and for large motor starting. This can be determined by a computer **load flow study** and confirmed during the plant operation. With the choice of **OnLTC** on our main transformers, we can consider that our plant distribution voltage will be relatively constant at 13.8 kV at all times, irrespective on what the utility throws at us.

The typical voltage drop criteria to be considered in the design of the plant distribution system is <15% for large motor starting, and <3% for large motor while running.

2.4.1 Source Impedance

This is the system *subtransient* impedance Z'' representing the generating capacity of the utility at the POI. It also includes the impedance of the interconnecting transmission line. The source impedance is derived from the short-circuit level at the plant as advised by the utility. The figure given will likely be based on a present and future generation planned by the utility. This value will be used as the base for determining the interrupting ratings of the plant circuit breakers that connect to the transmission line and the voltage regulation and capability of the plant large motors to start properly.

We have to determine the source impedance for two different extreme cases, the maximum and the minimum values, as follows:

- The maximum source impedance (minimum fault level) when the utility is operating on light load with a minimum generating capacity connected to the grid. This source impedance will be used for voltage regulation calculations and large motor starting duty. If the supply network is weak (low short-circuit level), soft, or variable frequency starting may be required for starting large motors in order to satisfy the utility flicker requirement and to minimize the impact on other nearby customers connected to the grid.
- The minimum source impedance (maximum fault level) is when the utility is operating on high load with maximum generating capacity. This impedance will be used to determine the short-circuit interrupting duty of the plant circuit breakers.

For our system studies and calculations, we will use $MVA_b = 30$ MVA figure as our per unit MVA base. This is the *base* rating of our main incoming transformers: 30/40 MVA, 230 to 13.8 kV.

2.4.2 Line Conductor

We received the conductor (name) information from the utility. It will be a single Hawk ACSR (aluminum conductor steel reinforced) conductor. The overhead conductors are symbolically called by the names of birds. The data for the Hawk conductor can be obtained from online sources. The best source of data for the conductors is the old T&D Westinghouse handbook, from which we find the following data:

Hawk
Type: ACSR, 477 kcmil
Stranding: 26/7
Ampacity: 660 A
Resistance: 0.135 Ω/km
Inductive reactance: 0.24 Ω/km
Capacitive reactance: 0.188 Ω/km

The Hawk line carrying capacity is well in excess of our plant requirements. Utilities like to build lines with sufficient capacity for future expansions. The maximum expected current from the plant at 230 kV is 100 A at 40 MVA. The line length from the plant to the local utility source of generation is estimated at 120 km.

➢ Calculate the line parameters in pu for the system studies:

$$R_{\text{line}} = 0.135\ \Omega/\text{km} \times 120\ \text{km} = 16.2\ \Omega$$

Now, calculate line characteristics in pu

$$R_{\text{line pu}} = R_{\Omega} \times \frac{\text{MVA}_{\text{b}}}{\text{kV}^2} \text{ or } R_{\Omega} \times \frac{\text{kVA}_{\text{b}}}{1000 \times \text{kV}^2}$$
$$= 16.2 \times \frac{30}{230^2} = 0.009 \text{ pu or } 0.9\% \quad (2.1)$$

$$Xl_{\text{line pu}} = 0.24 \times 120 \times \frac{30}{230^2} = 0.016 \text{ pu}$$
$$= 1.6\% \text{ Line inductive reactance in pu}$$

$$Xc_{\text{line pu}} = 0.188 \times 120 \times \frac{30}{230^2} = 0.0125 \text{ pu}$$
$$= 1.25\% \text{ Line capacitive reactance in pu}$$

➢ Convert line characteristics (pu) from one MVA base to another:

$$\text{From MVA}_{\text{b1}} \text{ to MVA}_{\text{b2}} \rightarrow R_{\text{pu b2}} = R_{\text{pu b1}} \times \frac{\text{MVA}_{\text{b2}}}{\text{MVA}_{\text{b1}}} \quad (2.2)$$

$$\text{From MVA}_{\text{b2}} \text{ to MVA}_{\text{b1}} \rightarrow R_{\text{pu b1}} = R_{\text{pu b2}} \times \frac{\text{MVA}_{\text{b1}}}{\text{MVA}_{\text{b2}}} \quad (2.3)$$

➢ Convert line characteristics (Ω) from one system voltage kV base to another:

$$\text{From } V_{\text{b1}} \text{ to } V_{\text{b2}} \rightarrow R_{\Omega\,\text{b2}} = R_{\Omega\,\text{b1}} \times \frac{V_{\text{b2}}^2}{V_{\text{b1}}^2} \quad (2.4)$$

$$\text{From } V_{\text{b2}} \text{ to } V_{\text{b1}} \rightarrow R_{\Omega\,\text{b1}} = R_{\Omega\,\text{b2}} \times \frac{V_{\text{b1}}^2}{V_{\text{b2}}^2} \quad (2.5)$$

The utility "informed" us that fault level at our plant bus, projected for the future with possible expansion is **10 kA at 230 kV**. This is calculated approximately as: $\text{MVA}_{\text{sc}} = 4000$ MVA.

