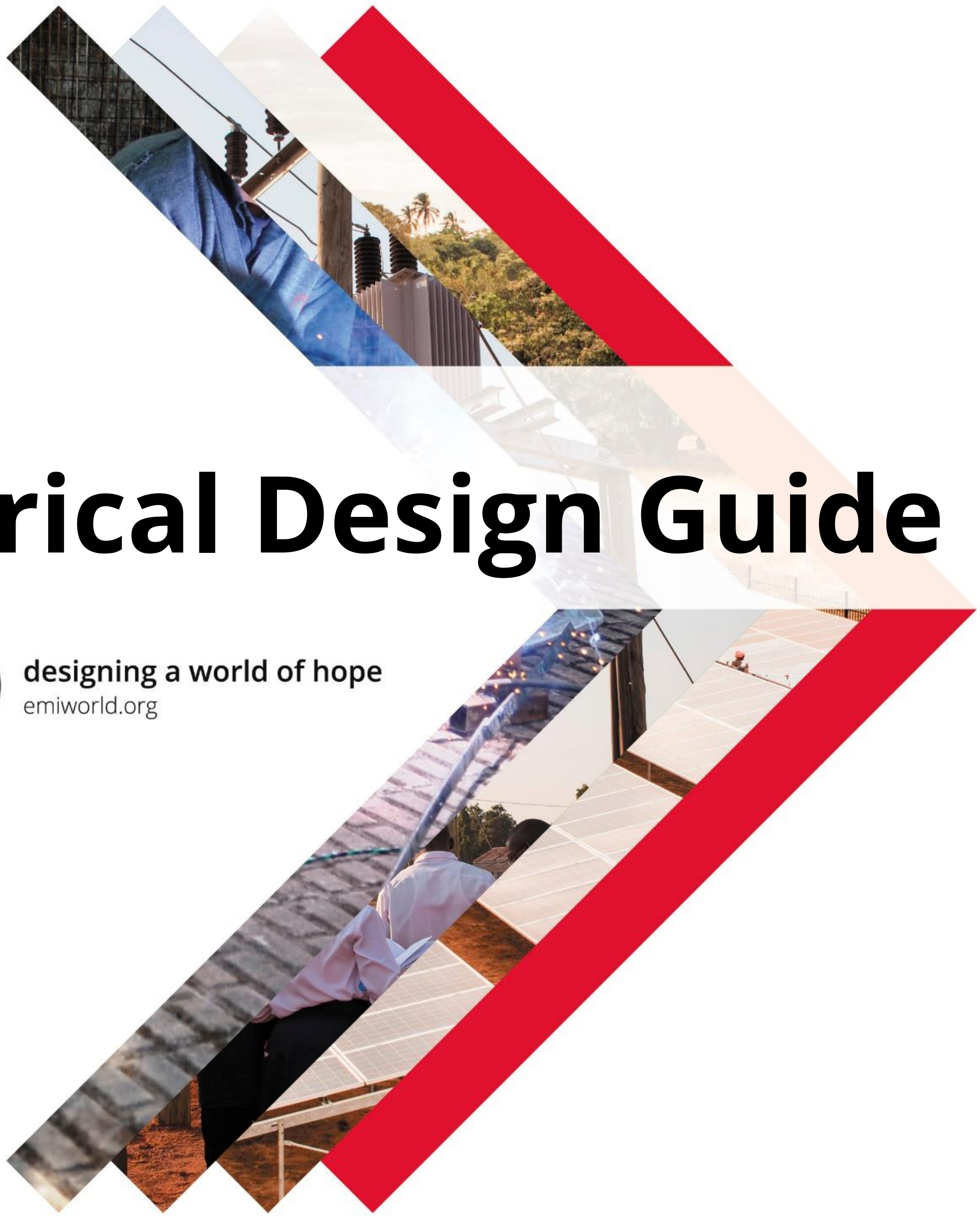

Electrical Design Guide

eMi designing a world of hope
emiworld.org

Developed and Compiled by:
Engineering Ministries International

Revised: August 2023

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

The design guide seeks to assist designers with electrical evaluation and design but does not cover construction or maintenance. 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 if links are unavailable or changed. The user should ensure to have the entire and latest **EMI Electrical Design** folder, which includes this document and all supporting files, including:

- The **EMI Design Tools** sub-folder contains worksheets and questionnaires 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.

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. EMI works in many countries with no established electrical code. Therefore, this document is written to comply with the **NFPA 70® National Electrical Code® (2023)** whenever possible.

Edition

This document is a living document and is intended to capture best practices for preliminary design and provide a guide to up-to-date design information needed to complete EMI projects properly. To continually improve the contents of this document, please provide your project leader with feedback on any errors you find, suggested improvements we could make, or your opinion on ways we could do things better.

Table 1: Revision History

Edition	Contributors	List of Changes
EMI Electrical Design Guide - 2014	Jim Cathey, Electrical Engineer, EMI Volunteer; Kirk Singleton, Electrical Engineer, EMI Volunteer; Ruedi Tobler, Electrical Engineer, EMI Volunteer; Bob Gresham, Electrical Engineer, EMI Volunteer; Bill Wright, Electrical Engineer, EMI Volunteer; Larry Bentley, Electrical Engineer, EMI Volunteer; Hannah Peterson, Electrical Engineer, EMI Staff; Andy Engebretson, Electrical Engineer, EMI Staff;	Initial Publication
EMI Electrical Design Guide - 2019	Andy Engebretson, Electrical Engineer, EMI Staff; Nick Hardman, Electrical Engineer, EMI Associate Staff, Hannah Peterson, Electrical Engineer, EMI Associate Staff; Fenton Rees, Electrical Engineer, EMI Volunteer	Added site evaluation chapter. Significant expansion of electrical design energy source Analysis chapters.
EMI Electrical Design Guide – 2023	Abby Rice, Electrical Engineer, EMI Fellow; Andy Engebretson, Electrical Engineer, EMI Staff; Adam Miller, Electrical Engineer, EMI Staff, Hannah Peterson, Electrical Engineer, EMI Staff; Kent Jones, Electrical Engineer, EMI Staff; Elly Akena, Electrical Engineer, EMI Fellow, Wynand de Swardt, Electrical Engineer, EMI Staff; Neil Eichstadt, Electrical Engineer, EMI Volunteer	New sections: Residual Current Devices, Motors and Starters, Overhead Power Lines, and Troubleshooting Common issues. Significant updates and expansion of sections: Grounding Systems, Power Quality, Energy Source Analysis. Updated links and references. Moved some detailed content to appendix. Changed “greenfield” to “undeveloped”.

DETERMINING SCOPE OF WORK

As part of project planning, EMI staff will determine the scope of work to be accomplished on each approved project. Project 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 2 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 developed sites with existing buildings).

Table 2: Electrical Design Deliverables by Project Type

Deliverable	Section	Undeveloped		Developed 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
Presentation & 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 project leader has determined the scope of work for the project (refer to Table 2).

1.1 Pre-trip Research

The *Pre-Trip Research—Electrical* worksheet will guide 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://globalsolaratlas.info/
- https://www.globalwindatlas.info/
- https://www.gaisma.com
- https://www.globalpetrolprices.com

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

- *Client Questionnaire—Electrical, Developed Site*
- *Client Questionnaire—Electrical, Undeveloped 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 project 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. Potential volunteers can attend EMI network events for training and deeper insight into the work of EMI. If timing does not permit attendance in person, training slides and some videos are available in the online folder. 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, as well as determine any local codes or standards in use. The project 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, Undeveloped* will guide the designer at undeveloped 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 to identify locally available components. For inspections on sites with existing buildings, one should follow the *Site Inspection—Electrical, Developed*, 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 or in Appendix A.

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.

EMI Electrical Panel Worksheet (ver. 2.1)

Name AIM Church and Office		Project Number KH-S137	Date 31 July 2023
Panel ID (e.g., "PPX-Y" where X=bldg #, and Y= letter of panel within bldg "A" is 1st panel)	DB-6	Panel location (photo of location)	wall by main gate
		ID of panel feeding this panel	utility disconnect
Panel photo #(s)	#2, 3	Distance from last panel (meters)	~56 m from transformer
Temperature (infrared) scan and photo #(s)	no hot spots #41	Safety concerns: Overheating? Damage? Improper cover?	none (recently replaced)
How many floors receive power from this panel?	ground floor +4		
Main breaker rating [A]	63 A	Accessible and labeled considering local maintenance practice?	yes labels for each circuit
Bus voltage [V]	400/230 V		
Phases	3	Special loads (description, quantity, device photo,nameplate photo, and breaker & conductor sizes)	4 AC units 1.2 kW each 16 A breaker 4 mm² wire
If multiple wires to one breaker, acceptable terminal size?	yes		

Draw a panel diagram below and include the following:

☑ Size & material of incoming phase conductor   4 x 16 mm² Cu

☑ Size & material of incoming ground wire   6 mm² Cu

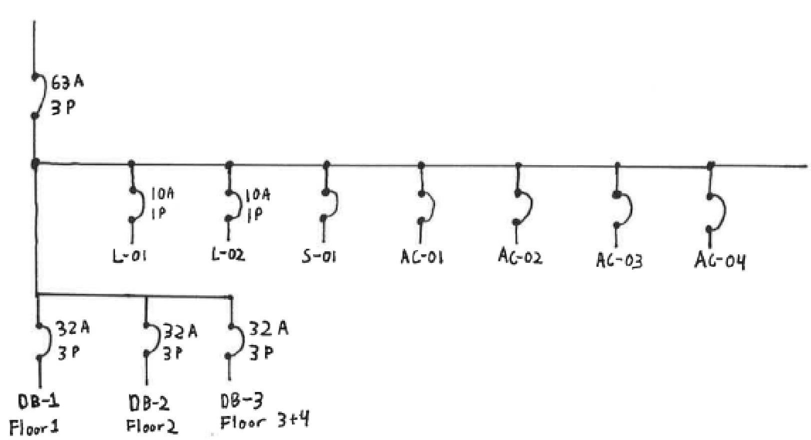


Figure 1: Example of completed Panel Worksheet

2.3 Overhead power distribution

Electrical power is distributed either overhead or underground, and often a mixture of the two is found on site. An inspection of the existing overhead power lines can identify potential safety issues and inform standard practices in that particular region. Even for an undeveloped site, a quick inspection of nearby utility power poles can be helpful when designing. For small sites all poles and overhead wires should be visually inspected, or just a random sample for larger sites, following the guidelines in *Site Inspection—Electrical, Developed*. Any issues should be documented with the conductors, poles, stays, boxes, or other concerns. Aerial Bundled Cable (ABC) uses insulated cables twisted or bundled together, sometimes with the neutral bare metal. Bare aluminum or aluminum conductor steel reinforced (ACSR) has the cables separated by air and insulators at every pole.

