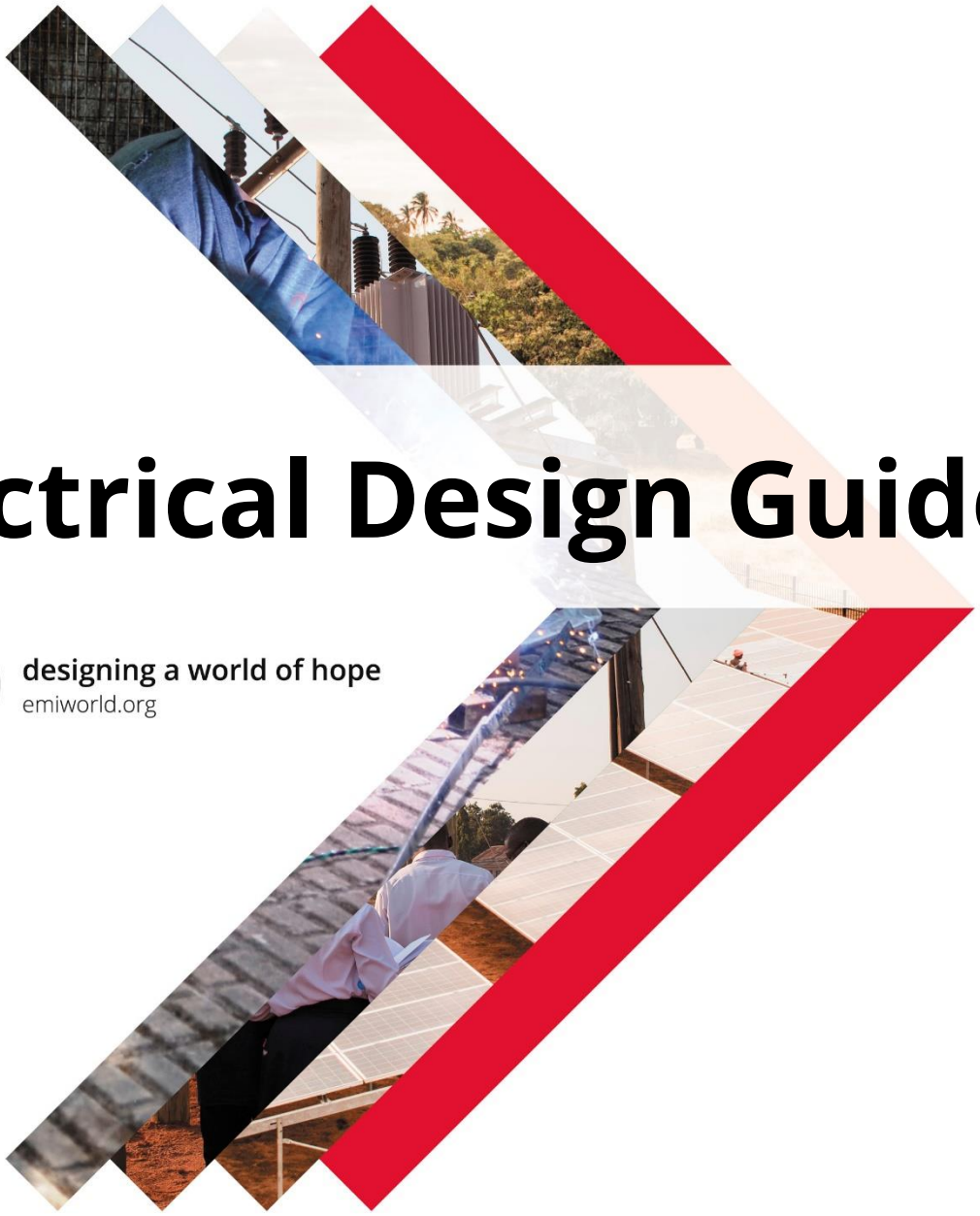


Electrical Design Guide

designing a world of hope
emiworld.org

Developed and Compiled by:
Engineering Ministries International

Revised: December 2019

Introduction

EMI Design Philosophy

Engineering Ministries International (EMI) is a Christ-centered nonprofit organization that serves charities and disadvantaged communities around the world through technical assistance in architecture, engineering, surveying, and construction management.

Our core value of design is:

EMI works within the local context to design and construct culturally appropriate facilities that are sustainable, affordable, and transformational.

In support of this, EMI publishes Design Guides based on the experience of project teams and in-country staff. These Guides equip EMI designers to approach their project work in a way that keeps the goals of EMI's core value of design in full view.

You are invited to explore this Design Guide as you prepare for a project trip or conduct design work in an EMI office.

Thank you for helping design a world of hope!

Guide Features

This document is augmented by a great amount of supporting material. In the web-based version, these other documents are hyperlinked, but care has been taken to describe the references so that the user may find them manually in the event that links are unavailable or changed. The user should ensure to have the entire and latest **EMI Electrical Design** folder, which includes the *Electrical Design Guide.pdf* (this document) and all supporting files, to include:

- The **EMI Design Tools** sub-folder contains worksheets and questionnaires that that support the design process and document research. The sub-folder contains templates that are formatted to EMI-standards and pre-populated with sample data. These are intended to be copied to a project folder and modified for specific projects.
- The **References** sub-folder contains reference material that supports the activities discussed in the Guide.

Disclaimer

It is expected that the reader possesses the education/training to apply this information safely and properly; this Guide is not a substitute for professional expertise.

EMI works in many countries with no established electrical code. Therefore, this document is written to comply with the **NFPA 70® National Electrical Code® (2017)** whenever possible. For specific projects, any governing codes applicable to the site location take priority. Installation shall follow the latest edition of those codes regardless of any specifications explicitly or implicitly set forth in this document.

Determining Scope of Work

As part of project planning, EMI staff will determine the scope of work to be accomplished on each approved project. Trip leaders must then determine the necessary electrical work needed to support the overall project objectives and communicate it to the electrical designer(s) selected for the trip. Table 1 will assist planners in determining the necessary deliverables/analysis for specific projects based on the level of design (conceptual vs. detailed) and type of site (undeveloped or "greenfield" vs. modification to existing buildings).

Contributors

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Table 1: Electrical Design Deliverables by Project Type

Deliverable	Section	Greenfield		Existing Site		Notes
		Conceptual	Detailed	Conceptual	Detailed	
Client Needs Assessment	1.1 & 2.1	✓	✓	✓	✓	Client questionnaire, confirmed with on-site interviews
Initial Site Evaluation	2.1, 2.2	✓	✓	✓	✓	Varies by site type
Grounding System Evaluation	2.3	✓	✓	✓	✓	Requires specialized equipment
Power Quality Analysis	2.4			✓	✓	Requires specialized equipment
Single Line Diagram, Existing	3.1			✓	✓	
Single Line Diagram, Proposed	3.1	✓	✓	✓	✓	
Electrical Site Plan, Existing	3.2			✓	✓	
Electrical Site Plan, Proposed	3.2	✓	✓	✓	✓	
Electrical Load Study	3.3.2	✓	✓	✓	✓	MS Excel-based analysis
Voltage Drop Calculation	3.3.3		✓	✓	✓	Included in above
Lighting & Power Designs	3.3.1		✓		✓	Generally accomplished post-trip or contracted to local contractors
Panel Schedules & Design	3.3.5		✓		✓	
Energy Source Analysis	4	✓	✓	✓	✓	MS Excel-based analysis
Outbrief & Project Report	5.1 & 5.2	✓	✓	✓	✓	Coordinated with other team members
Training	5.3		✓		✓	Subsequent trips or remote support
Contractor Selection/Oversight	5.4		✓		✓	

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1. Pre-Trip Preparation

The work for a successful trip begins well before leaving home. Prior to embarking on an EMI trip, the electrical designer must conduct research regarding the project and prepare to maximize the limited time spent onsite. This can begin as soon as the trip leader has determined the scope of work for the project (refer to Table 1).

1.1. Pre-trip Research

The *Pre-Trip Research --Electrical* worksheet will guide this research and should be archived after the trip as background information. Much of the data can be found online using the site location (either address or Lat/Long). For country-specific electrical information use a website such as:

- https://www.worldstandards.eu/electricity/plug-voltage-by-country/

For regional energy source selection information use websites such as:

- https://www.altestore.com/howto/solar-insolation-map-world-a43/
- https://www.globalwindatlas.info/
- https://www.gaisma.com
- https://www.globalpetrolprices.com

In order to accurately assess the client's needs, prepare a questionnaire to be sent to the client via the trip leader. The following are options depending on project type, which should be tailored for the specific project and possibly combined with questionnaires from other design specialties:

- *Client Questionnaire—Electrical, Existing Site*
- *Client Questionnaire—Electrical, Greenfield Site*

This data makes a good starting point to be confirmed through in person interviews, on-site evaluation, and coordination with the rest of the design team.

1.2. Trip Packing

The trip leader will send a general packing list to all team members. This will provide information on personal items such as clothes, toiletries, and general work materials. In addition, the electrical designer should use the *Trip Packing Checklist--Electrical* regarding electrical-specific items. One should expect to tailor the list to avoid bringing expensive diagnostic equipment for which there is no use. As part of this pre-trip preparation, the team must make plans for getting the equipment to the site. For specialty items, some EMI offices have a check out program if requests are made with sufficient advance notice.

1.3. Additional Trip Preparation

All electrical members should download and review all equipment manuals and support software. It is important to practice data collection at home for any unfamiliar procedures. Alternatively, one can attend EMI Network Conference electrical designer courses for training

and a deeper insight into the work of EMI. If the timing does not permit attendance in person, the training slides are available on the EMI website. Once selected for a project trip, electrical designers will be invited to join other EMI electrical designers to communicate project issues and get advice.

2. Site Evaluation

Once onsite, the electrical designer should first seek to confirm all pre-trip research and analysis. The trip leader will probably arrange for the team to meet with the clients on the first day. For most projects, this discussion will mostly focus on the clients' vision for development. As such, the architects or civil engineers will likely lead most of the inquiry. This is a chance for the electrical designer to verify that they have properly assessed the client's electrical needs. This is normally NOT the place to discuss the specifics of electrical design, as it often has not been considered. A notable exception is if the client has specifically requested an energy source analysis.