Therefore, we can now calculate the **source impedance** at our 230 kV bus as follows:

$$X_{s\,\text{pu}} = \frac{\text{MVA}_{\text{b}}}{\text{MVA}_{\text{sc}}} = \frac{30}{4000} = 0.0075 \text{ pu or } 0.75\%$$

Or pu source impedance if kA fault interrupting current from the source (power utility) is given:

$$X_{s\,\text{pu}} = \frac{\text{MVA}_{\text{b}}}{\sqrt{3} \times \text{kA} \times \text{kV}} = \frac{30}{1.73 \times 10 \times 230} = 0.0075 \text{ pu, or } 0.75\%$$

This source impedance will be used in our computer studies to represent the utility at our plant point of interface. It is a conservative value that will provide plenty of margin in our calculation.

However, for our quick hand calculations and for our interrupting ratings of the switchgear, we will rate our equipment on a conservative basis of an infinite fault level from the utility (zero source impedance). Therefore, the utility can now be called an Infinite bus at the point of interface with our plant.

If we now calculate the fault MVA_{sc} from the Utility on our selected MVA_b base, it is:

$$MVA_{sc} = \frac{MVA_b}{Z_s} = \frac{30}{0} = \text{Infinite MVA}$$

2.4.3 HV Circuit Breaker Fault Interrupting

Now we can determine the incoming 230 kV breaker as follows: It has to have interrupting capacity of at least 4000 A. We select 3 phase, 245 kV, 1200 A, 40 kA fault interrupting, basic impulse level BIL: 1050 kV peak (see Figure 2.5).

Why 40 kA? This may sound too excessive for our requirements, but these are the ratings at the low end for the 230 kV equipment.

The transformer differential protection scheme and metering would need current transformers (CTs) on the grid side of the HV breaker.

2.4.4 Double or Single Incomer Connection

The 30/40 MVA plant can be connected to the incoming utility transmission line with one or two transformers. This will depend on the plant reliability

Figure 2.5 245 kV circuit breaker.

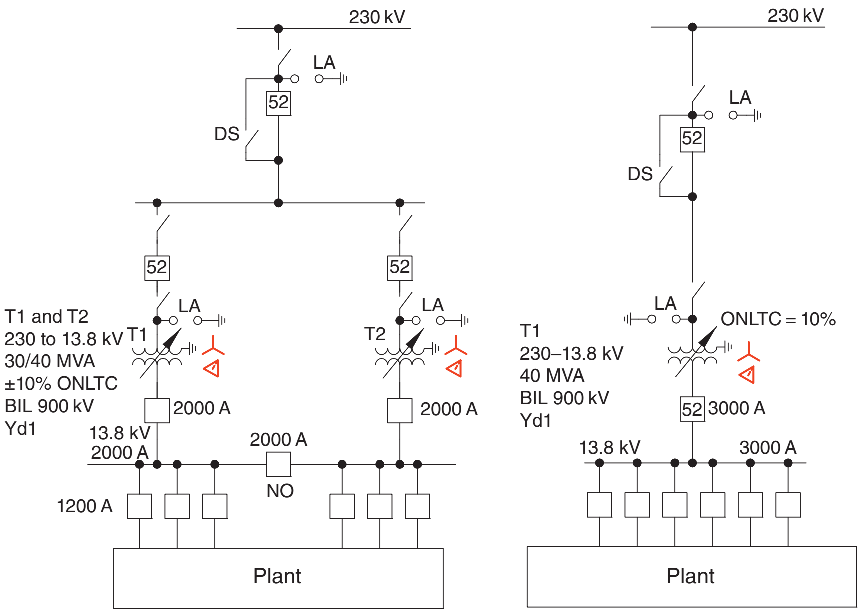

Figure 2.6 Double and single incomer diagram.

requirements. Earlier we determined that the plant must meet the "single contingency criteria." Therefore, we conclude that the plant will be connected to the grid with two transformers (two incomers). Each transformer must be capable of carrying the full load of the plant. Figure 2.6 shows the substations diagrams with two and single incomers for the same plant. A switchyard with a single HV breaker would not meet our reliability criteria of full redundancy for the plant operation. This is mainly because a major transformer failure may cause a total plant shutdown for an extended period of time.