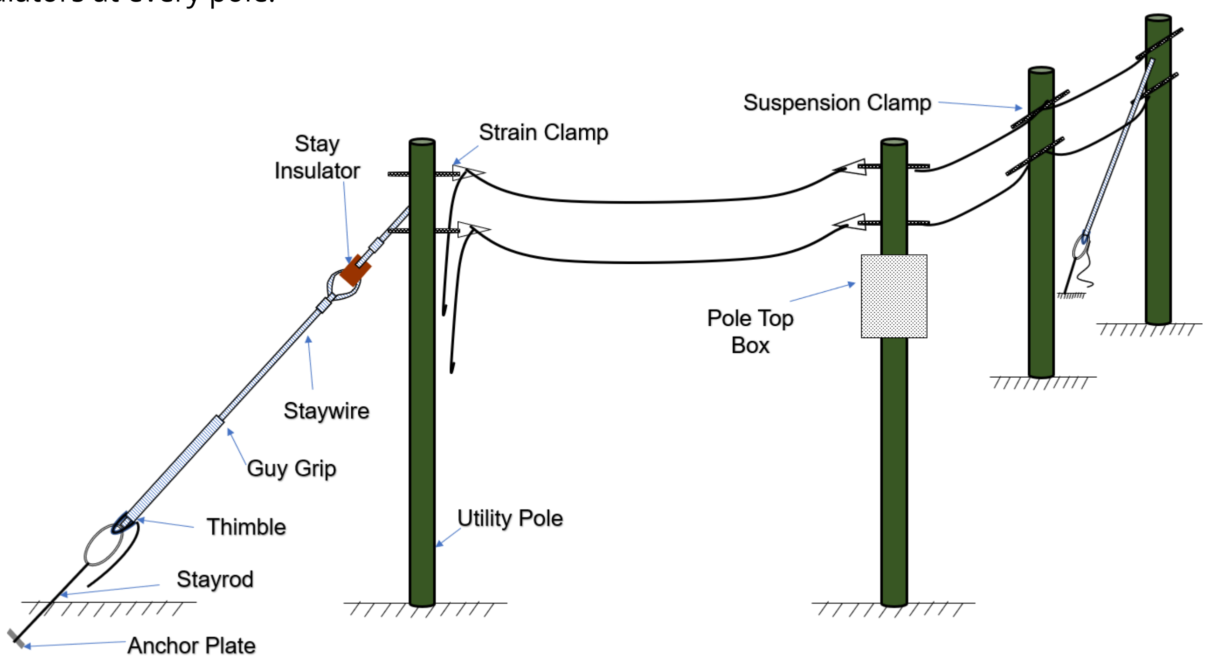


Figure 2: Diagram of the major components of overhead power distribution

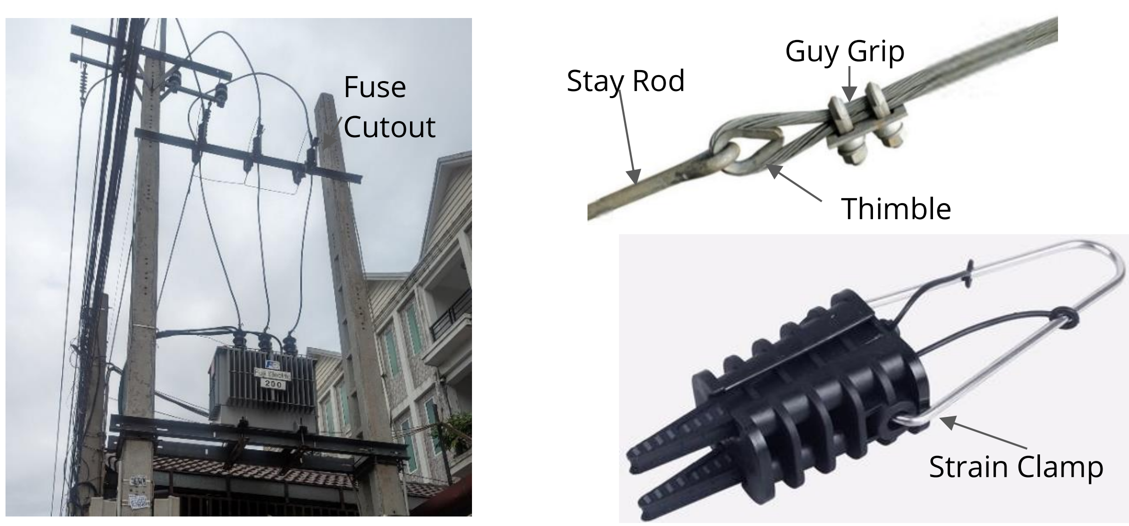


Figure 3: Examples of overhead line accessories

2.4 Grounding System

A properly designed and constructed grounding system is essential for protection from injury and equipment damage and is a critical component of lightning protection (see section 3.8). For an undeveloped 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. EMI recommends any grounding system have a total resistance of less than 25 ohms, and less than 5 ohms if it is protecting any sensitive electronic equipment or transformers.

2.4.1 Soil Resistivity

Soil resistivity data allows the electrical designers to 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 3 to estimate soil resistivity.

Table 3: 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 presentation 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 4. 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. It is advisable to repeat the test with the line of stakes orthogonal to the first series to check for distortion (for example from underground pieces of metal).

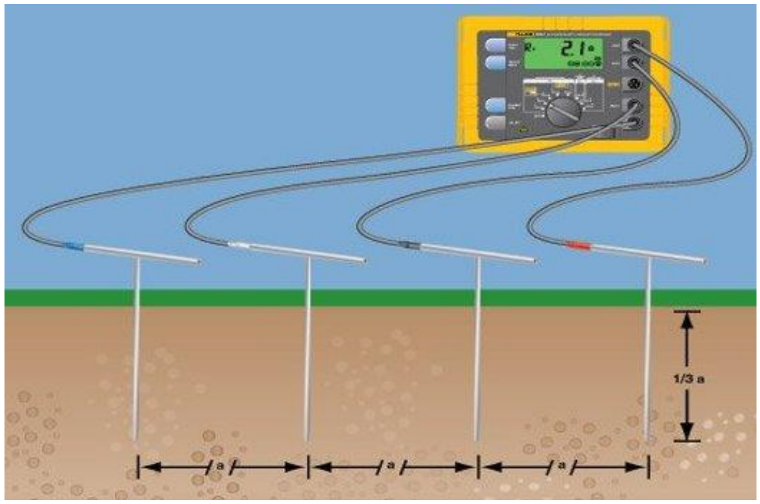


Figure 4: Four-Point Method Soil Resistivity Set Up
Source: Fluke 1625-2 Brochure

Assuming the test is set up correctly and that the probe spacing, *A*, is sufficiently greater than probe depth, *B*, (that is, $A > 3*B$), the soil resistivity (ρ), in ohm-meters, can be calculated using the simplified Wenner formula as:

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

where:
ρ is the soil resistivity in Ωm
A is the probe spacing in meters
R is the measured soil resistance in ohms

The measurement determines the soil resistivity down to a depth of approximately A (the distance between the spikes). By varying A, the resistivity in different soil layers can be checked to determine the suitable grounding electrode type. In the below graph, three different scenarios were measured with A varied between 2m and 30m.

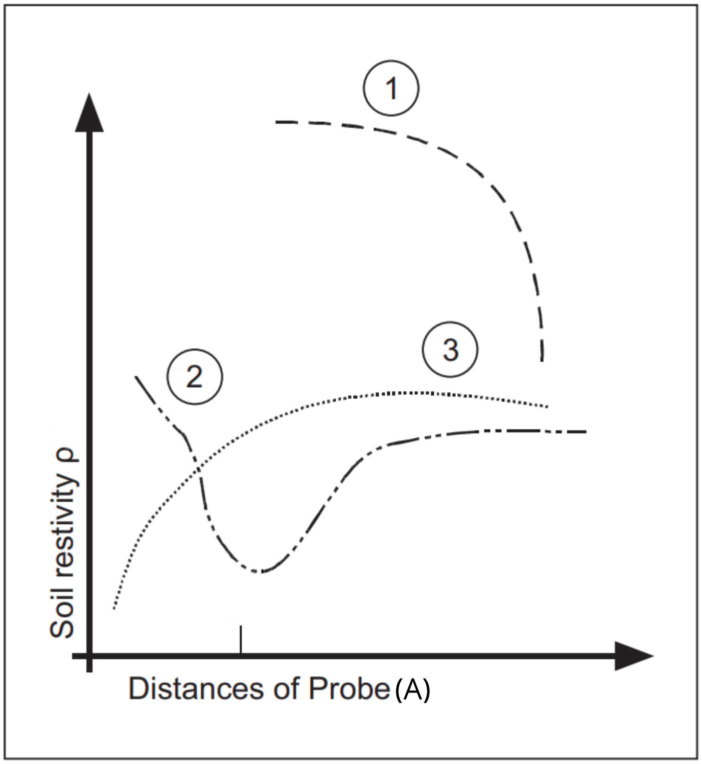


Figure 5: Soil Resistivity with Depth
Source: Fluke 1625-2 User Manual

Case 1: *ρ* decreases deeper down in the soil -> single deep ground electrode

Case 2: *ρ* decreases only down to a point, a further increase in the depth does not improve the values –> multiple shorter electrodes

Case 3: *ρ* does not decrease with depth –> strip conductor electrode mesh grid

2.4.2 Grounding Electrodes

A grounding system involves connecting a conductor (electrode) to a semiconductor (the earth), so 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 x *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. Other acceptable types of electrodes beyond rods include underground metal water pipes, building metal foundation electrodes, concrete encased electrodes, or ground rings/meshes. Therefore, the designer must use engineering judgement in the design of a grounding system.

Simplified calculations for various types of grounding electrodes are given in Appendix B.

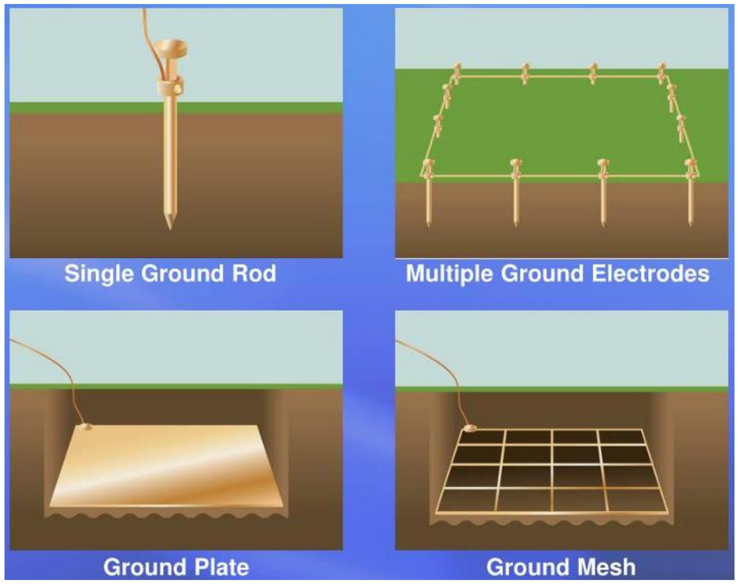


Figure 6: Overview of some ground electrode types

Source: Fluke, Grounding System Tests

For some soil types, soil conditioning (ground enhancing materials added to the soil) might be more cost-effective. EMI does not recommend the use of salt, charcoal, or bentonite; material should follow the IEC 62561-7 standard to ensure longevity of the low-resistance ground. For more information, refer to the reference documents on grounding system design.

2.4.3 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, using wire or equivalent sized copper braid or strips. The "grounding electrode conductor" connects the main ground electrode(s) to the service equipment and is sized based on the largest incoming phase conductor. Table 4 lists the sufficient grounding conductor size for corresponding feeder conductors. Second, the "equipment grounding conductor" connects the service equipment to the load or subpanel and is sized based on the circuit breaker feeding it, see Table 5. 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 size. 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 4: Grounding Electrode Conductor (GEC) Sizing

Largest Ungrounded Service-Entrance Conductor (or Equivalent Area for Parallel Conductors) *AWG or kcmil (mm^2)*		**Minimum Size of GEC Conductor or equivalent copper strip** *AWG or kcmil (mm^2)*	
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 2023 Table 250.66

Table 5: Equipment Grounding Conductor (EGC) Sizing

Rating or setting of automatic over current device in circuit ahead of equipment, conduit, etc. not exceeding: *Apmeres*	**Minimum Size of EGC Conductor** *AWG or kcmil (mm^2)*	
	Copper	**Aluminum or Copper-Clad Aluminum**
15	14 (2.5)	12 (4)
20	12 (4)	10 (6)
60	10 (6)	8 (10)
100	8 (10)	6 (16)
200	6 (16)	4 (25)
300	4 (25)	2 (32)
400	3 (35)	1 (50)
500	2 (32)	1/0 (70)
600	1 (50)	2/0 (70)
800	1/0 (70)	3/0 (95)

Source: NEC 2023 Table 250.122

2.4.4 Grounding Systems and 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 7. Refer to the *Panel Grounding & Bonding Diagram*.

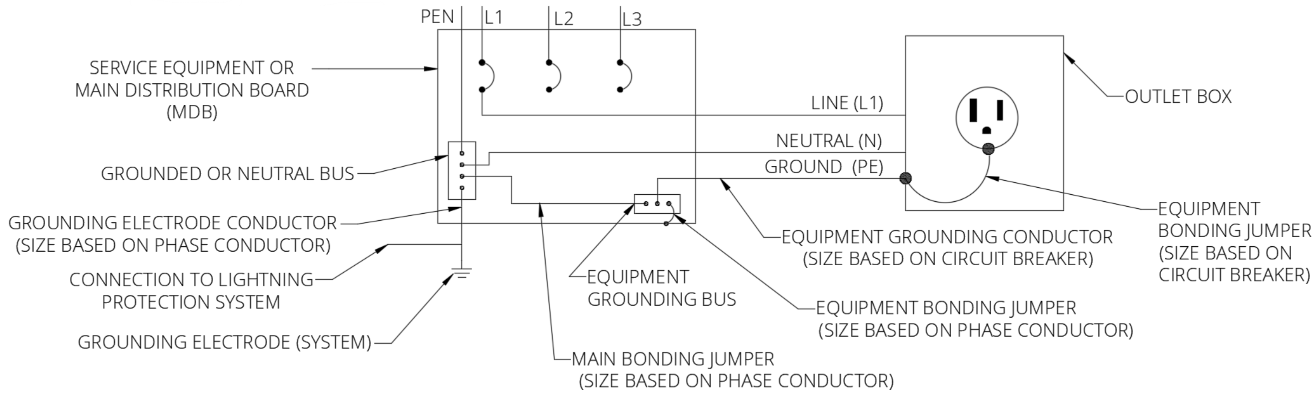


Figure 7: Proper Grounding and Bonding

There are five grounding methods as categorized by the IEEE, designated by a combination of letters. The first letter identifies the source connection to earth:

- T (Terre): one or more parts are connected direct to earth at the source
- I (Isolation): source is isolated from earth, or one point is connected through impedance

The second letter identifies the consumer's installation:

- T (Terre): also directly connected to earth, independent of the grounding at the source
- N (Neutral): Connection of earth directly to the neutral power supply cable
    - N-C (Neutral-Combined): the neutral and ground functions are combined in a single conductor on both the incoming supply and in the consumer's installation
    - N-S (Neutral-Separate): the neutral and ground functions are provided by separate conductors on both sides
    - N-C-S (Neutral-Combined-Separate): The neutral and ground functions are combined on the incoming supply and separated on the consumer's side

2.4.4.1 Recommended TN-C-S Grounding System

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 to create the separate conductors. This type of grounding, shown in Figure 8, is called TN-C-S, also known as Multiple Earthed Neutral (MEN) or Protective Multiple Earthing (PME). This is the same scheme used commonly in the US as recommended in the NEC article 250.