2.1. Initial Interview

After the initial meeting, the electrical designers should schedule to meet with someone that runs (or will run) day-to-day operations at the specific site. This is an important source of information, so the electrical designers should be prepared. That is, educated as to cultural differences, prepared with a translator if necessary, and ready to demonstrate EMI's core values. The clients are the experts on their ministry; the designers must flesh out their needs and goals and translate those into design requirements. The meeting should begin by reviewing (or completing) the client questionnaire.

For existing sites, electrical designers should meet with the maintenance technicians; ideally while they give a tour of the facilities. This is the time to discover and document any safety issues or known systems problems (e.g., brown outs not experienced by neighboring structures, injury to persons, premature breakdowns of electrical equipment, …). Document the circumstances around any equipment failures for evidence of possible electrical system problems. The means of communicating problems to the client ministry will be affected by cultural factors. The EMI team may need to refrain from pointing out issues to the maintenance personnel if it is unsolicited. This may cause embarrassment and damage the relationship. In any case, the issues should be well documented in the final report for the ministry leadership.

2.2. Site Inspection

The goal of the site inspection is to gather all data necessary to complete the electrical design without requiring a revisit. Due to time limitations, correct prioritization is essential. EMI has developed two worksheets to guide the inspection activities and document all findings. The *Site Inspection—Electrical, Greenfield* will guide the designer at greenfield sites. The activities include examining the soil and other onsite parameters, but it may also involve significant travel to neighboring sites, contractors, and government offices. For inspections on existing sites, one should follow the *Site Inspection—Electrical, Existing*, which is regularly updated with advice from experienced EMI staff regarding commonly encountered issues.

The inspection should always begin with proper safety precautions including: never working alone, donning appropriate safety equipment, and checking for energized surfaces using a non-contact voltage (NCV) tester and/or multimeter. This check should start from the surrounding area and work in--EMI engineers have encountered electric shock hazards in metal framing, clotheslines, and metal plumbing. While such testing is not a primary role of an EMI team, it can

serve as a valuable, and even lifesaving, contribution to the client. As part of the site inspection on existing facilities, the electrical designer should document all physical hazards encountered. This includes, but is not limited to those listed in the site inspection worksheet.

During site inspection of existing structures, details about electrical panels are documented using the *Electrical Panel Worksheet*. For smaller sites, all panels should be done. For sites with numerous buildings, the team must prioritize as necessary. At a minimum, the main distribution panel for each utility transformer or utility service entrance and the primary panel of each building should be documented. These worksheets support the subsequent single-line diagram and electrical load study. For each panel, make a note of all special or large loads by documenting the name, the voltage, and the power demand in W and VA. Also, note the size and material of the supply conductor. An example of a completed electrical panel worksheet is shown in Figure 1.

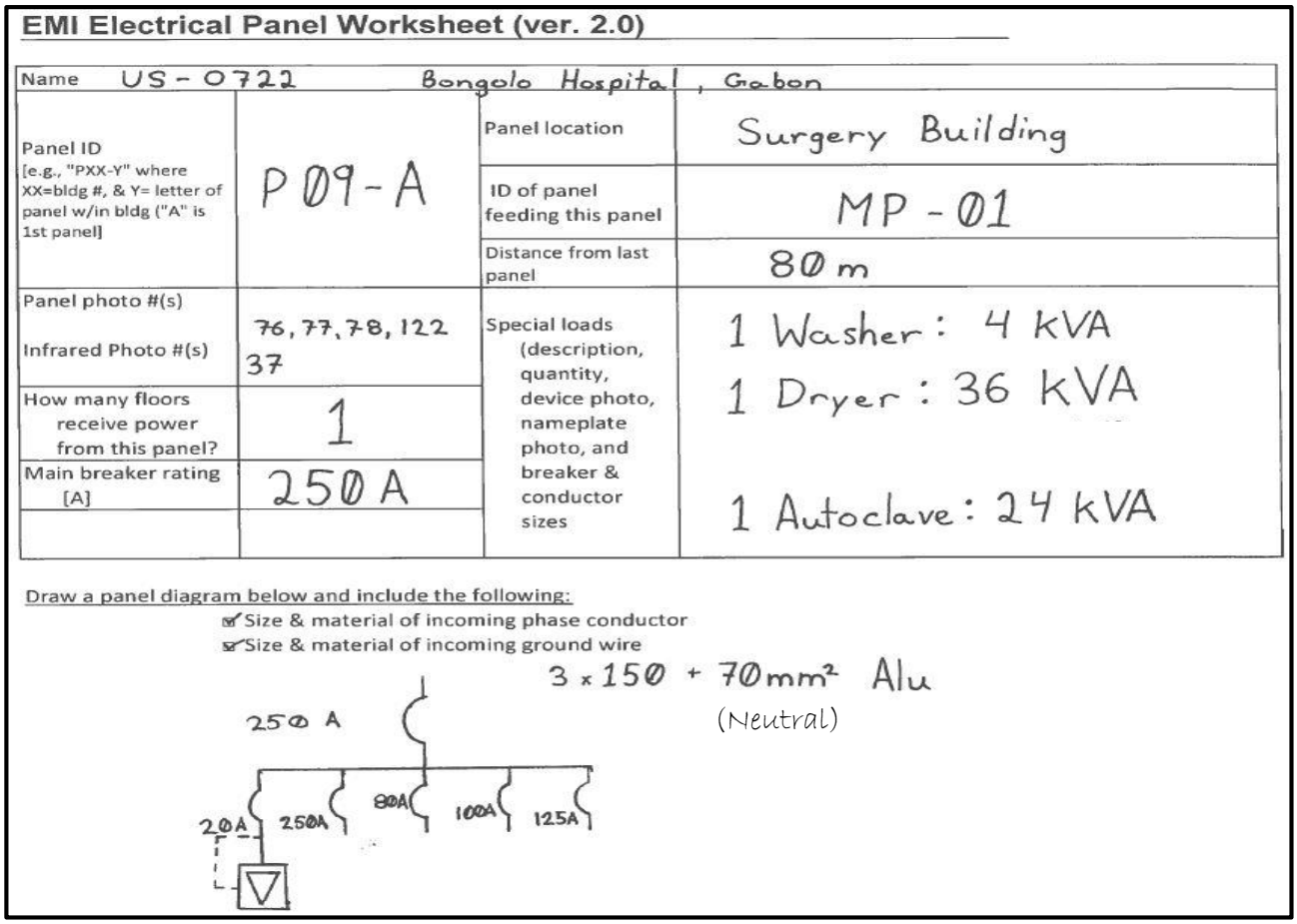


Figure 1: Example of completed Panel Worksheet

2.3. GROUNDING SYSTEM

A properly designed and constructed grounding system is essential for protection from injury and equipment damage. For a greenfield site or area of new expansion, this design requires a knowledge of the soil resistivity. For an existing site, the current grounding and bonding should be inspected and measured to verify suitability. The NEC recommends any grounding system have a total resistance of less than 25 ohms, and NEC 50.56 specifies less than 5 ohms if it is protecting any sensitive electronic equipment.

2.3.1. Soil Resistivity

Soil resistivity data allows the electrical designers determine the best location for a grounding system and to properly size the earth interface. Soil resistivity can vary widely by location and season as it is determined by electrolytes in the soil, which is a function of the quantity of dissolved salts, moisture, and temperature. As part of an initial site evaluation, the civil engineers will often conduct very detailed soil tests for structural and drainage calculations. If so, the electrical designer can use their findings and Table 2 to estimate soil resistivity.

Table 2: Soil Resistivity by Soil Type [Ω-m]

Soil Description	Median	Minimum	Maximum
Topsoil or loam	26	1	50
Inorganic clay of high plasticity	33	10	55
Fills--ash, cinder, brine, waste	38	6	70
Gravelly clay, sandy clay, silty clay	43	25	60
Slate, shale	55	10	100
Silty/clayey fine sand (low plasticity)	55	30	80
Clayey sand, poorly graded sand-clay mixtures	125	50	200
Fine sandy/silty clay	190	80	300
Decomposed gneiss	275	50	500
Silty sands, poorly graded sand/silt mixtures	300	100	500
Clayey gravel, poorly graded gravel/sand/clay mix	300	200	400
Well graded gravel, gravel/sand mixtures	800	600	1,000
Sandstone, granite, basalt, etc.	1,010	20	2,000
Poorly graded gravel/sand mixtures	1,750	1,000	2,500
Gravel, sand, stone	2,585	590	4,580
Limestone	5,050	100	10,000

Source: *Designing for a Low Resistance Earth Interface* (in references)

The project team should note any potential challenges to a proper grounding system in the outbrief and project report (i.e., extreme temperature or moisture fluctuations, high resistance soil type, highly corrosive environment, limited space for grounding grid, …). They should also propose mitigations to identified issues such as greater rod depth or soil conditioning. Refer to the reference document *Designing for a Low Resistance Earth Interface* for more information on grounding system challenges and solutions.

Once the most desirable location for a grounding system has been determined, actual soil resistivity tests will be needed before detailed design. The most accurate approach is to conduct a series of 4-point measurements using a ground resistance tester. The proper test configuration is shown in Figure 2. Soil water content should be consistent with normal conditions; high moisture significantly decreases resistivity. In this test, a known current is passed between the outer probes and the potential is measured across the two inner probes.