The transformers in our 30/40 MVA plant will be required to share the plant load, but each will also be capable of carrying the full load of the plant on their ONAF cooling in case one transformer fails.

Double power entry will be more reliable, though considerably more costly. A substation with two transformers, in addition to more HV switches will need three incoming HV circuit breakers to feed the two transformers. This substation will also require considerably more space.

For a smaller plant of up to 10 MVA, a single HV incomer may be considered acceptable as the cost of the HV breakers and two transformers might be excessive in comparison with the cost of the plant. In fact, a single incomer switching yard may include nothing more than a single H frame pole structure.

To support a smaller plant, several diesel generators (DGs) can be brought to site in trailers to temporarily replace a faulty transformer.

2.4.5 Utility Generating Capacity

This information we require to be able to determine if our plant will need some supplementary firm generation at site and also if we would be able to expand the plant in the future in case our ore body miraculously doubles up. We will look into a possibility of having a solar plant or a wind farm to augment our power sources. The solar and wind resources cannot be counted in as firm capacity, but simply as a source of power to displace the fuel consumption or import of power (see Chapters 25 and 26).

2.4.6 Firm Capacity

This term is used in generation to determine the overall available MW capacity not considering one unit (single outage failure); therefore, a power plant with two units of 50 MW each has a firm capacity of one unit (50 MW). That is one generator unit out of two units, or two out of three units. Therefore, a firm capacity of a generating plant is the available generation MW capacity not counting one unit which is held as spare. Firm capacity of a transmission line is defined as one out of two circuits. A single circuit line has no firm capacity.

2.4.7 Line Protection

Utilities use specific protective relays and have definite strategies for the line protection: two to three zone distance, negative sequence, etc. The utility will likely ask us to match the protection relaying at our end to that of their end and to coordinate the settings between the two ends. The line protection will likely be by pilot differential relaying with fiber optic communications.

2.4.8 Lightning

We can look at the historic data of the lightning days/year in the area. The plant may be in a desert environment with a low isokeraunic level or in some mountainous region of high lightning intensity. Hopefully, we can obtain this data from the utility and design the switchyard and the overhead lines accordingly with appropriate overhead shielding, grounding, and lightning arrester protection (see Chapter 10 for more details).

2.5 Main Plant Substation

Question? What is the difference between a switchyard and a substation? Is there a precise definition of one and the other? I have never heard one. In my circles, we called a facility with HV switches, circuit breakers, and transformers a substation. A switchyard was the same, but without transformers.

The main substation on this project will contain a number of major items of equipment: transformers, HV switches, HV circuit breakers, arresters, and protection panels as well as medium voltage (MV) switchgear connected to the low voltage side of the transformers. Specifications must be urgently written for the long lead items. In this substation, the transformers should be given a priority. Large transformers are long lead items, requiring 12—18 month delivery plus the procurement time. Transformers rated up to 10 MVA can be obtained within nine months. Often, large transformers may be purchased ahead of time with a provision of being cancelled if the project is not approved to proceed. To purchase the transformers, we need know: plant load, future load, voltages, and method of cooling.

Based on the projected load estimate let us assume the main transformers will be oil immersed/forced air cooled, as follows: two (2) 230 to 13.8 kV, 30/40 MVA, YNd1, ONAN/ONAF/ONAF(prov.), BIL 900 kV, 55 °C rise at 40 °C ambient. We will explain the details later.

For our plant, each transformer must carry 30/40 MVA on ONAN/ONAF/ONAF cooling. Each stage of fan cooling adds about 15% capacity to the base rating. In addition, we can specify the transformer to have a 55/65 °C temperature rise allowance. A transformer rated at 55 °C rise has about 10% spare MVA reserve over a transformer rated 65 °C rise of the same MVA rating. Obviously, a 55 °C transformer is built to a more efficient cooling design.

We choose a single ONAF cooling stage, including a provision (prov.) for adding additional stage of cooling fans if necessary in the future.

Remember, the transformer base rating is 30 MVA. This value will be used in the study calculations.

What are the designations for the transformer cooling?

ONAN: Oil Natural Air Natural → Without fans.
ONAF: Oil Natural Air Forced → With fans.

The transformers will be furnished with a conservator tank and all the standard auxiliaries. We noted the winding configuration as YNd1. Star Primary, HV Neutral solidly (effectively) grounded, Delta secondary, lagging 30° in counter clockwise (CCW) convention. The most popular winding configurations in the industry for high voltage (HV) transformers at 230 kV and above are Yd1 and Yd11.

Transformers up to 10 MVA can be ordered as "sealed tank design," without a conservator.