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 certain countries; consult the country-specific guidance for those projects.

The other four systems are explained in more detail in Appendix C. They are the TT system (source and consumer have electrically independent earths-two "Terres"), the TN-C (combined neutral and grounding), TN-S (separate ground wire to every building, also known as "5-wire"), and the IT (isolated grounding) systems.

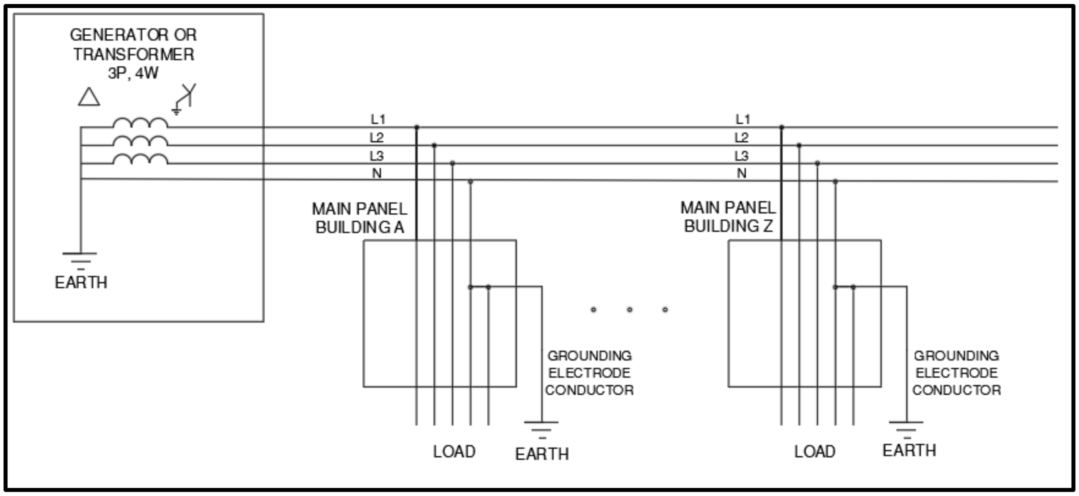


Figure 8: Site Grounding Layout for TN-C-S

2.4.5 Existing 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 and set-up 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 9. The current probe must be placed at a distance (D2) well outside of the interfacing hemisphere of the grounding system.

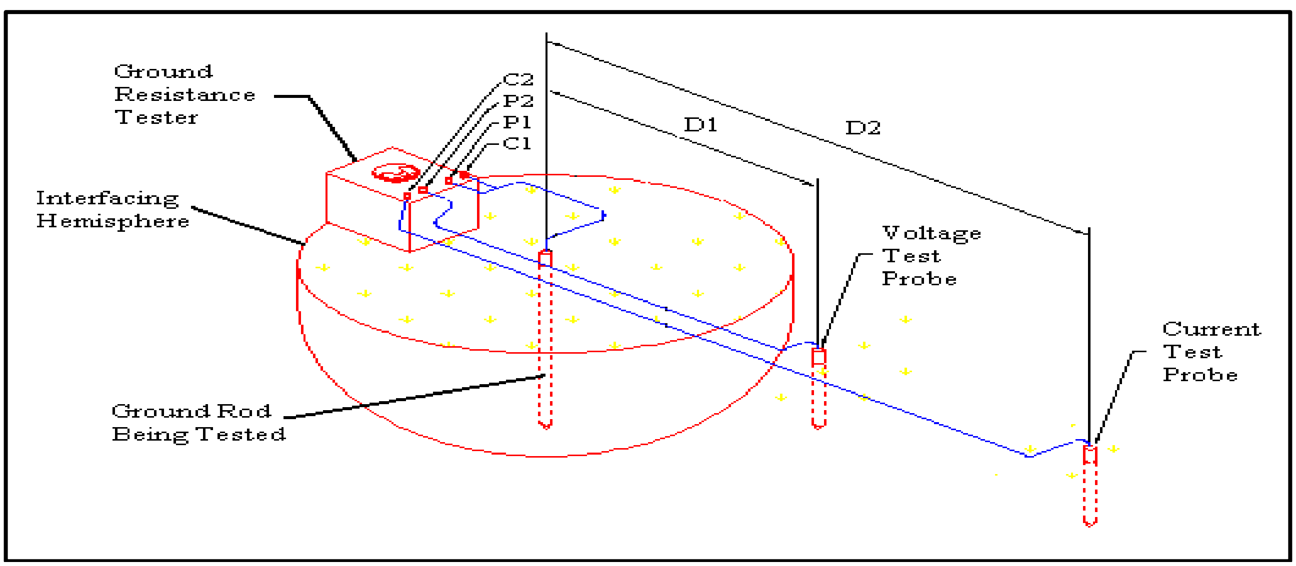


Figure 9: Fall of Potential Test Set up on Existing Grounding System

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 10. The normal practice is to use the value at 62% of distance to the current probe D2.

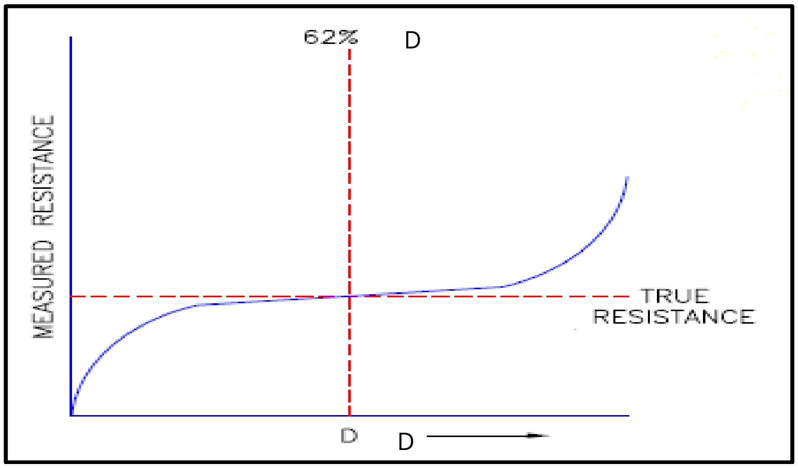


Figure 10: Plot of Properly Conducted FOP Test Results

If the results do not fit the expected curve (e.g., the resistivity never levels off), the current test probe is likely too close to the system under test. If the test equipment returns a voltage or "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.

2.5 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 of voltage spikes) damage and personal 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 logger, 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 need to be completed for a power quality analysis and to finalize the locations and ratings of the various solutions. Table 6 lists common power quality issues and possible solutions.

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.

Table 6: Power Quality Analysis Matrix

Issue	Potential Solution
High transient surges	Voltage Regulation.
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 (see section 3.5.2 Voltage Drop Calculation)
High inrush current	Latching relays for offending appliances (e.g., air conditioners, water heaters, pumps, …)
Harmonic distortion	Voltage Regulation; fully rated equipment neutral and neutral conductor; filter.
Poor Power Factor (< 0.8)	Switching fluorescent lighting for LED. Identify low power factor equipment that could be updated. Power Factor Correction (usually capacitance).

2.5.1 Surge Protective Devices

Problematic transient voltage surges usually come from one of two sources: either from lightning or from the switching on and off of large pieces of electrical equipment further "upstream" on the grid. These sub-cycle transient voltage surges can result in peak voltages many times the nominal peak of the 50/60Hz sinewave and can be especially damaging to sensitive equipment such as that found in a hospital or an administration office. Even seemingly more robust types of equipment with either a resistive heating element (e.g. kettle, clothes dryer) or something with a large electric motor (e.g. air-conditioner) can be affected due to failure of the associated insulation, even if no delicate electronics are present. A surge protective device (SPD) suppresses these excessive transient voltages. Table 7 summarizes the most common SPDs.

Table 7: Surge Protection Devices

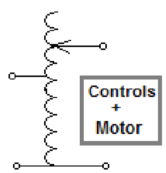
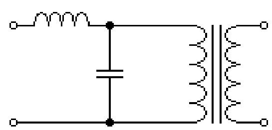
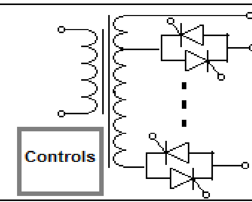
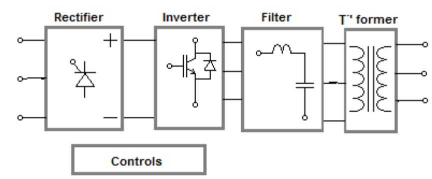
Parameters	Metal Oxide Varistor (MOV)	Constant Voltage Transformer (CVT)	"Double-Conversion" UPS
Main Advantages	Relatively cheap	Good surge suppression Provides very good and fast voltage regulation	Good surge protection, voltage regulation and back-up when grid is briefly absent
Main Disadvantages	Clamping voltage is 2x peak, so protection is not perfect	Heavy, noisy, hot Heat up when under loaded Limited overload capability so cannot be used for loads with large motors Limited kVA rating; ≤ 20 kVA / phase	More complicated than MOV or CVT
Initial cost	Relatively cheap	Expensive, if sourced in US (foreign options may be available)	Expensive, but offers additional capability
Lifecycle & maintenance issues	Degrades with use, and so needs occasional replacement	Minimal maintenance. Capacitors that come standard can fail quickly, and may need to be replaced with higher quality capacitors ~ 10-year life Also, draws current even with no load	Requires maintenance every ~7 years or less for fans and capacitors Occasional battery replacement if present 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 and large medical devices

2.5.2 VOLTAGE REGULATION

A voltage regulator must be incorporated into 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 for critical areas. 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. A generator with an automatic transfer switch can be used for voltage regulation if the thresholds on the ATS are adjusted to protect equipment. However, in the long term this is more expensive. A similar setup could also be done with batteries to create an alternative supply to switch to when the utility is out of spec. This comparison can assist in making a financial case for a voltage regulator.

Table 8 is a comparison of four major types of voltage regulation devices. For more details on these please see Appendix D.

Table 8: Voltage Regulation Devices

Parameters	Motorized Variable Transformer	Constant Voltage Transformer (CVT)	Solid-State Tap-Changer	"Double-Conversion" UPS
Main Advantages	Relatively inexpensive solution	Good voltage regulation, surge protection, and distortion isolation	Good overload capability, so can be used with large motors	Good voltage regulation and provides surge protection with optional battery back-up power
Main Disadvantages	Slow activation, not for sensitive equipment. Must pay more for independent 3 phase regulation. Motor noise	Can be too hot to touch (100°C), noisy, and heavy. Limited O/L capability so cannot be used with large motors Limited kVA rating; ≤ 20 kVA / phase	Until the tap is changed, input goes straight thru to the output.	More complicated electronics
Initial cost	Relatively cheap per kVA	Expensive, if sourced in US	Expensive, few suppliers	Inexpensive
Simplified Schematic				
Voltage Regulation	± 1% for ±15% standard version, ±25% available.	±5% for +10/-20%, Transiently +20/-35% i/p.	±3% output for +10/-20% input	± 1% static ±5% dynamic stability in 10ms for +20/-25% change in output
Response Time	0.1 to 3 sec. due to mechanically moving brushes	1½ cycles; but within that time the output will only be a few % out of spec.	< ½ cycle, Output back to ±3% within 1½ cycles.	Not applicable/0 seconds
Lifecycle & maintenance issues	Requires regular maintenance for wear on carbon brushes Electronic relay needs to be replaced every few years 7-year lifetime if unmaintained	Minimal maintenance (Clean out dust and bugs). Capacitors fail and need replaced ~ 10-year lifetime Potential for overheating	Minimal maintenance (Clean out dust and bugs). 20-year lifetime	Requires maintenance: Riello says MTBF of bus caps is 5 years Fans need to be replaced, and batteries if present 20-year 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 continuously clean power & surge protection; such as the admin computer system and large medical devices
Example Mfr	Galco	SOLA	Siemens	Riello

2.5.3 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 operating rooms), the standard recommends <3.0%.