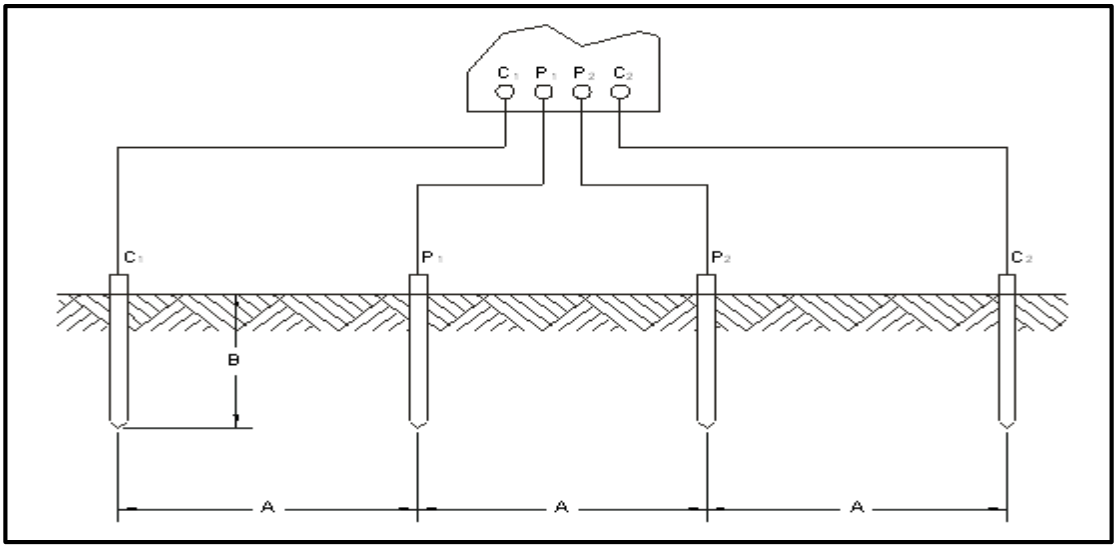


Figure 2: Four-Point Method Soil Resistivity Set Up

Assuming the test is set up correctly and that the probe spacing, *A*, is sufficiently greater than probe depth, *B*, (that is, *A* > 20**B*), the soil resistivity (ρ), in ohm-meters, can be calculated using the simplified Wenner formula as:

$$\rho = 2\pi \cdot A \cdot R$$

where:
A is the probe spacing, in meters, and
R is the measured soil resistance, in ohms.

2.3.2. Grounding Electrodes

Being that a grounding system involves connecting a conductor (electrode) to a semiconductor (the earth), the total resistance is a function of the area of interface. This results in design tradeoffs between electrode (rod) length, diameter, and spacing. Each electrode in a grounding system has a surrounding *interfacing hemisphere* of earth that completes the connection. For a vertical rod of depth *L*, a hemisphere of radius 1.1**L* contains ~94% of the earth connection. This means that rods should be spaced apart at least twice their length to avoid overlapping interfaces from reducing the total grounding system effectiveness. One can reduce the number of rods, and thus the number of connections and total land area, by using longer and/or thicker rods. In addition, the longer rods will reach soils that are less susceptible to moisture and temperature fluctuations. However, the longer or thicker rods can be more expensive and yield rapidly diminishing returns. Also, soil resistivity generally increases with depth (further decreasing the effectiveness) and such a system will have a higher surge impedance than an equivalent amount of material put into thinner and shorter rods. Therefore, the designer must use engineering judgement in the design of a grounding system.

The simplest and least expensive grounding system consists of a single vertical rod. There are several references for calculating the theoretical resistance of a grounding systems such as IEEE 80-2013. For a one rod system, the resistance (R_1) can be predicted by the equation:

$$R_1 = \frac{\rho}{6.283\,L}\left[ln\left(\frac{8L}{d}\right) - 1\right]$$

where:
ρ is the soil resistivity, as calculated above
L is the rod length, in meters
d is the rod diameter, in meters.

NEC 250.52 (5) limits the minimum value for rod length as 8′ (2.44 m). For rod diameter it is no less than 3/4″ (21 mm) for galvanized steel and 5/8″ (15.9 mm) for copper, zinc, or stainless steel. There are no maximum values, but as the above equation shows, the physics involved create rapidly diminishing returns for large values of rod length and diameter.

If one grounding rod will not yield a value less than or equal to the necessary resistance for the grounding system (R_{req}), one can estimate the necessary number of rods (N) in a multi-rod connected grounding system by iteratively calculating for the smallest N such that:

$$N \geq \frac{R_1 K}{R_{req}}$$

where:
K is called a combining factor ≈ 0.377527 ln (N) + 0.89057.

EXAMPLE:
A new building requires a grounding system with a ground resistance of less than 5 Ω. The proposed location consists of clayey sand, and test results confirm an average soil resistivity of 100 Ω-m. The designer proposes using grounding rods available in country that measure ¾″ x 10′. Therefore, the resistivity of a one-rod system to true earth, subject to the above conditions, is calculated to be 32.1 Ω and an adequate grounding system is estimated to require no fewer than 12 rods.

If a satisfactory solution cannot be found for the space allowed, the designer must consider a mesh or ground plate system. For some soil types, the grounding system will even require soil conditioning. Due to cost and maintenance requirements, these solutions should be considered a last resort. For more information, one should refer to the reference documents on grounding system design.

2.3.3. Grounding Conductor

Once the number and size of grounding rods are determined, they must be connected to the electrical distribution system by adequately sized grounding conductors. Table 3 lists the sufficient grounding conductor size for corresponding feeder conductors. If the wire sizes are unknown and not printed on the conductors, the team should use a caliper and the *EMI Wire Chart* to document sizing. Note that the ground terminal block in the electrical panel must be compatible with the material choice of *both* the ground conductor and neutral conductor (i.e., a Cu/Al rating if a mix of wires are used).

Table 3: Grounding Electrode Conductor Sizing

Largest Ungrounded Service-Entrance Conductor (or Equivalent Area for Parallel Conductors) *AWG or kcmil (mm²)*		**Minimum Size of Conductor** *AWG or kcmil (mm²)*	
Copper	**Aluminum or Copper-Clad Aluminum**	**Copper**	**Aluminum or Copper-Clad Aluminum**
2 (35) or smaller	1/0 (50) or smaller	8 (10)	6 (10)
1 or 1/0 (50)	2/0 or 3/0 (70)	6 (16)	4 (25)
2/0 or 3/0 (70)	4/0 or 250 (120)	4 (25)	2 (35)
Over 3/0 through 350 (95-185)	Over 250 through 500 (120-240)	2 (35)	1/0 (50)
Over 350 through 600 (185-300)	Over 500 through 900 (300-500)	1/0 (70)	3/0 (95)

Source: NEC 2017 Table 250.66

2.3.4. Grounding System Bonding

A correctly installed electrical system must be properly bonded to allow the grounding system to dissipate electrical discharge. For an existing site, the site inspection should look for the components of proper grounding and bonding as shown in Figure 3. Refer to the *Panel Grounding &Bonding Diagram*.

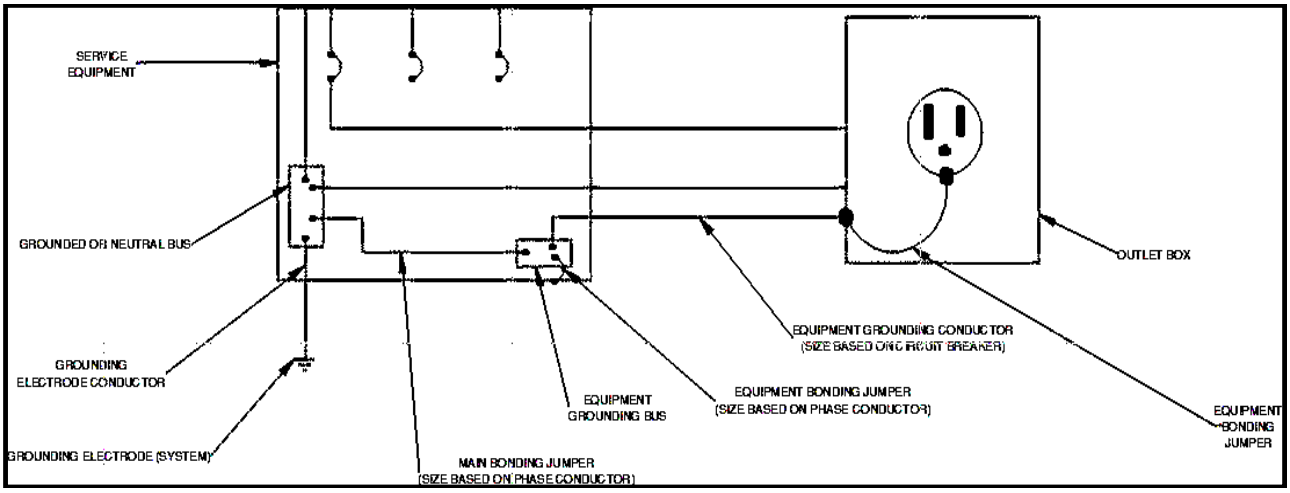


Figure 3: Proper Grounding and Bonding

A typical site in the developing world will not connect the ground of the main distribution panel to those of the subpanels. Instead, each building will have its own grounding system connected to the neutral of the power distribution and the main building panel ground. This type of grounding, shown in Figure 4, is called TN-C-S, also known as Multiple Earthed Neutral (MEN) or Protective Multiple Earthing (PME). Contractors do such a layout to ensure that the

ground and conductive surfaces in each building are as close as possible in electrical potential. For designers, it means that new structures can be added without requiring a ground wire to existing distribution lines. Of note, this is NOT an allowed grounding scheme in India; consult the country-specific guidance for those projects.