The main and plant oil immersed transformers will be placed outside, next to the plant buildings in their independent vaults with oil containment basins. The walls of the vault will be fire rated (see Chapter 4 for the NFPA guidelines). The main transformers will be provided with the Deluge water mist protection system (see Chapter 22).

Furthermore, we decided that the transformers would have OnLTC in the range of ±10%. As we are 120 km away from the power plant, the voltage may not be stable. Daily 24-hour load cycle will vary from hour to hour. The automatic tap changers will give us some form of voltage stability for the plant operation. We may also need some additional means of voltage regulation within the plant to enable us to further improve the voltage profile through power factor correction. To meet this requirement, additional capacitors and reactors may be considered (see Chapter 13).

2.6 Load Site Placement

At this conceptual phase of the engineering design, we have to determine the locations of loads within the plant as well as their kW ratings to determine the major power routes of the distribution system. Depending on the kW load magnitudes, we will determine the corresponding voltages for the distribution equipment.

Loads (motor and feeders) up to 200 kW	480 V, Motor voltage: 460 V
Loads (motors with VFDs) up to 500 kW	480 V, Motor voltage: 460 V
Loads above 200 kW	4.16 kV, Motor voltage: 4000 V

We will obtain the load data from our mechanical engineers. Roughly, we expect that the plant-connected load will be about 50 MW. The mining load is typically a motor load with 0.8 pf, but with power factor correction, we will get it over 0.9. This MW figure is assessed generally from the plant flow diagrams, based on the hardness of the ore, raw material processed, and product produced. In their flow diagrams, mechanical engineers may suggest a kW (HP) rating figure for each motor. However, the final kW (HP) ratings will be taken from the actual bids received from the suppliers. The tendency seems to be that suppliers more often overestimate rather than underestimate the load.

From the plant layout drawings, we determine the locations of the groups of loads: mining, crushing, conveying, grinding, process plant, tailings, and camp. The load centers will generally follow the flow of the ore. These locations may be kilometers apart from each other. The biggest groups of loads will be in the grinding and the process plant for conveying, pumping, agitation, and floatation. The camp, crushing, and tailings will be away from the process plant.

The power load centers may include either 480 V loads only, or both: 4.160 and 480 V.

Typical 4.16 kV controllers for large motors are rated at 400 A. Controllers rated 800 A are also available, but rarely used. Let us calculate the current of a

2000 kW, pf = 0.8 motor and verify if a 4.16 kV, 400 A controller can operate it safely:

$$\frac{2000}{1.73 \times 0.8 \times 4.16} = 347 \text{ A} < 400 \text{ A. OK!}$$

The power will be fed from the main substation to the plant load centers by 15 kV overhead lines or medium voltage (MV) cables, depending on the relative location of the main substation. In North America, the 13.8 and 4.16 kV voltages are often called 15 and 5 kV, respectively.

2.6.1 Crushing

This facility may be close to the grinding plant, but at a certain distance, to limit the dust spreading to the rest of the plant. Also a large (seven-day) ore stockpile will be placed between the crushing station and the grinding plant. Crushing usually operates a single 12-hour shift, while the rest of the plant marches on two shifts. A load center will be required to feed the 4 kV and 460 V motors. We will use 1.5 MVA transformers (13.2 kV/480 V or 4.16 kV/480 V) with MV controllers for motors >200 kW and 480 V MCC starters for motors rated ≤200 kW.

2.6.2 Grinding and Conveying

This is the location of the largest load, the 8 MW, (10 MVA) cyclo-converter motor. This load is too big for 4.16 kV and must be powered at 13.8 kV. It will have its own power feeder fed directly from the main 13.8 kV switchgear located at the main substation. For this variable frequency drive (VFD), the main power supply is converted to DC voltage and then back to AC voltage of varied frequency to operate at variable speed to suit the ore quality and hardness. This large piece of equipment is a complete package. It includes a number of smaller auxiliary loads, such as MCC, fans, lube pumps, lighting, and heating, all of them fed from the same power source feeder.

The grinding facility will also need a 4.16 kV load center for MV motors (Ball Mills) and a number of load centers for a large number of low voltage (LV) motors and drives. Drives mentioned here are typically referred to as the VFD operated motors. Two grinding ball mills may even use synchronous MV motors, which by controlling their excitations may help us improve the plant power factor (see Chapter 13).

The MV load center with 5 kV switchgear and MV motor controllers will be fed from two 13.2 to 4.16 kV, 10/15 MVA, Dy11, ONAN/ONAF, oil type transformers, which will be placed outdoors adjacent to the plant and have a joint provision for oil containment.

Oil containment is a concern in the plant due to a fire hazard. Dry transformers for feeding smaller loads are preferred due to their flexibility to be