Harmonic distortion can be caused by some common equipment that converts AC to DC, especially the odd (3rd, 5th, 7th) harmonics, such as large battery inverters, UPS systems, or large numbers of LEDs. These all can inject harmonics upstream. 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). Additionally, some utilities will penalize customers with high harmonics. New equipment can be specified to limit distortion. Harmonic distortion can be addressed using reactors (chokes), isolating transformers, or filters.

2.5.4 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 11. The remainder, called reactive power, exists in the creation and collapse of magnetic and/or electric fields in inductors such as motor coils and capacitors. 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.

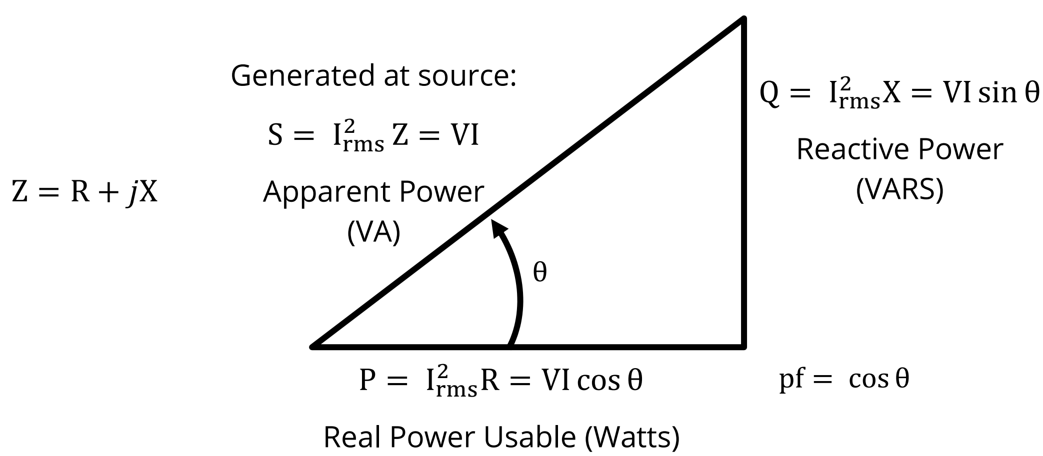


Figure 11: The Power Triangle

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 can 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.

To correct poor power factor, easy solutions such as converting fluorescent lighting to LED or upgrading the motors can be considered. Additionally, solar inverters can have features to correct power factor. If one cannot correct the inductive loads, and the cost penalty justifies it, as a last resort the customer can add a capacitive load, which creates a leading power factor. Table 9 summarizes how this can be done. As 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 should be placed at the loads or must adjust with the variation of the loads.

Table 9: 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).

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.

Reference drawing E0.0 shows the standard symbols used by EMI to depict the components of the electrical system, 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.

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* E2.0, is an example of a conceptual-level single line diagram for a small site. The three power sources in this example are the public utility, backup generator, and grid-tied solar.

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 the *Developed Single Line Diagram E2.0* 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. 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, for an example see drawing E2.1. This can be done by showing changes to the existing diagram (such as using a red line color 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 3.5. These details should be added to a new version of the detailed single line diagram.

3.2 Panel Naming Recommendations

Every power panel should be given a unique name that indicates something about its function and location. Here is a recommended naming scheme using the type (main panel, building power panel, or subpanel), the building number, and then a letter designation if there are multiple subpanels in one building. If the site already has panel identifiers on the physical panels or drawings, it is usually best to continue the convention. If you use another naming convention, it is recommended to include a small legend tab explaining it.

MDP

- Main Distribution Panel (typically just one per project)
- Service entry into the site

PP#

- Power Panel # (# is the building number from the site plan)
- Examples PP1, PP2, … PP10 etc.
- Main feed into each building. These can contain further distribution and/or branch circuits.

SP#X

- SubPanel # (# is the same building number) X is the lettered subpanel designator.
- Examples SP1A feeds from PP1, SP2A and SP2B both feed from PP2, etc.
- Branch circuits to a particular area (for example ground floor, 1st floor, etc.)

3.3 Electrical Site Plan

The *Electrical Site Plan*, shown in drawing E1.0, 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, PP1, etc.) are also specified.

3.4 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. 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. 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 *Electrical Design Tools 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 10 can be used for initial calculations.

Table 10: 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	**Fluorescent**	$5W/m^2$ ($0.46W/ft^2$)		General Purpose $7W/m^2$ ($0.6W/ft^2$)	Operating or Procedure Room $27W/m^2$ ($2.5W/ft^2$)
	LED	$2W/m^2$ ($0.18W/ft^2$)		$3W/m^2$ ($0.24W/ft^2$)	$11W/m^2$ ($1W/ft^2$)
Receptacle (Outlet) Loads		Calculate HVAC & A/V as special loads	$1W/m^2$ ($0.09W/ft^2$)	Calculate equipment as special loads	
Fans		$3W/m^2$ ($0.28W/ft^2$)			

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 them 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.

3.5 Detailed Electrical Design

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

3.5.1 Lighting and Power Drawings

The building wiring diagrams *E4.0 Ground Floor Lighting Wiring Plan* and *E5.0 Ground Floor Power Wiring Plan* 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 Tools folder to show EMI standards for such drawings if they are to be part of the project deliverables.

3.5.2 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. With an expected voltage drop of up to 5% from the power generation to the main panel, and an additional 1% estimated between the subpanel and the load, this leads to a maximum drop of 10% at the equipment. While this recommendation is less conservative than the NEC, EMI has found this to be reasonable and balances practical considerations. 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:

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

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

3.5.3 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 *Example Panel Schedules.xlsx*, the total load for circuit #2 on panel PP2 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:

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

3.5.4 Ground Fault, Earth Leakage, and Residual Current Devices

Electrical faults can cause fatal injuries to people, even with low amounts of current (above 30mA). To increase the safety of electrical systems, sensors have been developed that detect a fault and interrupt the circuit to protect the person that fault may be flowing through. There are several names of the devices that vary across regions, but the basic principle is the same for a ground fault circuit interrupter (GFCI or GFI), residual-current device (RCD), or earth leakage circuit breaker (ELCB).

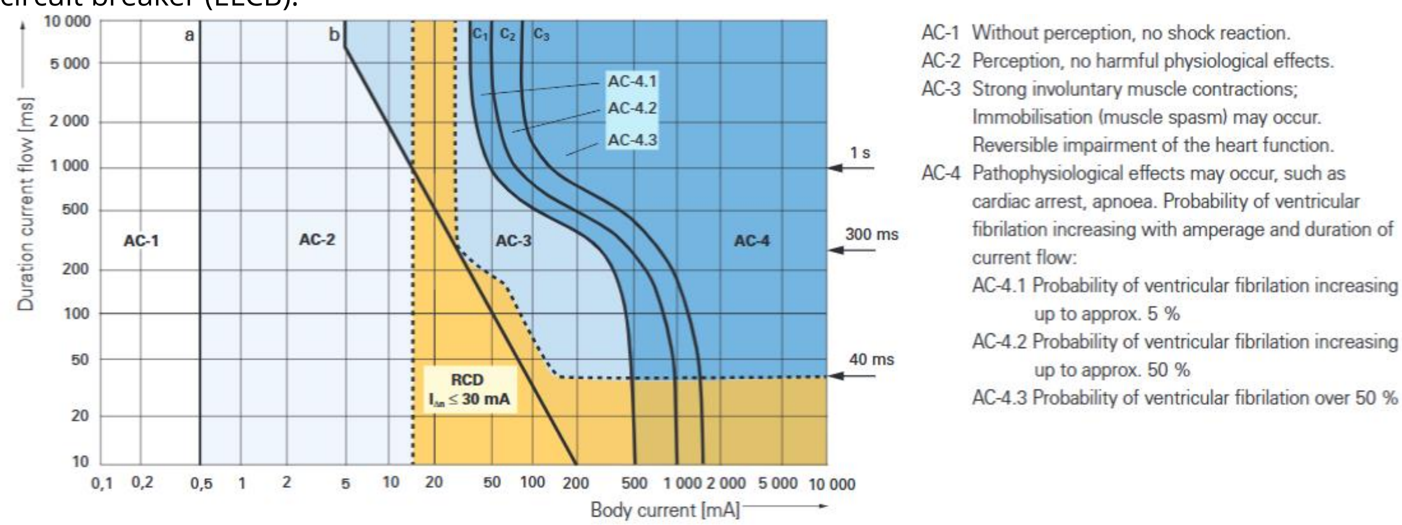
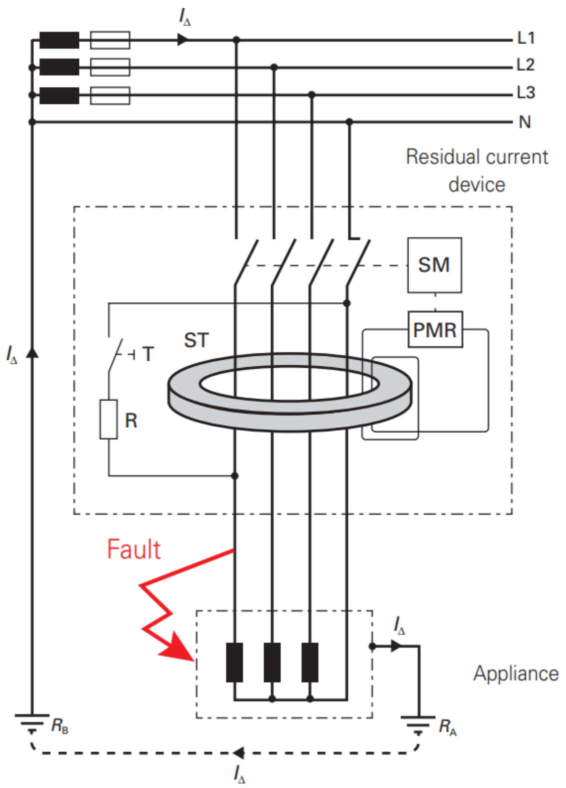


Figure 12: Effects of AC on persons from the left arm into the feet
Source: Eaton RCD Application Guide

Essentially these devices are used to detect a ground fault and turn off the circuit. They continually measure the current coming in and out of a circuit. In normal operation, the current in (or sum of all phases, L1, L2, and L3) is exactly the same as the current out (along the neutral), thus the current loop around all wires detects zero differential (or residual) current. However, when there is an alternate path to ground from a fault, some current will flow on that path leading to an imbalance in the wires which will trigger the switch and interrupt the current.



SM	switching mechanism
PMR	permanent magnet relay
ST	summation current transformer
T	test button
R	resistor
I_Δ	residual current
R_A	appliance earthing resistance
R_B	power supply earthing resistance

TT network is used for description here, but the same applies analogously for other

Figure 13: Residual Current Device connection
Source: Eaton RCD Application Guide

RCDs are typically installed in the panel and protect the entire branch circuit but will also trip the entire circuit if there is a fault anywhere along it, for example see the left picture of Figure 14. They are identifiable by their test button, usually labeled with a large T and they must list their residual current limit ($I_{\Delta N}$). For human safety this should be 30mA or less. Simple RCDs will only have fault detection and must be installed with separate over current protection (RCCB). However, they can also be integrated with overcurrent protection known as a residual current circuit breaker with overcurrent protection (RCBO).

The other option is for these devices to be part of the outlet itself (right of Figure 14). This is common in the US with GFCI outlets which will also include the test and reset buttons with the circuitry. With this type, the fault can be isolated just to the faulty load itself or any additional outlets connected downstream and can be easily reset at the outlet once the fault is corrected rather than having to trace it back to the panel.

Figure 14: Examples of RCDs, DIN rail mounted and integrated to the outlet

Placement should be in compliance with local codes, which commonly require them in areas that could be wet such as bathrooms, kitchen/laboratory counters, and outdoor outlets. Generally, any outlet within 2m (6 feet) of a sink should have protection. But when a TT ground system is used all outlet circuits must have RCD protection since the neutral is never bonded to ground. RCDs are also not recommended in operating rooms as the risk to the patient of medical equipment suddenly tripping off is high. Note that the neutral and ground cannot be bonded downstream of an RCD.