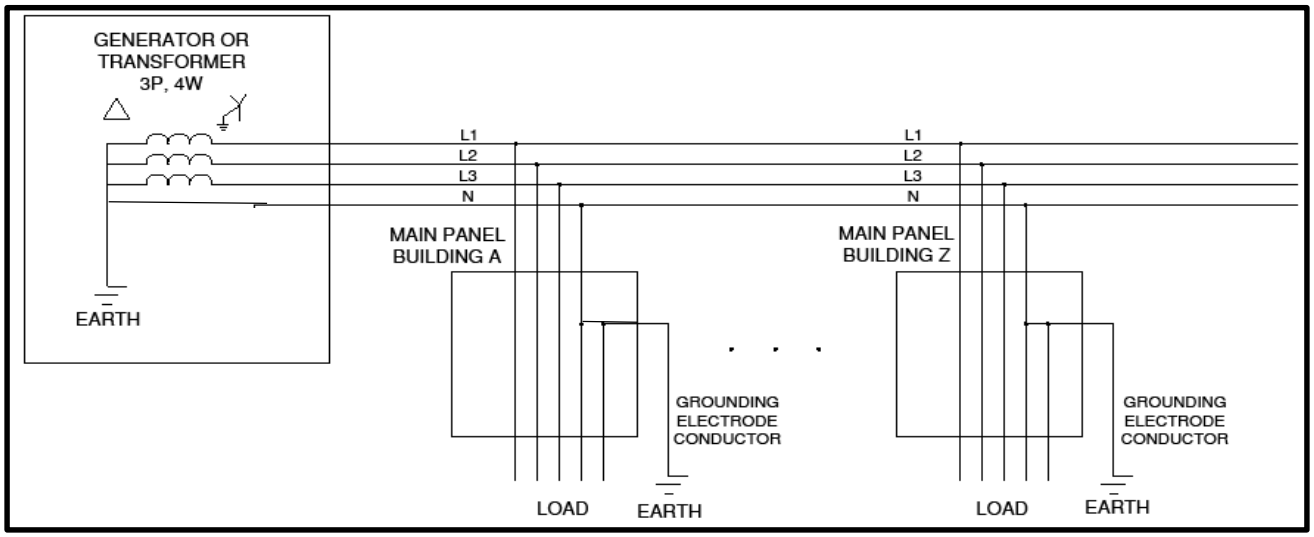


Figure 4: Site Grounding Layout

2.3.5. Grounding System Measurement

For existing electrical systems, or once a new or modified grounding system is complete, the actual resistance of the installed electrodes should be measured. As mentioned above, soil water content should be consistent with normal conditions. Clamp-on ground resistance testers are available, but one must check the manual for the limitations of specific equipment. A more robust method is to perform a fall-of-Potential (FOP) test. This test requires a series of measurements with probes driven into the ground. This is colloquially called a 3-point test; the three points being the grounding system and two test probes, as shown in Figure 5. The current probe must be placed at a distance (D2) well outside of the interfacing hemisphere of the grounding system.

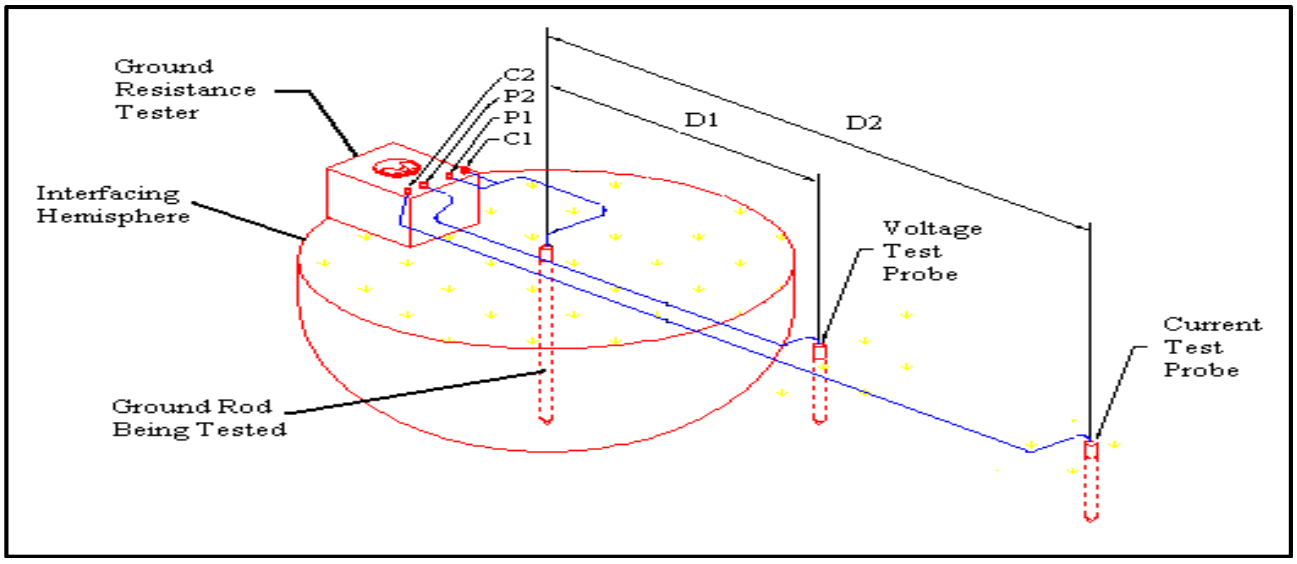


Figure 5: Fall of Potential Test Set up on Existing Grounding System

A rule of thumb is that D2 must be more than three times the length of a single grounding electrode and greater than five times the length of the diagonal measurement of a grounding grid. After placing the current probe, insert the voltage probe at about the midpoint between the grounding system and the current probe. Record the resistivity for the given distance (D1). A basic test consists of two more samplings at distances of D1 ± 1 meter along the same line. If the resistivity does not change more than 30%, this is a sufficient test for most purposes. If a greater degree of certainty is required, continue gathering data points. When plotted, the results should fit to a monotonically increasing curve with a central region of little change, as shown in Figure 6. The normal practice is to use the value at 62% distance.

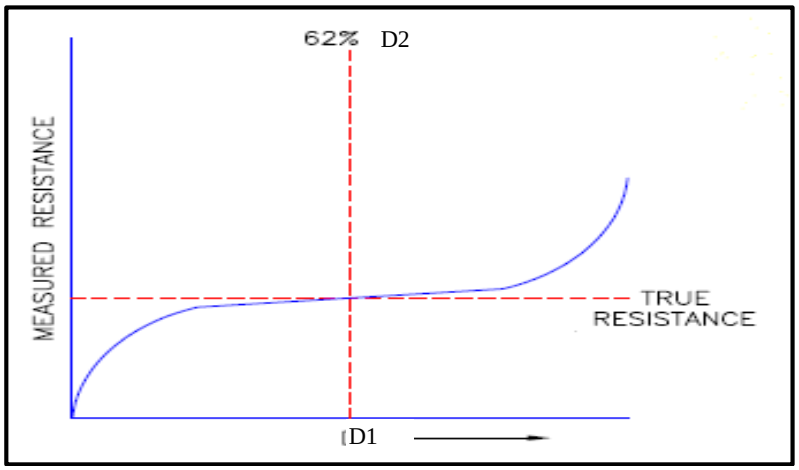


Figure 6: Plot of Properly Conducted FOP Test Results

If the results do not fit the expected curve (e.g., the resistivity never levels off), the current test probe is likely to close to the system under test. If the test equipment returns a "NOISE" warning, or the readings are not stable, it is likely that the grounding system is energized. The test should be repeated with the grounding electrodes isolated from the electrical system. A complete site FOP test consists of multiple radial lines extending away from the electrode under test spanning the area available for grounding.

2.4. Power Quality Analysis

Many sites in developing countries will have issues with power quality. As such, clients may be experiencing premature equipment failures, inefficient operation, or (in the case voltage spikes) damage and injury. A power quality analysis, as part of the site evaluation, will help determine the nature and extent of the root causes. Ideally, this will be performed using a power quality analyzer (PQA), but if one is not available, a basic analysis can be conducted using clamp ammeters and multimeters. This is an iterative process as the single line diagram and the electrical site plan will compile the information for a complete power quality analysis. Table 4 lists common power quality issues and possible solutions.

Table 4: Power Quality Analysis Matrix

Issue	Potential Solution
High transient surges	Surge protective devices
Voltage drop "brown out"	If <20%, may be addressed with voltage regulation. If culprit is utility: consider energy alternatives and storage If culprit is on site (e.g., large equipment start up): Create sub-system isolation and/or soft starters.
Over or under voltage (> ± 10%)	Add voltage regulation Under voltage may indicate improperly sized cabling upstream
High inrush current	Latching relays for offending appliances (e.g., air conditioners, water heaters, pumps, …)
Harmonic distortion	Voltage regulation; fully rated neutral conductor cable
Poor Power Factor (< 0.8)	Power factor correction (usually capacitance)

2.4.1. Surge Protective Devices

A surge protective device (SPD) suppresses excessive transient voltage such as those caused by lightning strikes or large equipment startups. Table 5 summarizes the most common SPDs.

Table 5: Surge Protection Devices

Parameters	Metal Oxide Varister (MOV)	Constant Voltage Transformer (CVT)	"Double-Conversion" UPS
Initial cost	Relatively cheap	Expensive, if sourced in US (foreign options may be available)	Expensive, but offers additional capability
Performance	Clamping voltage is 2x peak, so protection not perfect.	Very good surge suppression & voltage regulation. Heavy, noisy, hot. Limited KVA rating;- ≤ 20 kVA / phase.	Good surge protection & voltage regulation Also provides back-up power (limited)
Lifecycle & maintenance issues	Degrades with use, and so needs occasional replacement.	Minimal maintenance. ~ 10-year life. Also, draws current even with no load	Requires maintenance 20 yr lifetime
Best Use	Install at each building's main panel as a first line of defense	Sensitive, expensive or difficult to fix equipment;- such as that in a hospital.	Equipment that needs back-up power & surge protection;- such as the admin computer system.
Example Mfr	Bourns	SOLA	Riello

2.4.2. Voltage Regulation

A voltage regulator must be incorporated to any electrical design if the supplied power regularly fluctuates in voltage by greater than ±10%. Even beneath this value, some form of voltage regulation may be desired. This protection is needed as sensitive electronics are not designed to handle input in excess of this. Even if there are no sensitive electronics, resistive heating elements or induction motors are also vulnerable to burn out or insulation failure. A system incorporating voltage regulation must adjust input cable and circuit breaker sizes to account for proportional increase in current flow that corresponds to voltage drops as the device maintains constant power.