3.5.5 Panel Design

The *Template of Panel Schedules.xlsx* contains EMI's standard panel schedule format, and the *Example Panel Schedules.xslx* shows how to design the layout of electrical system panels. This includes a main distribution panel (MDP), main building panels (PP#), and subpanels in both US style (breakers arranged vertically) and European style (breakers arranged horizontally) which are commonly found throughout Africa and Asia. 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 bus bars and their connection to each circuit breaker. Circuits shown with a line connecting them together represent a 3-phase circuit breaker. The total power consumption of the three-phase loads should be evenly distributed across the three phases. 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 PP2 (US style) 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 (in Amps) on each phase. This is to aid the designer in balancing the total load across the phases.

3.6 Motors

Motors are used all throughout the world to allow mechanical advantage to make tasks easier and to be completed faster. Pumps and fans are used to move water and air.

3.6.1 Types of Motors

The majority of all motors are single phase or three phase induction motors. Other motors might be considered for specific needs, below is a brief description of the available types.

3.6.1.1 DC Motors

- **Series (Universal) -** Also called a universal motor because it can be used in DC or AC applications. It has a high starting torque and a variable speed characteristic. The motor can start heavy loads, but the speed will increase as the load is decreased.
- Shunt - Give essentially constant field strength and motor speed.
- Compound - Has high starting torque and good speed torque characteristics at rated load. Because complicated circuits are needed to control the compound motor, this wiring arrangement is usually only used on large bi-directional motors.

3.6.1.2 AC Motors

- Single-Phase Motors
  - **Synchronous** – Able to maintain a constant speed synchronized with the frequency of the incoming current. They have high efficiency, and are used for compressors, pumps, and fans.
  - **Shaded-pole induction** – original AC induction motor with an auxiliary single-turn winding surrounding a portion of each pole that “shades” it enough to delay the phase of magnetic flux and provide a rotating field. Produces a small starting torque, but economical and reliable for small loads.
  - Split-phase - commonly used in major appliances such as air conditioners and clothes dryers that provide a higher starting torque.
  - Series – modified version of the DC motor for use with AC, high starting speed and torque.
- Three-Phase Motors
  - **Induction (Squirrel-cage)** – most common motor, simple design, low cost, high reliability, good longevity. They are self-starting but have a low starting torque and can have low power factor.
  - Synchronous – better power factor than induction motors, often also used as alternators to generate electricity.
  - Dual-Voltage – ability to be used with two different power line voltages or configured in wye or delta.
  - Part-Winding - Motor windings are split in two, so it starts with full voltage and 1/2 windings, then switches to full windings after motor is going.

3.6.2 Definitions

- FLA / FLC / RLA - Full Load Amps. Full Load Current. Running Load Amps. This is the running amps that will be drawn during normal operation.
- LRA / LRC - Locked Rotor Amps (current). Inrush current at full voltage start up. Typically, 6 * FLC.
- MCA - Minimum Conductor Ampacity. Select wire size equal to or greater.
- MOCP - Maximum Over-Current Protection. Max size of circuit breaker that will still protect equipment. Select breaker equal to or smaller.

3.6.3 Sizing of motor protection

Sometimes EMI designs require sizing of the feeder circuits and overcurrent protection for motors. The first step is to figure out how much current it will draw. The full load amps (FLA) can be calculated from the power (in kW or hp read from the nameplate) using the following equations or tables that can be found in the NEC table 430.

- Single Phase AC Motor FLA (Amperes) = $(P\ [kW] \times 1000) / (V \times \cos\varphi)$
- Single Phase AC Motor FLA (Amperes) = $(P\ [HP] \times 746) / (V \times \cos\varphi \times \eta)$
- Three Phase AC Motor FLA (Amperes) = $(P\ [kW] \times 1000) / (V \times 1.732 \times \cos\varphi)$
- Three Phase AC Motor FLA (Amperes) = $(P\ [HP] \times 746) / (V \times 1.732 \times \cos\varphi \times \eta)$

Where:

P [HP] or P [kW] = Motor power rating in HP or kW
V = Motor rated voltage (Volts)
η = Motor efficiency (decimal)
$\cos\varphi$ = Motor power factor
1000 = Conversion factor to convert kW to W
746 = Conversion factor to convert HP to W

Source: https://goodcalculators.com/motor-fla-calculator/

1. Motor feeder: (MCA) = 1.25 x FLA
2. Motor maximum overcurrent protection: (MOCP) = 1.5 x FLA
3. Motor disconnect: (MCA) = 1.25 x FLA

3.6.4 Power factor and inrush information

Most fully loaded induction motors operate between 0.8 and 0.9 power factor (pf). This will drop to as small as 0.2 pf when unloaded.

Induction motor inrush can be as high as 20 times nominal current in the first ½ cycle and then continue to be as high as 4-6 times for a few seconds.

3.6.5 Special Considerations

In many environments where EMI does work there are numerous power quality issues. For that reason, the following might be considered for motor and motor load protection.

- Phase Sequence Relay- In some areas power service sequence might shift from ABC, to CBA. This would cause three phase motor to run in reverse.
- Phase Loss Relay- In many areas it is common to drop a phase. This can quickly damage three phase motors.
- Under Voltage and Over Voltage Relays- Voltage regulation can be a significant problem and will do motor damage and reduce life. Variation should be less than +/- 5%. But greater than +/- 10% might be quite common. Some investigation at a site is often warranted.
- Phase Voltage Relay (PVR) – it common to use these to incorporate all these functions.

3.7 Motor Starters

A starter is made up of two components: a controller (most often a magnetic contactor) and overload protection. See section 3.7.3 for typical details.

The controller is a switch or a set of contactors that start or stop electric current flowing to the motor. Contactors are fitted with operating coils that can utilize pushbuttons to open and close the motor control circuit or they can also be operated using a remote-control signal. Take care to verify that the coil is rated for the correct frequency and voltage.

The overload protection is a device that protects motors from drawing too much current and over-heating, from literally "burning out."

Safety must be paramount. Always ensure that motor circuits can be "padlocked" off. If the motor control is not visible when working at the motor, then add a simple switch near the motor for lock-out.

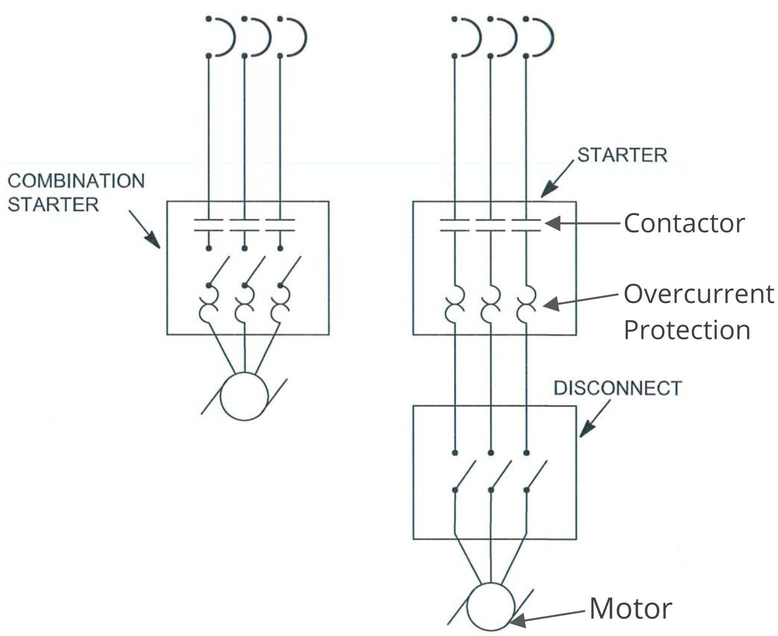


Figure 15: Motor starter components

3.7.1 Types of Motor Starters

- Reduced Voltage:
  - Also called "Soft Start"
  - Types include:
    - Auto-Transformer ("Korndorfer")
    - Wye-Delta ("Star-Delta")
    - Part-Winding
- Full-Voltage, Non-Reversing:
  - Also called "Across-the-Line" or "Direct-on-Line" (DOL)
  - Single direction
  - Single speed
  - Magnetic
- Full-Voltage, Reversing:
  - Also called "Reversing Starter"
  - Two directions (Forward and Reverse)
  - Single speed
  - Magnetic
- Multi-Speed:
  - Single direction
  - More than one speed

3.7.2 Types of Reduced Voltage ("Soft Start") Starters

- Wye-Delta ("Star-Delta"):
  - Starts with the Wye (reduced voltage) wiring, then switches to Delta (full voltage) wiring.
  - 2 sets of cables going to motor.
  - 6 terminal motor required. ("Delta Connected")
- Auto-Transformer ("Korndorfer"):
  - Can be set to start at 50, 65, or 80% full voltage, then will switch to 100% after motor is going.
  - Single electrical connection to motor.
  - No special motor needed.
- Electronic Soft Starters and Variable Frequency Drives:
  - Allows programming.
  - May require a special motor.
  - Greatly increases the life of a motor.
- Part-Winding:
  - Motor windings are split in two. Starts with full voltage and 1/2 windings, the switches to full windings after motor is going.
  - Can be single voltage or dual voltage.
  - Part winding motor required.

3.7.3 Combination Starters

- A combination that uses a Circuit Breaker disconnecting means with a contactor and an overload relay:
  - Mag-Breaker (provides isolation switching and short-circuit protection (magnetic), but no overload protection (thermal)),
    - Optionally, a Thermal-Mag Circuit Breaker (provides isolation switching, overload protection (thermal), short-circuit protection (magnetic)). A thermal magnetic breaker should only be used if it can be demonstrated that the short time thermal performance will allow motor starting.
  - Controller (most often a magnetic contactor)
  - Overload Protection (Usually on overload relay)
- A combination that uses a fused switch disconnecting means with a contactor and an overload relay:
    - Fused disconnect switch (provides an isolation switch, and fuse protection. This fuse can be selected as time delay type (slow blow) to facilitate motor. For example, NEMA Class "R".
  - Controller (most often a magnetic contactor)
  - Overload Protection (Usually on overload relay)

3.7.4 Starter Size

Motor voltage, frequency, HP rating (or kW rating), and duty cycle are required for starter selection. The contactor and overload relay must be rated for the continuous current of the inductive motor load. Slower acting overload relays are available for constant torque or constant horsepower loads.

Most overload relays are adjustable. Initially, you might simply select a worse case ampacity, and it can be adjusted when final circuit and motor characteristics have been determined.

3.7.5 Starter Duty

- Standard: infrequent starting/stopping
- Less frequently encountered:
  - Jogging (Inching): frequent starting/stopping, machinery requiring precise position.
  - Plug-Stop: reverse phases while in operation to stop motor suddenly.
    - Special duties may require special motors and starter designs

3.8 Lightning Protection Systems

Lightning poses significant risks to humans, animals, and equipment at many sites, but lightning protection systems (LPS) are often poorly understood. This guide serves as a starting point to understand the basics of a system to help the electrical engineers identify sites/structures at risk and select a system to reduce the risk of damage from lightning. For more information see the following standards and references:

- NFPA 780 Standard for the Installation of Lightning Protection Systems
  free access at https://link.nfpa.org/free-access/publications/780/2023
- IEC 62305 series (EN 62305-3 and EN 62305-4) available at: https://solargostaran.com/files/standards/IEC/IEC%2062305-3-2010.pdf
- UL (Underwriter Laboratories) UL 96A
- Lightning Protection Institute LPI 175
- Lightning Protection Guide – 3rd Edition
  reference in folder from: https://www.dehn-ua.com/en/lightning-protection-guide
- IEEE C62.41 Guide on the Surge Environment in Low-Voltage (1000 V and less) AC Power Circuits

3.8.1 Risk Assessment

A risk assessment is used to decide if a lightning protection system (LPS) is necessary, or what level of protection to use. However, certain characteristics require such a system regardless of the calculation result – for example places with large crowds, a structure providing a critical service, or areas with known high lightning frequency or as required by local codes. Solar arrays (especially roof mounted or in large fields), livestock, or other special installations should be protected as well. Refer to the reference document *Lightning Protection Guide* for more detailed information on installations.

There are two primary risk calculation methods in use. One is the standard in North America from the NFPA 780 Appendix L. The NFPA simplified calculation method is summarized here, or you can use a variety of free online calculators. The second method is European based on the IEC standard and accompanying calculator.

The simplified risk assessment method starts with calculating the annual threat of occurrence:

$$N_D = (N_G)(A_D)(C_D)(10^{-6}) \text{ events/year}$$

where:

N_D is the average lightning strike frequency to the facility (threat of occurrence).

N_G is the lighting flash density in flashes/km^2/year, see lightning density maps for example Viasala from https://interactive-lightning-map.vaisala.com/ by state/province for every country.

A_D is the equivalent collection area of the structure in m^2 of the structure with a line with a slope of 1/3 around it to the ground. For a rectangular building:

$$A_D = LW + 6H(L + W) + 9\pi H^2$$

L is the length of the building in meters
W is the width of the building in meters
H is the height of the building in meters

C_D is the location coefficient as given in Table 11:

Table 11: Lightning Risk Location Factor

Coefficient:	Low-risk			High-risk
Location factor	**0.25** Structure surrounded by taller structures or trees within 3*H	**0.5** Structure surrounded by structures of equal or lesser height within 3*H	**1.0** Isolated structure, with no other structures located within 3*H	**2.0** Isolated Structure on a hilltop

Second, calculate the tolerable lighting frequency.

$$N_C = \frac{1.5 \times 10^{-3}}{C}\ events/year$$

where:

C is the product (C_2 x C_3 x C_4 x C_5) of the various coefficients in the following table:

Table 12: Lightning Risk Structure Coefficients

Coefficient:	Low-risk				High-risk
Construction C_2	**0.5** Metal Structure and metal roof	**1** One nonmetallic and one metal, or both nonmetallic	**2** One combustible, one metal	**2.5** One combustible, one non-metallic	**3** Combustible roof and combustible structure
Structure Contents C_3	**0.5** Low value, non-combustible	**1** Standard value, non-combustible	**2** High value, moderate combustibility	**3** Exceptional value, flammable liquids, computers, electronics	**4** Exceptional value, irreplaceable cultural items
Structure Occupancy C_4	**0.5** Unoccupied		**1** Normally occupied		**3** Difficult to evacuate or risk of panic
Lightning Consequence C_5	**1** Continuity of facility services not required, no environmental impact		**5** Continuity of facility services required, no environmental impact		**10** Consequences to the environment

If the annual threat occurrence is greater than the tolerable lightning frequency, an LPS system is needed.

$N_D > N_C$: LPS recommended

$N_D < N_C$: LPS not required

Example:

A dorm building is proposed for a campus in Pailin, Cambodia, with a lighting flash density of 44.1 events/km^2/year. The dorm building is 16.5m x 12m, 4 stories with a peak height of 19.5m. It will be located on a flat site with no trees and will be taller than nearby surrounding structures. The construction will be a concrete structure with a tile roof. Does this building need an LPS?

Step 1: Annual threat of occurrence:

N_G = 44.1
A_D = $16.5\ x\ 12 + 6\ x\ 19.5(16.5 + 12) + 9\pi 19.5^2 = 14{,}283.8,$
C_D = 0.5

$$N_D = (44.1)(14283.8)(0.5)(10^{-6}) = 0.31495 \text{ events/year}$$

Step 2: Tolerable lightning frequency:

C_2 = 1 (non-metallic structure and roof)
C_3 = 2 (standard value, moderately combustible wood furniture, bedding, kitchen items)
C_4 = 1 (normally occupied)
C_5 = 1 (no critical services, no environmental impact)
C = $1\ x\ 2\ x\ 1\ x\ 1 = 2$

$$N_C = \frac{1.5\ \times\ 10^{-3}}{2} = 0.00075\ events/year$$

Step 3: Evaluate:

$0.31495 > 0.00075$, therefore, a lightning protection system should be designed.

3.8.2 Basic components

There are six major components of a lightning protection system. The first three comprise the "external" parts, and the final three are "internal".

3.8.2.1 Capture the Lightning Strike

Lightning energy is captured by an air-termination system, which is designed to protect the actual structure or volume being protected from direct contact with the lightning strike. These are commonly rods, spanned wires or cables, or meshed conductors. Most importantly these need to protect the corners and edges of roofs or the upper part of a façade. There are several methods to determine the arrangement and position of the air terminals, typically the rolling sphere method and the angle of protection method detailed in section 3.8.4 and 3.8.5.

There are three types:

1. Integral air-termination system – strike termination devices mounted on the structure
2. Mast system – one or more poles with a strike termination device
3. Catenary system – wires stretched between the tops of two or more masts

3.8.2.2 CONVEY THIS ENERGY TO GROUND

Once the lightning strike is captured, the current needs to flow down to the ground. This is accomplished by down conductors. International standards recommend at least two on any kind of structure, or large structures longer than 250 ft (76 m) should have one every 100 ft (30 m). These should be placed to make the most direct course from the terminal to the grounding system. Ensure that there are no loops (or nearly closed squares) as the magnetic force generated by the high currents can cause significant mechanical damage.

The down conductors should carry all the lightning current to ground, but there is a risk of uncontrolled flashover between it and any metal/electrical installations in the building or solar array being protected. The risk is mitigated by maintaining a minimum separation distance between the LPS components and unrelated metal. The distance depends on many factors, see chapter 5.6 of the Lightning Protection Guide for calculation details.

Down conductors need to be made from copper strip, flat braid, and/or stranded wire (high surface area) because lightning is by nature a high frequency (low period) event and high-frequency currents travel on the surface of conductors due to the skin effect. The minimum conductor size according to the IEC standard is 50mm^2, but if secured so that its mechanical strength is not an issue the size may be lowered to 25mm^2. If the structure is steel framed, the steel or other metal can be used as the down conductor as long as all metal components are properly bonded all the way to the ground electrode. Down conductors can be protected by non-conductive conduit from the ground up to a typical person's reach to prevent mechanical damage/fraying of the wires as well as reduce the potential for touch.

3.8.2.3 DISSIPATE THE ENERGY INTO THE EARTH

Solid, low-impedance grounding carries the energy of the lightning strike to the earth and dissipates it safely across the surface. The current typically spreads out horizontally across the surface, so grounding designs that are shallow tend to work better. This could be a ground ring around a structure with horizontal radials branching outward at each corner, or a mesh underneath the structure.

Refer to section 2.4 for more information on grounding.

3.8.2.4 PROTECT PEOPLE BY BONDING ALL GROUND POINTS TOGETHER

Creating an "equipotential plane" within the lightning protection zone prevents dangerous side-flashes due to potential differences between devices and it reduces the induced magnetic field, see section 3.8.3 for an explanation of these. The idea is to create a network of all the metal components so that they all have the same voltage by bonding them together with appropriate connectors including: metal pipes, metal reinforcements in concrete floors, walls, or ceilings, grating, ducts, cable shields (for example from antennas), as well as the main grounding for the AC service. A bonding jumper must connect the LPS ground to the main electrode system at a single point either at the grounding electrodes or inside on a main grounding bar as pictured in Figure 16.

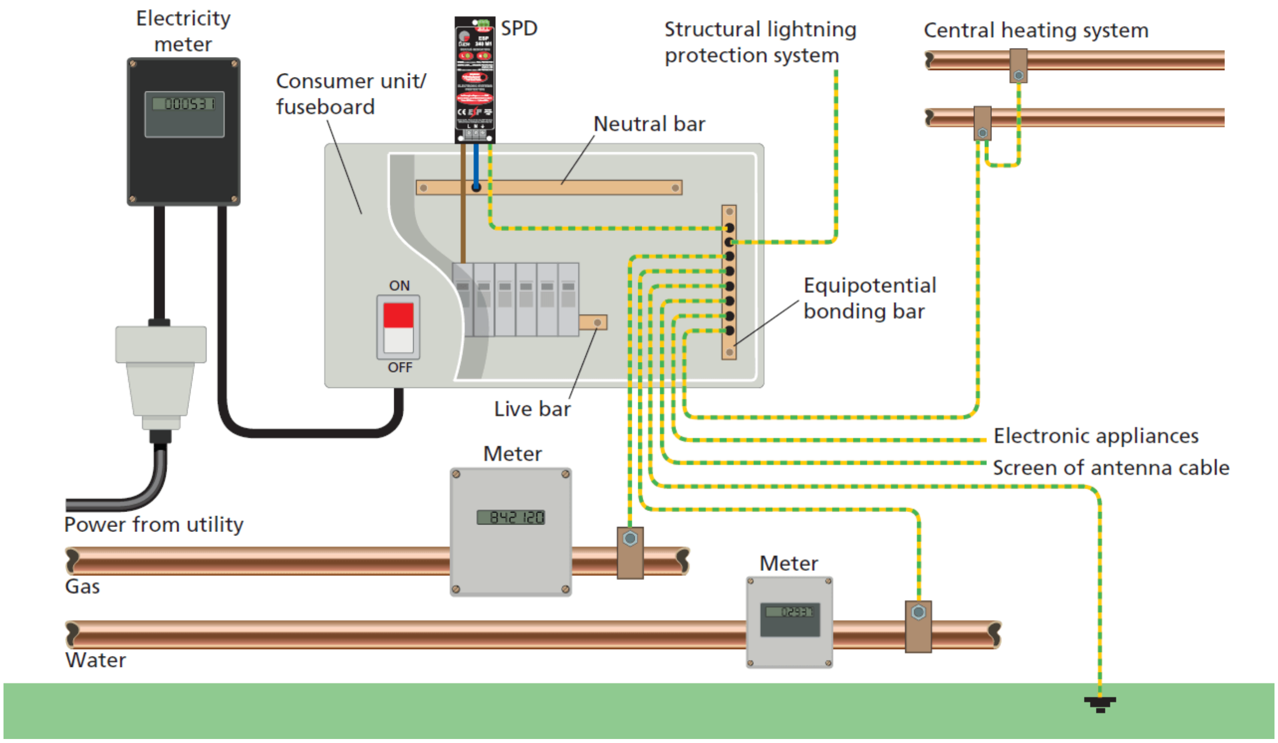


Figure 16: Equipotential bonding

Source: Lightning and Surge Protection https://www.lsp-international.com/bs-en-iec-62305-lightning-protection-standard/

Note: This is for a TT grounding system where the source ground is independent from the consumer's ground. For a typical TN-C-S system, also add a bonding jumper between the neutral and equipotential bonding bar.

3.8.2.5 Protect incoming AC power feeders

Incoming AC power feeders can carry large, potentially damaging surge currents from lightning strikes in the distribution system and magnetically induced voltages from the high lightning currents nearby. Surge arrestors or surge protective devices (SPDs) divert a portion of this energy to ground, reducing the surge to a tolerable level. For complete protection, coordinated SPDs should be installed at all levels such that the upstream SPDs discharge the large voltages and reduce the surge to a safe level for the smaller downstream devices. On typical projects in lightning areas EMI recommends at least installing a type 2/category B SPD in the main panel.

Table 13: SPD Categories for Lightning Protection

Protection type	Type 1	Type 2	Type 3
IEEE Category	Category C	Category B	Category A
Location	Line side/service entrance as close as possible to the entry point or for a transformer	Main panel or sub distribution boards, fixed installation	At the load at least 10m from the service entrance, socket level, on power strip, or plug-in
Primary use	Lightning Current arrestor or combined surge arrestor	Surge arrestor for distribution boards, subpanels, or fixed installations	Differential mode protection between line and neutral for socket outlets/terminal devices
Typical Technology	Spark Gap to ground conductor	Metal Oxide Varistor (MOV) to ground conductor or similar, see Table 7	MOV
Notes	Can see combined type 1 and 2 Cannot be installed downstream of an RCD See section 2.4.1 on some additional considerations for selecting surge protective devices.		Can be used with RCD/GFCI on the upstream circuit

3.8.2.6 PROTECT INCOMING LOW-VOLTAGE DATA/TELECOM CIRCUITS

Similarly, surges can come over incoming internet/telecommunications wires especially if routed overhead. Surge protective devices designed for communication wires should be included in a full LPS plan to protect sensitive and expensive networking equipment and computers.

3.8.3 EQUIPOTENTIAL BONDING RATIONALE

Equipotential bonding refers to a system that has all metal components connected so that they all have the same potential. When a direct lightning strike hits, all parts rise equally. This greatly reduces the potential difference between grounding conductors, pipes, ducts, etc. Zero potential difference is critical for life safety, to protect people or animals from electrocution due to a side flash (arcing between metal components), high touch voltages between an exposed metal and the ground, or step potential. If all conductive parts inside a building are at the same potential, even if it is high, people are not in danger of shock. It also can prevent equipment failure, if there is an auxiliary ground electrode that is not connected to the lightning grounding electrode, the equipment may provide a path for the lightning to travel through the equipment to get to that local ground.