Table 6: Voltage Regulation Devices

Parameters	Motorized Variable Transformer	Constant Voltage Transformer (CVT)	Solid-State Tap-Changer	"Double-Conversion" UPS
Initial cost	Relatively cheap per KVA	Expensive, if sourced in US	Expensive – few suppliers (US)	Inexpensive
Performance	Slow activation (~1 sec), so not for sensitive equipment. Must pay more for independent 3 phase regulation.	Good voltage regulation, surge protection, and distortion isolation Same limitations as above	Good O/L capability, so can be used with large motors.	Good voltage regulation. Also provides surge protection and back-up power (limited)
Lifecycle & maintenance issues	Requires maintenance 7 yr life	Minimal maintenance. ~ 10-year life. Potential for overheating	Minimal maintenance 20 yr lifetime	Requires maintenance 20 yr lifetime
Best Use	Install one for entire campus or major sub-campus as initial regulation.	Sensitive, expensive or difficult to fix equipment;- such as that in a hospital.	Could be sole regulator for non-sensitive equipment	Equipment that needs back-up power & surge protection;- such as the admin computer system.
Example Mfr	Galco	SOLA	Siemens	Riello

2.4.3. Harmonic Distortion

Another way to quantify electric power quality is harmonic distortion. For power distribution, total harmonic distortion (THD) is expressed as a percentage of the amount of power contained

in harmonics as compared to the fundamental. Harmonics are created by nonlinear loads and are easily measured with a PQA, energy logger, or laptop-based oscilloscope. As with poor power factor, a high THD results in lower efficiency and more current in a system than one with cleaner power. Also, sensitive electronics may not be able to handle high THD on their inputs. For general loads, IEEE Std 519 recommends a THD of no greater than 5% and the largest single harmonic to be no more than 3% of the fundamental. For special applications (such as operation rooms), the standard recommends <3.0%.

High harmonic distortion means that the phase current flowing in the neutral is higher than would otherwise be calculated, so one should look for the possibility of exceeding the ampacity of the neutral. This is especially a concern if 3.5 conductor cable is used (i.e., with the neutral conductor only rated for half current). Harmonic distortion can be addressed using reactors (chokes), isolating transformers, or filters. For more information, refer to the reference: *Addressing Harmonic Distortion*.

2.4.4. Power Factor Correction

Power Factor (pf) is the cosine of the angle between the voltage and current. It is also, the component of apparent power (what is delivered by a source) that exists as real power (what is usable), as shown in Figure 7. The remainder, called reactive power, exists in the creation and collapse of magnetic fields. Therefore, a pf other than 1.0 means the system is distributing power at less than 100% efficiency. A pf less than 0.8 is considered a poor power factor in need of correction.

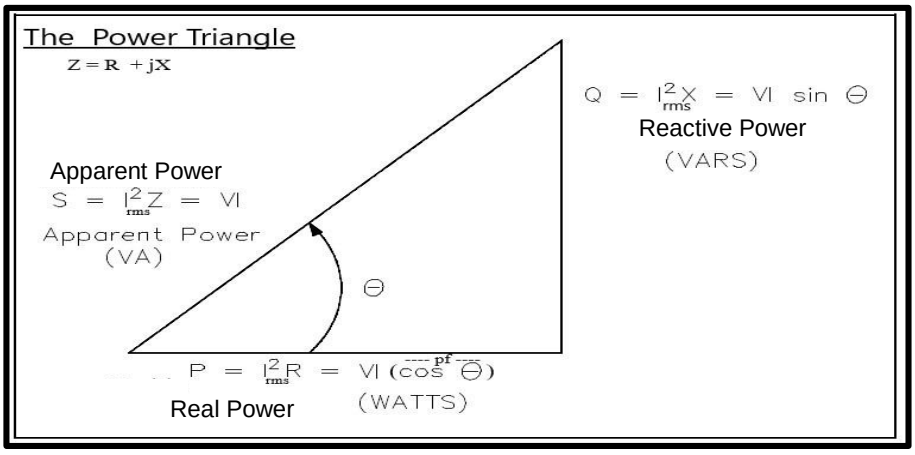


Figure 7: The Power Triangle

In addition to wasted power, a poor power factor means more current is passing through the electrical components than is otherwise necessary. This puts a greater burden on the distribution lines and increases voltage drop. Utilities often penalize customers whose loads create a poor power factor. The normal culprits are inductive-type loads such as motors and florescent lighting. These create a “lagging” power factor. That is, the current lags the voltage. If one cannot replace the inductive loads, and the cost penalty justifies it, the customer can add a capacitive load, which create a leading power factor. Table 7 summarizes how this can be done. As it is shown, one should only use fixed value capacitors if the load is well defined and/or small. For larger and more variable systems, the pf correction must adjust with the variation of the loads.

Table 7: Power Factor Correction Devices

Parameters	Fixed Value Capacitor	Automatic PF Correction
Initial cost	Cheaper	More Expensive
Performance	Very Good. Rugged.	Good. More complicated; more can go wrong.
Lifecycle & maintenance issues	Very Rugged and Reliable. Simple device, just capacitors and series fuses	Good. Control electronics are more vulnerable.
Best Use	Either equipment with a defined PF (such as a pump motor) or on smaller campuses (≤ 50kVA).	Entire campus, especially when the max demand is significant (≥ 100kVA).

2.4.5. LOAD STUDY

While conducting a power quality analysis, a PQA or energy logger can gather valuable data for the electrical load study and energy source analysis. The user must ensure that the PQA is properly configured for this data collection, and the team should plan to ensure the collection time spans real or simulated normal and maximum loads. Once should collect as many days as possible to accurately capture the fluctuation in demand.

3. Electrical Design

Electrical design is the process of creating graphical representations of the electrical system that capture the information obtained in the site evaluation and other analysis. The primary documents created on any project are the single line diagram and the electrical site plan. Two sets will normally be created to show the existing system and what is proposed to be removed or added. Existing structure drawings should be created early on; however, the drawings for proposed systems will have to wait on decisions from other team members, such as the civil engineers and architects. This is often an iterative process with the other deliverables of design.

Figure 8 shows the standard symbols used by EMI to depict the components of the electrical system. This is also available as a separate file in the supporting documents folder. It is not an exhaustive list, so the designer may need to supplement. If so, new symbols must be defined on any drawings where they are used. Also, if local electrical drawings are available, EMI deliverables should conform to the symbols used on those.

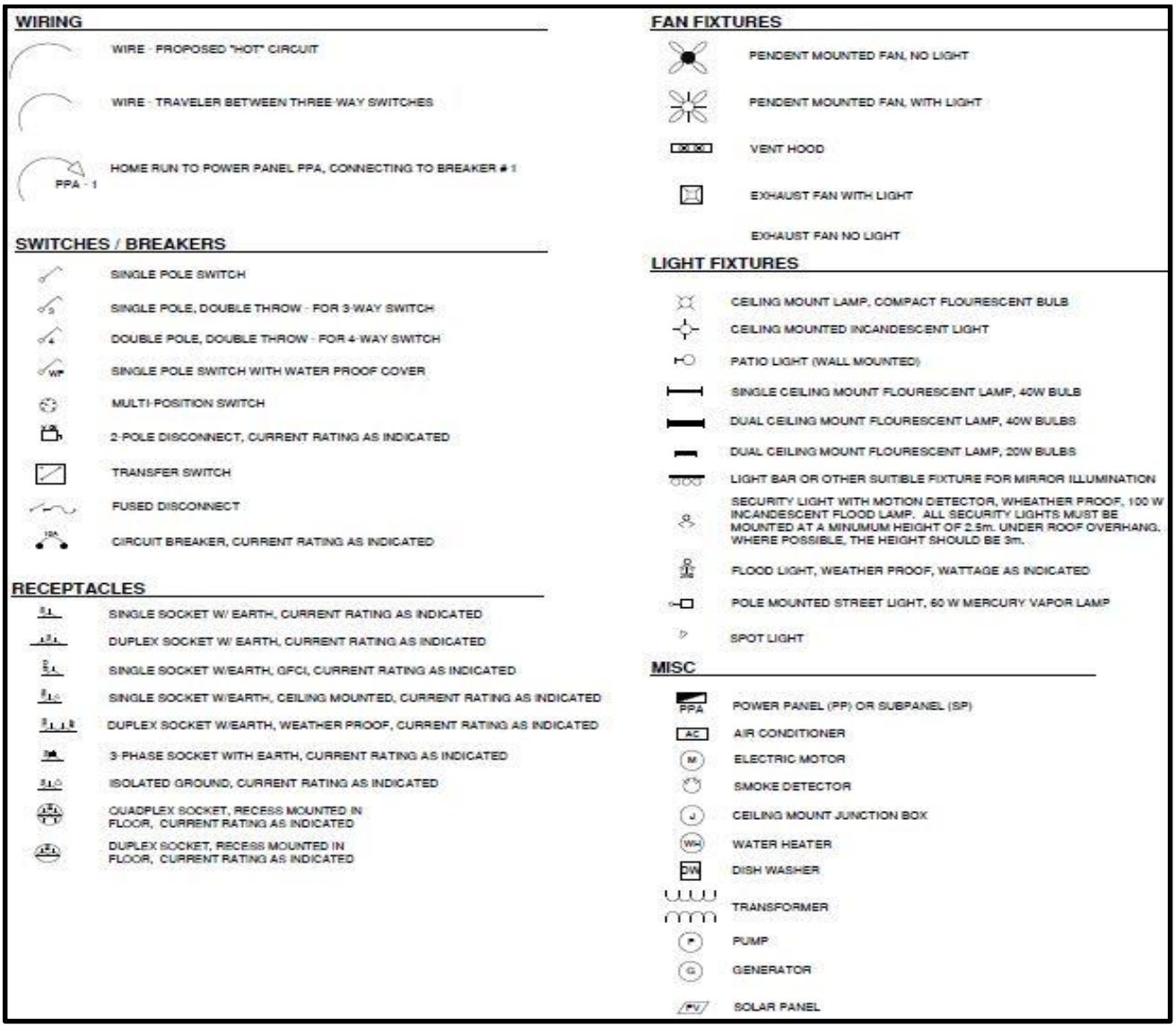


Figure 8: EMI Standard Electrical Symbols

3.1. SINGLE LINE DIAGRAM

Electrical designers use the single line diagram to capture information on an existing system and to communicate proposed modifications. The flow of electric energy should be down and to the right from power sources at the top of the page to loads at the bottom The *Single Line Diagram Template*, shown here in Figure 9, is an example of a single line diagram for a small site. The two power sources in this example are the public utility and a backup generator.

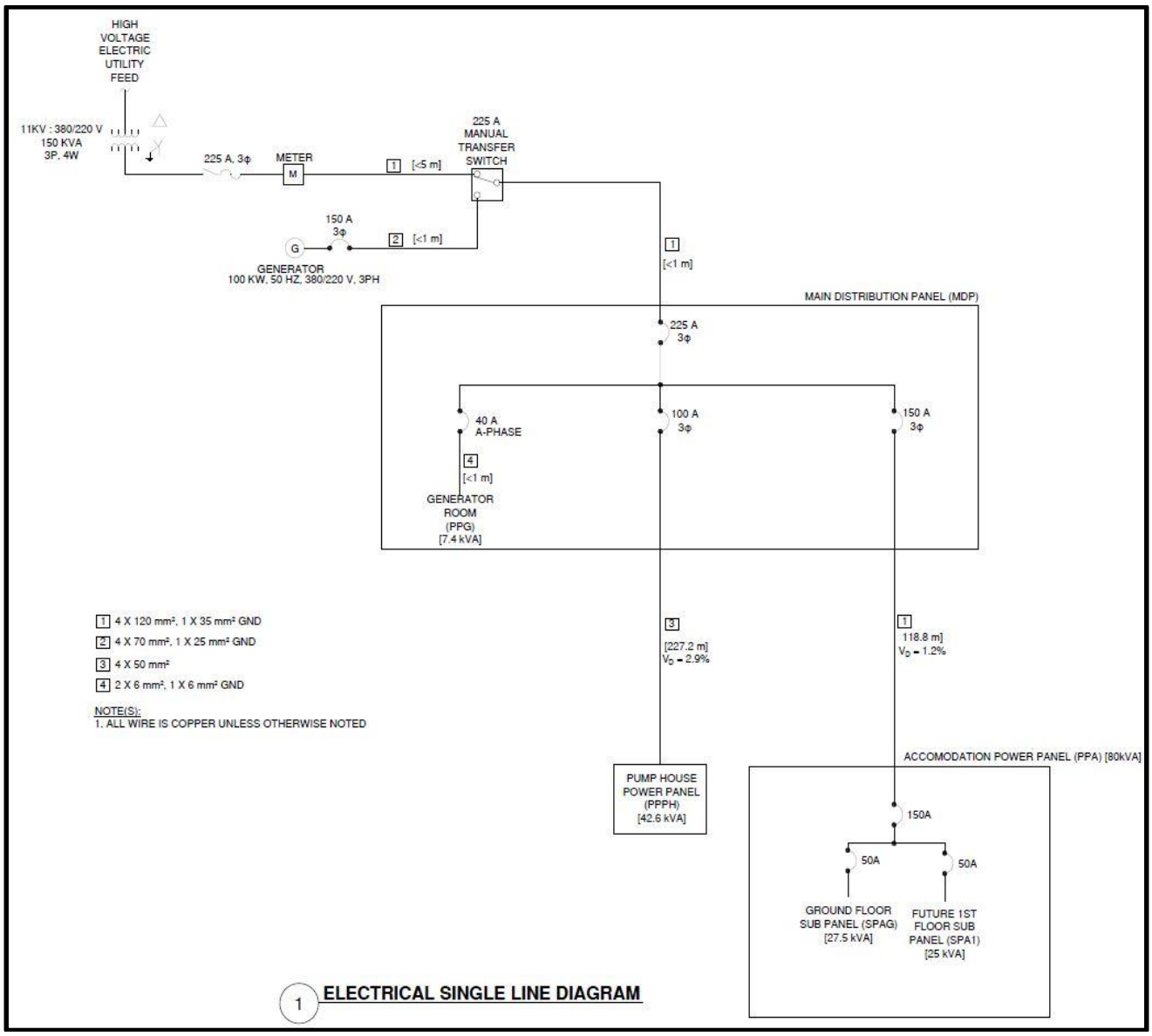


Figure 9: Example Single Line Diagram

A project will often require several versions of the single line diagram. The first one should be created as part of the initial site evaluation to capture the existing electrical system. This includes system details, such as existing wire and breaker sizes, as well as all identified hazards or deficiencies in need of correction. Creating a single line diagram early is important as it allows for further analysis and facilitates communication with others. For example, an inspection of Figure 9 reveals that the transformer is sufficient to accommodate all present loads, but the generator can only serve as the backup power for part of the demand. The client must make a choice. Either the generator and feeders to the transfer switch must be upgraded,

or separate circuits and panels will be needed for the loads receiving backup power from the generator (up to 100 kW). Alternatively, the output breaker of the generator should be sized to trip before the generator is overloaded. Loads would have to then be manually turned off when the site is on generator power.

The next version of the single line diagram will be created during conceptual design to show proposed changes to the existing system. This can be done by showing changes to the existing diagram (such as using a dashed line type to show new wiring and components); however, if the project is proposing significant additions and subtractions, it is often more clear to create a new single line diagram. For presentation purposes, the two diagrams can be juxtaposed to show a before and after. The conceptual single line diagram should include power source and main breaker sizing, but no further details are necessary.

If the project proceeds to detailed design, the electrical designer will perform additional analysis, as discussed in section 3.4. These details should be added to a new version of the single line diagram.

3.2. Electrical Site Plan

The *Electrical Site Plan Template*, shown here in Figure 10, details how the electrical system will be laid out across the site. It shows all the main feeder cables and their routing as well as all the site lighting. The names and locations of the main panels (MDP, PPG, PPA) are also specified.

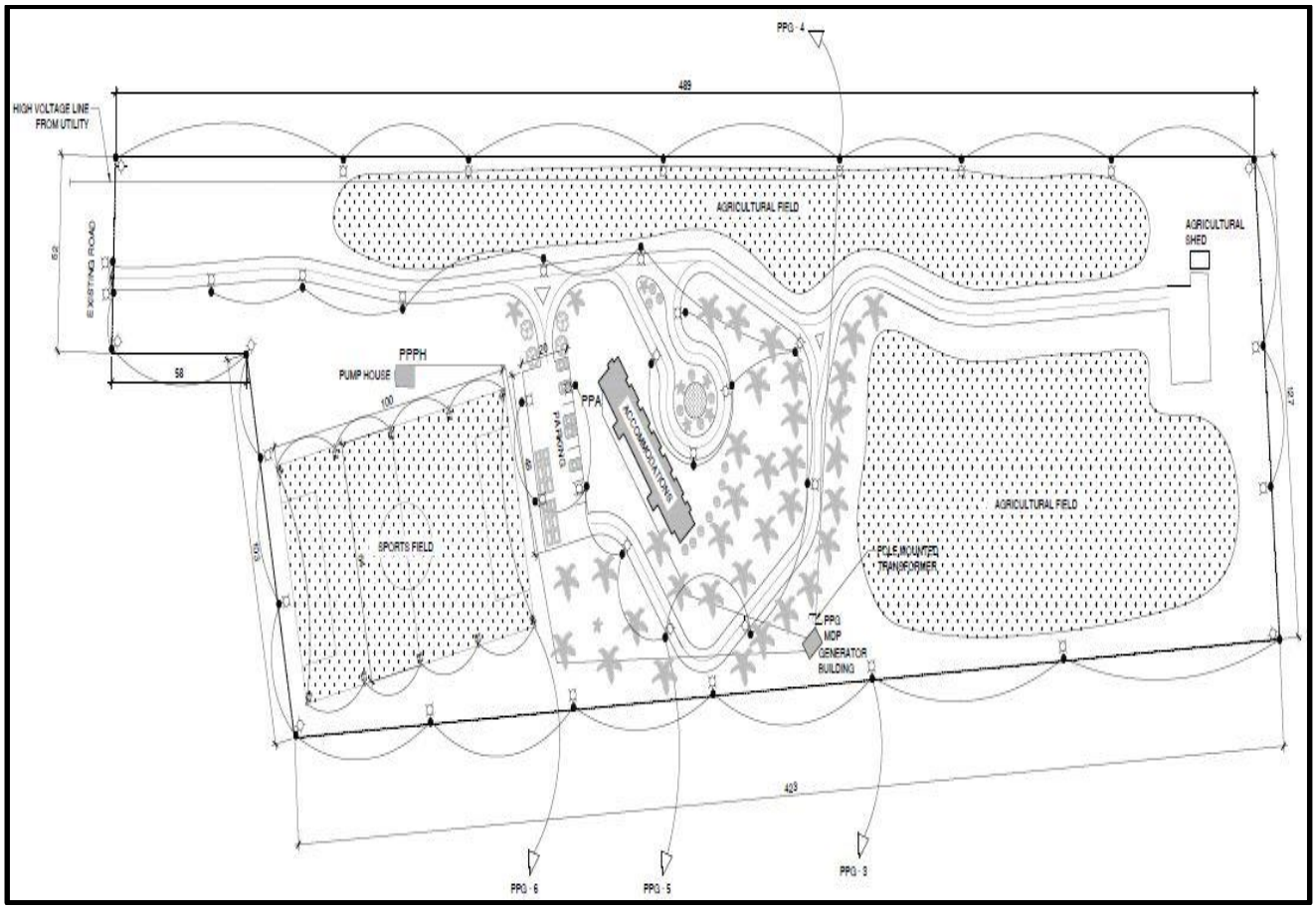


Figure 10: Example Conceptual Electrical Site Plan

3.3. Electrical Load Study

An electrical load study helps determine the proper size of an electrical system. Existing systems can be measured using a PQA or energy logger. Basic clamp ammeters can also be used, but that creates the tedious burden of logging the data at regular intervals for a long duration (every 15 minutes for several days is desired).