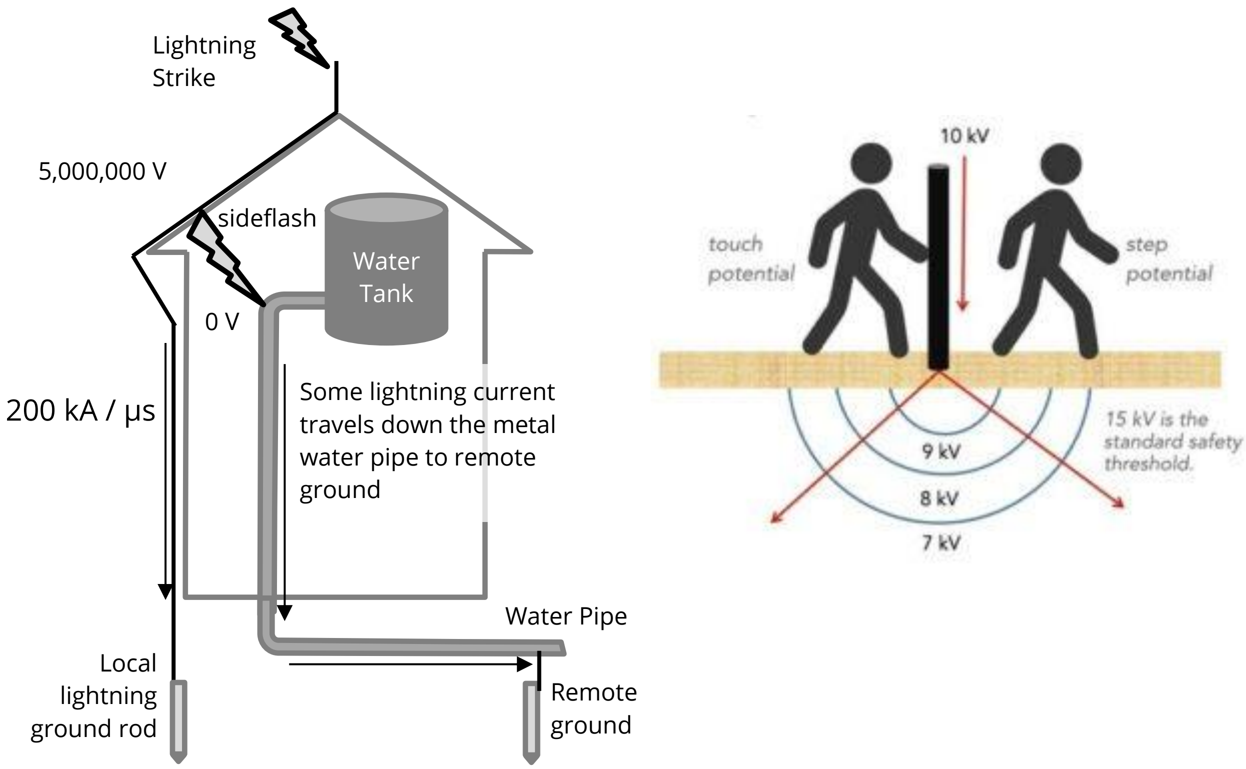


Figure 17: Potential dangers to people without equipotential bonding.
Source: adapted from the *Lightning Protection Guide, 3rd Edition*

3.8.4 Rolling Sphere method

To calculate the placement and height of the air terminals, you need to calculate the volume being protected. The first method is the rolling sphere method, sometimes called the electro-geometric model.

First, create a sphere with a radius equal to the strike distance. The final striking distance increases with larger lightning currents. The distance is based on a probabilistic model of lightning.

Table 14: Radius of the rolling sphere

Lightning Protection level	Minimum peak value of the lightning current	Probability that the actual lightning current is greater than the minimum peak value	Rolling Sphere Radius (final strike distance)
I	3 kA	99%	20 m
II	5 kA	97%	30 m
III	10 kA	91%	45 m
IV	16 kA	84%	60 m

Note: In the US, the NFPA prohibits using any radius greater than 150ft (45m) and recommends 45 or 30m for critical buildings. The IEC defines four lightning protection levels based on a more complex risk assessment process than described here and in the NFPA.

Then roll this sphere in all directions of the site, going up and over the terminals. Any structure or equipment below (i.e. not touching) the curved surface of the sphere is protected. Add air terminals where the sphere touches a building or equipment such as antennas, or masts can be used if you need to protect a larger open area.

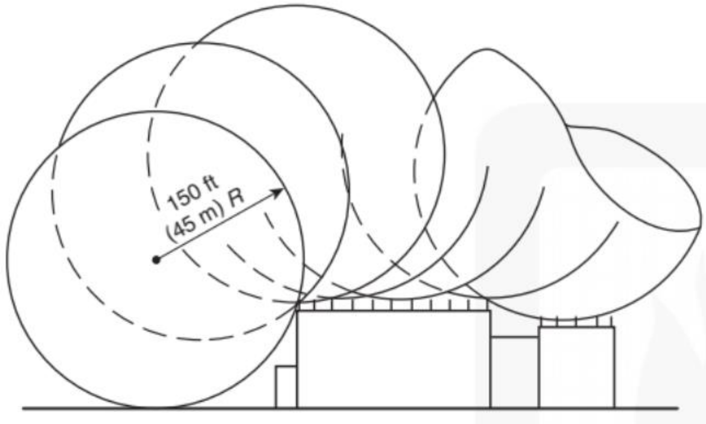


Figure 18: 2D diagram of the rolling sphere method.
Source: NFPA 780

Once you have generally placed air terminals, the following formulas calculate the exact spacing (d) and height (Δh) needed based on the geometry of the sphere held above the roof. Air terminals typically come in standard heights, try to start with what is locally available that is greater than the penetration distance (*p*) of the sphere. Figure 19 shows the geometry for a flat roof with air terminals on each corner, but this method can be extended to roofs with any shape or pitch.

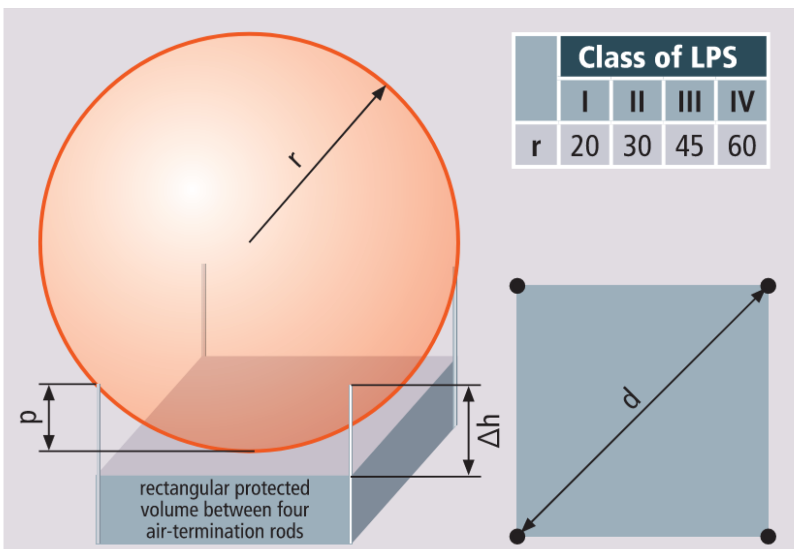


Figure 19: Geometry of the rolling sphere method
Source: Lightning Protection Guide

$$p = r - \sqrt{r^2 - \frac{d^2}{4}}$$

$$d = 2 * \sqrt{2r\Delta h - \Delta h^2}$$

$$\Delta h > p$$

where:
p is the penetration distance of the sphere below the top of the air terminal
r is the radius of rolling sphere
d is the maximum distance between two air termination rods
Δh is the height of air termination rods above the plane of the protected structure.

3.8.5 ANGLE OF PROTECTION METHOD

The second method is the Protective Angle method (Cone of Protection), derived from the rolling sphere. This method must be used for buildings with a steep roof or roof mounted structures like antennas, but only up to a height of 50ft (15m).

A cone is formed with the apex at the tip of the air terminal sloping outwards with an angle (α) depending on the category of protection and the height of the air terminal above ground.

The NFPA recommends general rule of α = 45° angle for ordinary structures, down to 30° for critical structures, or up to 63° for short structures under 25 ft (7.6 m). The *Lightning Protection Guide* contains table 5.1.1.4 with specific angles depending on the lightning protection level and the height of the air terminal.

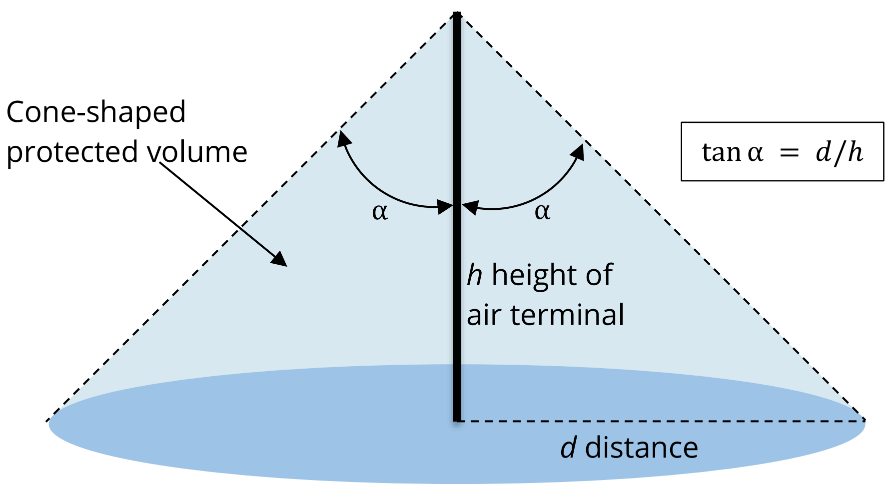


Figure 20: Diagram of the angle of protection

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: cost (both initial and for operation and maintenance), availability, and complexity. 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: ***Alternative Energy Source Analysis*** located in the *Training Resources and Videos* subfolder.

4.1 Energy Source Comparisons

Table 15 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 15: Cost for Energy, by Source

Energy Source	$/ MWh
Public Utility (cost to user)	$80-420
Diesel Generator	$326-419*
Natural Gas Generator	$115-221
Solar, Residential Scale PV	$117-282
Solar, Commercial Scale PV	$49-185
Wind, Large Turbine	$24-75
Battery Storage	$225-241

Source: Version 16 of *Lazard's Levelized Cost of Energy Analysis* (April 2023 values)
* Diesel values estimated from globalpetrolprices.com

4.2 Utility (Grid) Power

For an undeveloped site intending to have utility grid power connection, the price of running new lines and a transformer must be determined. If the ministry must purchase the transformer, prices may range from $50-90 USD per kVA. 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.

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 11. Since almost all three-phase generators are rated assuming a 0.8 power factor, typical ratings equivalents are 80kW == 100kVA. For generators that need to provide the best power quality to critical loads such as hospitals they should be rated as ISO 8528 performance class G3. Generator ratings will consist of three key numbers:

Table 16: Generator Ratings

Rating	Typical use	Maximum loading	Maximum hours/year
Prime Rated Power	on–site generation in place of a utility electricity supply or peak shaving	70% max average load in 24h period	Unlimited number of hours per year
Continuous Operating Power	Genset paralleled to utility	Constant 100% load	Unlimited number of hours per year
Emergency Standby Power	For supplying emergency power for the duration of a utility power failure	70% max average load in 24h period	< 200 hours/year

Source: ISO 8528

In most of the situations EMI works in, "prime" is the best fit as they tend to be run more than 200 hours per year because of low utility availability. 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 underloading 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 1500RPM and a 60Hz machine at 1800RPM. 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 1GPH (~4LPH) 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 be accessible for fuel deliveries but 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 possible.

There must be sufficient access around the generator for proper cleaning, including room for filters, etc. In coastal areas that can be exposed to a lot of salt, generators may need to be rinsed. Refer to the manufacturer's generator maintenance book.

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 0.32 liters per kWh. Thus, a 50kW load for 12 hours 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

Solar power systems are becoming increasingly popular for a variety of reasons. They provide low-cost power in almost any geographic location, are relatively easy to scale, and can be used to correct some power quality issues. These systems typically rely on photovoltaics (PV) which convert sunlight into electricity. Solar systems are becoming increasingly cheap, efficient, and available throughout the world.

EMI's *Energy Source Analysis.xlsx* can be used to quickly size a conceptual solar system and compare costs with other conventional power sources, using the "Cost projections" tab. This energy must be harvested during the window of usable sunlight. This must be adjusted to account for the number of days a year, on average, the skies are clear. This information is readily found online, such as at Gaisma.com that will give monthly sun hours, sun angles, etc. for most cities around the world. 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. The unit of measurement is kilowatts/m²/day, often referred to as equivalent sun-hours (*ESH)*. The worst-month data is commonly accepted as a valid solar energy index for designing systems with battery storage which must independently support a load 12 months per year. For grid-tied systems, it is acceptable to use the overall annual average daily insolation value (Reference: Gaisma.com).