The load study for proposed construction must be estimated. The *Load Study Spreadsheet.xlsx* is a template for this process. General loads are estimated for each structure by measuring the useable area and multiplying by total power density. If the designer does not have normal power density information for the region, such data can be obtained by visiting representative buildings in the local area. Barring that, Table 9 can be used for initial calculations.

Table 9: Power Density Estimates by Structure Type

Power Density Components	Churches, Dining Halls, Auditoriums, & Large Open Spaces	Dwellings, Offices, Schools, Dormitories, Small Clinics	Hospitals, Large Clinics	
Lighting	5 W/m^2 (0.46 W/ft^2)		General Purpose 7 (0.6)	Operating or Procedure 27 (2.5)
Receptacle (Outlet) Loads	None Calculate HVAC & A/V as special loads	1 (0.09)	Calculate equipment as special loads	
Fans	3 (0.28)			

Special loads are calculated for each structure by multiplying the number of items of each special load type by their respective power consumption. The maximum demand is the sum of general and special loads.

The next step is to determine the percentage of time loads are expected to operate. This is called the demand factor. Determining demand factors should be guided by input from the ministry and observed patterns of use. For example, in a recent project, the air conditioners were given a demand factor of 75% because the client specified that no more than 75% of would be used simultaneously. The pumps were given a demand factor of 100% because a site evaluation conclusion was that, during the dry season, all pumps would run almost continuously.

3.4. Detailed Electrical Design

If the project will advance to detailed design, the following additional deliverables will be required of the electrical designer.

3.4.1. Lighting and Power Drawings

The building wiring diagrams *Ground Floor Lighting Wiring Diagram Template* and *Ground Floor Power Wiring Diagram Template* show the general location of all the electrical devices, how they are connected, and the home runs to the panel. Each floor will have both sheets to avoid overcrowding the drawings. Additional templates are included in the EMI Electrical Design Guide Templates folder to show EMI standards for such drawings, if they are to be part of the project deliverables.

3.4.2. Voltage Drop Calculation

For projects where wiring will span large distances (> 50m), a voltage drop calculation must be performed. For existing systems, calculations should be spot checked during simulated maximum load at locations furthest from the distribution. The voltage drop should be less than 4% from the distribution panel to the furthest subpanel. This ensures correct operation of overcurrent protection devices and avoids premature failure of equipment. Excessive voltage drop will necessitate larger conductor sizes than would otherwise be required. For proposed systems, the percentage voltage drop, $V_{D\%}$, can be estimated by:

Single-phase circuit:

$$V_{D\%} = \frac{(2 \times L) \cdot \left({}^{R}/_{1000}\right) \cdot I}{V_{SRC}} \times 100$$

Three-phase circuit:

$$V_{D\%} = \frac{(2 \times L) \cdot \left({}^{R}/_{1000}\right) \cdot I \cdot (0.866)}{V_{SRC}} \times 100$$

where:
L is the one-way length of the feeder, in meters
R is the resistance factor of the wire, in Ω/km (see *EMI Wire Chart*)
I is the current, in amps
V_{SRC} is the supplied voltage (i.e., 110, 220, 380 V, …)

Example:

A building is supplied with 220 V single phase electric power. The furthest subpanel in the building is 40 meters from the supply. The electrical contractors want to use 2.5mm^2 wire. The load study determines that the loads supplied by the subpanel will draw a total of 11.2 A. Will this wire be sufficient?

The voltage drop would be:

$$V_{D\%} = \left[\left(\frac{2 \times 40\ m \times (8.99\ \Omega/km/1000\ m/km) \times 11.2\ A}{(220\ V)}\right)\right] \times 100 = 3.6\%$$

Since the voltage drop is less than 4% on this feeder branch, the wire size chosen is adequate.

3.4.3. Circuit Breaker and Wire Size Determination

The circuit breaker size and wire size can now be determined by calculating the maximum current through a circuit.

Example:

In the *Template of Panel Schedules.xlsx*, the total load for circuit #2 on panel PPA is 2,464 VA. Therefore:

$$I = \frac{P}{V} = \frac{2464\ VA}{220\ V} = 11.2\ A$$

where:
I is the current, in amps
P is the power, in Volt-Amps
V is the voltage, in volts

Circuit breakers come in standard sizes, so part of the project research is to determine the standard sizes available in the region. To select a breaker, one adds a factor of 25% (to avoid nuisance tripping) and then chooses the next higher size available:

$$11.2\ A\ x\ 1.25 = 14\ A$$

So, a 15 Amp breaker would suffice.

With the breaker size selected, the wire size for the circuit can now be determined by referencing the *EMI Wire Chart*. The circuit breaker is protecting the wire, so wire that is able to carry 15 amps of current or more should be used on this circuit. In this example, 2.5 mm^2 wire was selected because column 3 of the chart shows that it is capable of carrying up to 22 amps.

The same calculation as above can be followed for the three-phase loads except the voltage is the phase to phase voltage (380 V) and the current is calculated as follows:

$$I_{3\phi} = \frac{P_{3\phi}}{V \cdot \sqrt{3}}$$

3.4.4. Panel Design

The *Template of Panel Schedules.xlsx* shows how to design the layout of electrical system panels. This includes: main distribution panels (MDP), main building panels (PPA), ground floor subpanels (SPAG), and generator power panels (PPG). Both typical three-phase panel schedules and typical single-phase panel schedules are shown. At the top of the panel schedule all the pertinent information about the panel is displayed. The middle of the panel is a graphical representation of the three-phase bus bars and their connection to each circuit breaker. Circuits #1, 3, 5 on panel PPA are shown with a line connecting them together to represent a 3-phase circuit breaker. The total power consumption of the 3-Phase loads is evenly distributed across the three phases. For example, the total load on SPAG is 27.498kVA, or 9.166kVA per phase. The wire size, circuit breaker size (CB Trip), load size (wattage) and a description of the equipment being served by that circuit are all shown on the panel layout.

The load on each circuit is calculated by summing up the power consumption of all the electrical devices connected to that circuit. For example, circuit #2 on panel PPA is feeding two single phase air conditioners for the small classrooms in the basement of the Accommodations. Each air conditioner is rated at 1,232 VA and they are connected to phase A, so 2,464 VA is the value placed for phase A on circuit #2.

The ‘Summary’ table shows the total load (in kVA) and current on each phase. This is to aid the designer in balancing the total load across the phases.

4. Energy Source Analysis

Many clients desire an objective partner to help them make decisions regarding energy source options. This section discusses the most common options for a site in a developing country and lists the factors of tradeoff analysis and design. The decision process should use the *EMI Energy Source Analysis Tool.xlsx* design tool to make a quantitative comparison of all options. For more information regarding the use of this analysis spreadsheet, refer to the EMI training course: **2019 EMI Conf Energy Source Analysis** located in the Electrical Design Training subfolder.

4.1. Energy Source Comparisons

Table 10 is a summary of the unsubsidized levelized cost of sources of energy for reference. This does not take into account the subsidies on utility power in many developing countries.

Table 10: Cost for Energy, by Source

Energy Source	$/ MWh
Public Utility (cost to user)	$80-420
Diesel Generator	$260-300*
Natural Gas Generator	$150-194
Solar, Residential Scale PV	$150-242
Solar, Commercial Scale PV	$75-154
Wind, Large Turbine	$37-81
Battery Storage	$223-384

Source: Version 13 of Lazard's Levelized Cost of Energy Analysis (2019 values)
* Diesel values estimated from 2017 report

4.2. Utility (Grid) Power

For a greenfield site intending to have utility grid power connection, the price of running new lines and a transformer must be determined. If the ministry has to purchase the transformer, prices may range from $50-90 US per kVA. The cost of extending the utility grid can be estimated as $13,000 US per kilometer. Often the line installation price may be negotiated or partnered with other utility customers in the area. New power line installation can be prohibitively expensive if there is no way to do a price share with the utility company or neighboring sites.

4.3. Generators

Generator-derived power (i.e., obtaining electricity from fuel combustion) is often used in places where reliable backup power is a design priority or in locations not serviced by utility power. Technically, it is alternators that produces electricity, but when driven by a combustion engine, they are commonly called "gensets", or simply generators. Generators output alternating current (AC), so they are compatible with equipment designed to operate with utility power. Recall that in AC systems, power, voltage, and current calculations use root mean square (rms) values, which are direct current equivalents of the same property. Peak values are higher

than the rms value by a factor of √2 (~1.41), so a nominal 120 V AC system will measure peak voltages of about 170 V, and 220 V AC systems will measure peak voltages of about 308 V.

4.3.1. Sizing

Generators have both a real power (KW) and apparent power (kVA) rating. In America, they are generally sold by KW capacity, but many other parts of the world refer to the kVA. The two values are related by the power triangle as shown in Figure 7. Since almost all three-phase generators are rated assuming a 0.8 power factor, typical ratings equivalents are 80KW == 100kVA. Generator ratings will consist of two numbers: Prime for continuous duty and Standby for limited duty. The designer should correctly size the generator so that it will operate between 30% and 80% of the rating, keeping in mind that operating in higher, hotter, or more humid environments will result in less power production than at sea level and standard temperature. Most people understand that regular operation near maximum loading shortens the life of equipment, but regularly under-loading a generator is also undesirable. In addition to less efficient operation, prolonged use of a diesel-powered generator under 30% of rated loading can result in what is called "wet stacking" where the engine begins to ooze a tarry liquid of unburned diesel fuel and soot. Wet stacking can reduce the ability of a generator to supply its full rated load and, if left unresolved, cause breakdown.

4.3.2. Phase

Generators are readily available in both single and three-phase, and the correct matching to the need is ideal. A single-phase generator can be connected to a three-phase panel so that each phase is powered, but it will, of course, NOT support true three-phase loads. The KW and kVA ratings will still be the same. A three-phase generator can be connected to a single-phase panel, but the windings in the alternator will be heating unevenly. The ratings must be reduced by 1/3 if connected to one leg and 2/3 if connected to two legs of a panel (such as a standard US 120/240 panel).

4.3.3. Frequency

The frequency of the output voltage is directly related to the engine speed. Thus, with typical 4-pole armatures, a 50Hz machine will be designed to run at 1500 RPM and a 60 Hz machine at 1800 RPM. Engine speed is controlled by the governor, so frequency problems often point back to it. It is possible to use a generator at an RPM other than what it was designed for, but it will increase the failure rate and decrease efficiency. Other than motors and CVTs, most loads (such as lighting, stoves, and electronic devices fed by a power supply) are not frequency sensitive. Check the nameplate of the device to be sure.

4.3.4. Power Factor

Designers must also consider the power factor of the loads being supported, as discussed in Chapter 3. Incandescent lights and resistance heaters have a power factor of 1.0. Induction motors typically cause the current to lag and have power factors closer to 0.8. Capacitive loads, such as UPS input filters, cause the current to lead the voltage, which can be problematic for generators and can result in loss of voltage stability. If the total power factor is leading, corrective components will be necessary.

4.3.5. Fuel Storage

A significant part of energy source design is planning for fuel storage. A below ground tank will have higher installation cost and inspection challenges, but it is more secure and reduces temperature fluctuations (which increase moisture content due to condensation). The storage area must be designed with a secondary containment to retain spills. For design purposes, assume that for each 10KW of load a diesel generator will use about 1 GPH (~4 LPH) of fuel. This assumption is less accurate for larger (>150KW) generators which are both more efficient and generally have fuel return lines so unused fuel is re-deposited if there is less engine loading than what is drawn by the fuel pump. Determining correct tank size involves some design tradeoffs: a tank too small leaves an unsatisfactory level of reserve, but an oversized tank means the average age of the fuel will be higher and/or it will sit in a partially filled container for longer periods before consumption. Both of these contribute to fuel deterioration and contamination.

The fuel storage area should remain locked and regularly inventoried for both resource security and safety. A separate concealed reserve is necessary if the site has critical backup needs (such as a hospital). This is necessary for both surge events and delays in resupply.

4.3.6. Generator location

In general, a generator should be located as close as possible to the loads it is supporting. This minimizes distribution costs and voltage drop in the lines. However, there are some restrictions on placement:

4.3.6.1. Ventilation

Most generators under consideration will be radiator-cooled. These need a clear inlet area of more than 1.5 times the area of the radiator. This area must draw fresh air as re-circulated exhaust will reduce engine cooling and reduce power output. The radiator should not be oriented into prevailing winds or open windows without scoops or diverters to direct the exhaust away. The designer may consider incorporating a heat exchanger to use the waste engine heat to produce hot water.

4.3.6.2. Noise

Generators are noisy. This may make the location challenging for sites that require nighttime operation near sleeping quarters or hospitals. Also, in areas without air conditioning, buildings with open windows will not attenuate outside noise very well; Orienting the radiator fan away from sensitive areas will minimize the noise impact. Scoops that divert exhaust air upwards can also contribute to quieter operations. If this is insufficient, one should consider baffling of the air inlets. Many generators can now come equipped with noise-attenuating enclosures as an add-on accessory.

4.3.7. Maintenance

Preference should be given to manufacturers with good support in the region; freight and import duties will significantly increase the maintenance costs of less common equipment. The designer should plan for the minimum of necessary maintenance by designing in things like a

fuel/water separator unit and specifying long life oil and air filters. The generator location should be designed to provide the cleanest intake air as possible.

4.3.8. Operation and Maintenance Costs

When making energy source comparisons, generators will generally have lower initial but higher operation and maintenance costs than other alternatives. The fuel consumption for a diesel engine will be about 0.07 gallons per kW-hr. Thus, a 50 kW load for 12 hrs per day with $5 per gallon diesel fuel costs $210 per day. The engine will require an oil and filter change every 100-150 hours of operation. A major engine overhaul will be required every 25-30,000 hours of operation. There will be additional expenses which will vary significantly depending on the client's level of preventative maintenance consistency.

4.4. Solar

The *Electrical Cost Comparison.xlsx* is regularly updated with current solar component costs. The first step of solar power design is to determine the total system energy needs (E_t) expressed in units of power x time per day (such as kWh/day). This energy must be harvested during the window of usable sunlight. In regions near the equator (±15° of latitude) that is a relatively constant 7.5 hours a day. This must be adjusted to account for the number of days a year, on average, the skies are clear. The Reference Document *World Solar Insolation Maps* shows the equivalent sun hours on the surface of the earth. Insolation is expressed as the average value of the total solar energy received each day on an optimally tilted surface during the month with the lowest solar radiation. This worst-month data is commonly accepted as a valid solar energy index for designing systems which must independently support a load 12 months per year. For grid-tied systems, it is accepted to use the overall annual average daily insolation value (Reference: Gaisma.com). The unit of measurement is kilowatt-hours/m²/day, often referred to as equivalent sun-hours, or ESH. System efficiency is estimated to be 85%, so the solar panel power, *P*, is estimated as:

$$P = \frac{E_t}{7.5(\mathrm{I})\ \mathrm{x}\ 0.85}$$

Charge controllers must be sized to match the solar panel wattage. If a system will include battery storage, the inverter must be sized to match the maximum power demand expected at any point during the day.

Table 7 lists typical solar system costs. It is useful for design estimates and comparisons with local contractors. These are 2019 values; some developing countries may have much higher costs due to a longer supply chain.

Table 7: Solar Components, Commercial Scale (> 10kW)

Item	Cost
Solar modules (panels)	400 $/kW
Charge Controller	372 $/kW
Inverter (grid-tied only)	100 $/kW
Inverter (with off-grid capability)	1000 $/kW
Solar Module Racking	138 $/kW
Supt hardware and wiring	200 $/kW

4.5. BATTERIES

If the site desires energy storage for consumption outside the solar harvest window, batteries must be sized to store the energy required, E_b, measured in watts x hours. Since batteries typically have around 80% efficiency, and since a deep cycle lead acid battery can be safely cycled to about 50% depth of discharge (DOD), the real world energy storage of a battery bank will be:

$$E_{\text{b_real}} = \frac{E_b}{(0.8 \text{ x } 0.5)}$$

For lithium ion batteries, some newer models are rated to 90% DOD, so one must consult the manufacturers' data in the above calculations. Table 8 lists average battery costs by type:

Table 8: Battery Costs

Item	Cost
Integrated Lithium-Ion battery, inverter/charger, & microgrid controller system	650 $/kW-h
Batteries (Lithium-Ion)	200 $/kW-h [5000 cycle, 15 yr lifespan]
Batteries (Deep Cycle Lead Acid AGM. Ex: Trojan 31-AGM)	190 $/kWh [1000 cycle, 2.7 yr lifespan]
Batteries (Deep Cycle Flooded Lead Acid. Ex: Trojan T-145)	124 $/kWh [1200 cycle, 3.3 yr lifespan]

4.6. WIND

Wind can be converted into electric power through a propeller-driven alternator mounted on an elevated tower. Clients are often intrigued at the possibility of harnessing what appears to be a free energy source; however, very few sites will have the consistent stable wind required to make them good wind harvesting candidates. In fact, unless the trees show moderate flagging (limb growth longer on one side) or a list of at least 10°, wind power is not a likely option. Wind speed needs to exceed 6 m/s (12 mph) for wind turbines to start producing power. Even greater annual average wind speeds are necessary to make the expense cost effective. In addition, wind turbines require an elevated structure 10 m above other objects within 150 m. If the site is a candidate for wind power, refer to the reference *How to Generate Electricity in Remote Areas*.

4.7. HYDROELECTRIC

Similar to wind power, moving water can be converted into electric power through a propeller-driven or turbine-driven alternator installed in channeled water. Also, like wind power, clients are often intrigued at the possibility of harnessing what appears to be a free energy source; however, very few sites have access to such a water source. Consistent water flow rate needs to exceed 2 m/s (4 mph) or have a drop of 10 m (30 ft) with a flow volume of .5 L/s (1/2 qt per sec) to make the expense cost effective. If the site is a candidate for hydroelectric power, refer to the reference *How to Generate Electricity in Remote Areas*.

5. Reporting and Followup

5.1. Outbrief

Near the conclusion of a project trip, the trip leader will normally have a scheduled time for the EMI team to present their work to the client. Typically, the electrical section of this outbrief will be around 3-5 slides and be structured as shown in the *EMI Outbrief--- Electrical Section Template*. The focus is to communicate how the proposed electrical design supports the overall project objectives (i.e., the architectural or civil engineering portion), so the electrical designer must fully coordinate with the rest of the team. The presentation should also address any items specifically requested by the client. This includes current issues of safety or reliability or alternative energy recommendations.

5.2. Written Report

The *EMI Project Report – Electrical Section Template* shows a correctly-formatted electrical section of an EMI report. As with the outbrief, it should clearly communicate how the electrical design supports the overall project objectives. Typically, the electrical section of the report is a 1-3 page high-level summary of the proposed electrical design. The report does not include technical details, but will reference drawings and spreadsheets that support the recommendations discussed. The electrical load study is included as a report appendix. The project leader will send this final report to the point of contact for the client organization, but often, a copy will also be provided to the lead technician or maintenance staff member.

5.3. Contractor Selection and Oversight

The client may desire EMI's assistance all the way through final construction. This will require the electrical designer to work closely with a local design firm and contractor, which involves ongoing involvement from the personnel involved. Any electrical designers qualified and willing to serve in this capacity should identify as such to EMI staff. This continued support will often also include the need to train the client ministry staff members that will be tasked with maintaining the installed system. The *Electrical System Training* subfolder contains syllabi and visual aids that have been used effectively to train local workers. These can be tailored based on the literacy and technical background of the audience. Keeping the courses hands on and using ample visual aids will help overcome language barriers, but it is still advisable to have competent translators available.