4.4.1 Solar configurations

The configuration must be selected from a huge variety of ways that solar power can be incorporated into a larger system.

1. **Utility connected or Standalone (off-grid)**

Solar can be grid-tied where it supplements power from an external utility connection or off-grid where the solar/battery inverters generate their own grid. Grid-tied systems can have smaller inverters that provide a portion of the total energy in parallel with the rest of the grid and can be sized based on the available power of all the solar panels. The optimal DC-to-AC ratio depends on many factors, but is typically between 1.13 and 1.3, so that all the DC power produced can be used without the inverter clipping it and reducing the efficiency.

If there is no nearby grid, use an off-grid standalone system. The inverters must be sized to provide the maximum load of the full site.

Hybrid systems that can do both are also available, meaning that they normally parallel with the incoming grid but when that is unavailable, they can switch to a standalone setup using the battery/solar power.

2. **AC-Coupled or DC-coupled**

Solar systems with battery storage can be connected in one of two ways. The first is AC-coupled, where the panels and the batteries each have their own inverter connected on the AC side. The main advantages are that it is easier to retrofit into existing buildings, with two inverters there is a potential for more capacity, and the solar AC inverters are more efficient than the multimode inverters. AC is more common, especially in large sale systems.

DC-coupled is the other option, to connect the solar panels to the batteries with a charge controller, and then have one inverter to convert the DC solar/battery system to the main AC system. These can be simpler to install as there are fewer components, and they are more efficient between the solar and batteries as there is never clipping from the inverter. If there are any low-voltage DC loads they can be easily powered directly (motors, water pumps, some LED lights).

3. Centralized or Distributed

The inverters are often connected to the main distribution panel, but they can be connected at any panel either in one centralized place or distributed around the site. Centralized systems have many advantages: there can be a higher utilization, reduce the amount of communication cables, and ease of maintenance. Many small inverters in each building can be an attractive option instead of one large inverter for some spread out sites. Micro-inverters offer additional flexibility as they convert to AC at each panel and operate independently, reducing single points of failure. When deciding the optimal solution, consider the proximity of the source(s) to the major loads, maintenance access and safety, and reducing wiring, costs, and losses.

4. Micro-grid and other controller options

Other options include micro-grid controllers that can monitor and adjust real-time the percentage of power from a combination of sources (solar, battery, generator, and utility) to supply the cheapest power at any given time. Solar can also be paired with generators with controllers with fuel-saving technology to reduce consumption but that will make sure that the generator load does not fall below 30% of its rating to cause issues with wet-stacking (see the discussion above in section 4.3.1).

Grid-tied inverters by default will export excess power to the utility. Some utilities will pay some amount for this power. The best set-up for the clients is if the utility supports net-metering, meaning that they only charge for the total energy imported (total kWh consumed – total kWh produced) meaning they buy back power at the exact same price they charge for it. If planning to send excess to the utility, ensure that the meter can run forwards and backwards, so the client is not charged for exporting power. Even if the utility does not allow power to be sent to their system solar can still be installed with a zero-export controller. This measures the load at any given time and will curtail the output of the inverter to match with no excess.

4.4.2 Location considerations

A designer must carefully consider the best placement. This can be ground mounted, which is the most common and straightforward, where the solar panels are held on a rack outside in a solar field, and they can be easily oriented for optimal sunlight. Another option is roof-mounted which can save valuable space but be sure to consider safety as workers clean and maintain the panels as well as making sure the roof structure was designed to handle the additional weight. Panels can be mounted on the roof in ballasted racks held to the roof by weights or by clips that are tested to remain waterproof if they penetrate the roofing material.

In either case the topography, tree locations, and other existing buildings must be surveyed to determine if there will be excessive shading on the solar panels. Typically, it is recommended that there be no shade from the hours of 9AM to 3PM.

Solar panels should never be placed completely flat so that rain can flow off and help clean the panel. On a flat roof the minimum tilt should be 5-10°.

4.4.3 Safety and Security considerations

Ground-mounted solar panels should have a fence around the perimeter of the field for safety as well as security (to reduce theft that is increasingly common).

Good grounding must be maintained to safely ground the racking and frames of the solar panels. Many systems currently do not ground the negative conductor, the connection is established within the inverter, but this should be verified with the manufacturer.

Fault protection must be incorporated. There are two methods – in the US AFCI/GFCI is most common and in Europe insulation testing is performed by the inverter.

Lightning protection systems should be considered for all solar arrays, with ensuring that the ground for the LPS is bonded to the AC ground (interconnected across the site) to maintain the equipotential plane (see the Lightning Protection section for additional details). An existing LPS that provides protection for the entire array is acceptable. Additionally, it is recommended to install DC SPDs at every DC combiner box to prevent dangerous lightning currents from travelling back to the buildings.

Solar systems can currently be up to 600V, 1000V, or 1500V by code. However, in most contexts that EMI works in there are insufficient safety precautions and training to maintain a 1500V system, so it is recommended to not go above 1000V DC. Note that standard gloves and meters are not rated for 1000V+.

4.5 Batteries

Chemical batteries are currently the most common energy storage solution. 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. There are several ways to size the battery system depending on the priorities of the client. The minimal option would be to size just based on the excess solar energy produced during the day, especially in sites that cannot export it to the grid. It could be sized like an off-grid system (even if still grid connected) where the solar/battery combination covers 100% of the daily load. If the battery is primarily for backup or standby power (like a UPS), it should be sized for the load during the maximum utility outage expected. Depending on the reliability of other sources this application may be too expensive compared to generators. Similar to solar systems, the batteries can either be in one centralized location or distributed around the site.

Batteries will need a charge controller that can provide the required DC voltage as well as monitor the health of the batteries and charge them safely, sometimes called a battery management system (BMS). If the battery is intended to supply AC loads an inverter will also be needed. A simple charge controller should be sized to match the solar panel. The inverter can be sized to provide 100% of the load if the batteries are intended to be the sole energy source for a time, or a smaller percentage that will parallel with the grid or generator.

Commonly the inverter and charge controller are sold as one unit, with optional connection to a utility source as well for grid-tied solutions. Another option is to purchase an integrated solution, known as Energy Storage Systems (ESS). These combine a battery (lithium-ion), the inverter/charger, and a microgrid controller that can be used to configure and operate the larger system in one packaged equipment that provides simplicity of installation and maintenance.

Since lead-acid 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:

$$\text{Lead Acid: } E_{\text{b\_real}} = \frac{E_b}{(0.8 \text{ x } 0.5)}$$

$$\text{Lithium Ion: } E_{\text{b\_real}} = \frac{E_b}{(0.98 \text{ x } 0.7)}$$

One must consult the manufacturers' data for the maximum depth of discharge in the above calculations. Table 17 lists average battery costs by type:

Table 17: Battery Costs

Item	Initial Cost	Lifespan	LCOES Average Costs*
ESS: Integrated Lithium-Ion battery, inverter/charger, & microgrid controller system	650 $/kW-h	5000 cycle, 15 yr lifespan	0.19 $/kW-h
Batteries (Lithium-Ion)	200 $/kW-h	5000 cycle, 15 yr lifespan	0.06 $/kW-h
Batteries (Deep Cycle Lead Acid AGM. Ex: Trojan 31-AGM)	225 $/kWh	1000 cycle, 2.7 yr lifespan	0.47 $/kW-h
Batteries (Deep Cycle Flooded Lead Acid. Ex: Trojan T-145)	135 $/kWh	1200 cycle, 3.3 yr lifespan	0.25 $/kW-h

*LCOES – Levelized Cost of Energy Storage is a more uniform way to compare total battery costs over the full lifespan. Reference: simpliphipower.com/support/levelized-cost-of-energy-storage-lcoes-calculator/

$$LCOES = \frac{initial\ cost}{total\ kWh\ capacity * \%DOD * cycle\ life * efficiency}$$

4.5.1 Safety concerns

Batteries can catch fire and continue burning for a long time, especially lithium-ion batteries. Fire extinguishers and smoke detectors should be installed in every electrical room. However, particularly for lithium-ion batteries that produce both oxygen and flammable gases during thermal runaway, the common ABC type will not put out a battery fire and the only mitigation technique is to use a lot of water to cool off the battery. For this reason, batteries should not be installed in critical areas such as within an ICU of a hospital or other areas that are difficult to evacuate.

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 6m/s (12mph) for wind turbines to start producing power. Even greater annual average wind speeds, 6.3 to 7m/s (14.3 to 15.7mph) at 50m are necessary to make it cost effective. In addition, wind turbines require an elevated structure 10m above other objects within 150m. If the site is a candidate for wind power, refer to the reference *How to Generate Electricity in Remote Areas*. To calculate approximate annual average energy production for a grid-tied horizontal axis turbine of reasonable efficiency:

$$Energy = 2.09 * Diameter^2 * Wind^3$$

where:
Energy is in kWh per year
Diameter of the wind turbine rotor is in meters
Wind speed is annual average for the turbine hub height in m/s

The equation uses a Weibull wind distribution with a factor of K=2, which is about right for inland sites. The overall efficiency of the turbine, from wind to electrical grid is 30%. That is a reasonable, real-world efficiency number.

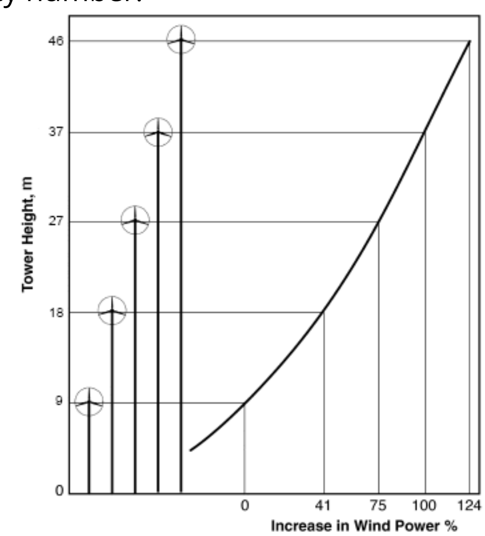


Figure 21: Required tower height of wind turbines for maximum power

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 In-country presentation

Near the conclusion of a project trip, the project leader will normally have a scheduled time for the EMI team to present their work to the client. Typically, the electrical section of this presentation will be around 3-5 slides, plus describing any existing issues, and be structured as shown in the *Example In-country presentation*. 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 and alternative energy recommendations.

5.2 Written Report

The *EMI Project Report Example–Electrical Section Template* shows a correctly-formatted electrical section of an EMI report. As with the presentation, 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, then a 2-3 page explanation of an alternative energy analysis if completed. The report does not include technical details but will reference drawings and spreadsheets that support the recommendations discussed. The electrical load study, energy source analysis spreadsheet, and/or load study measurements are included as report appendices. 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.

Appendix A Solutions for common issues on sites

EMI often serves in areas with less established electrical codes and infrastructure than most electrical engineers have previously experienced. Electrical engineers are often asked to address existing issues on site with equipment, power quality, or reliability. However, it is also part of the site inspection process to look for and identify any potential safety problems before they cause damage and suggest possible solutions. Below is a list of some common issues faced on sites in the developing world and some potential solutions. This is by no means an exhaustive list but meant to identify areas for the engineer to research further. Many of these are explained with photos in the presentation ***Electrical Design in the Developing World*** available in the training folder.

Table 18: Electrical Issues Analysis Matrix

Issue	Effect or symptom	Potential Solutions
Safety		
Overheating	Fire hazard, Loss of efficiency, Shorter equipment life	Check connection tightness. Increase wire/breaker/equipment size. Upgrade ventilation (passive, fans, or AC).
Improper or no overcurrent protection	Fire hazard, Overcurrent protection device too large for wire	Increase the wire size. Decrease the overcurrent protection size. Add protection to multiple taps on the line side of overcurrent protection.
Loose connections	Fire hazard, Hot spot in panel/junction box	Tighten all connections with a torque wrench/screwdriver. Mark tight position.
Feeder line contact or sag	Fire hazard, Fault	Repair/replace poles and tension cables. Add a “kicker” pole or adjust guy wires. Add spacer between lines.
Exposed live conductors, panel covers off or damaged	Shock hazard, Electrocution	Repair or replace panels, covers, or hinges. Add locks on panels or rooms. Inside a panel add a plexiglass cover.
Galvanic corrosion	Corrosion at connections between Al and Cu, Fire hazard	Replace all connections with a bi-metallic compatible component (e.g. COPALUM).
Trip/slip hazards	Personnel safety hazard	Relocate equipment or extension cords. Implement proper maintenance, cleaning, and storage processes.
Blocked access to power equipment	Personnel safety hazard	Remove clutter and mark area with tape on the floor in front of equipment.

Issue	Effect or symptom	Potential Solutions
Water and debris in electrical equipment	Shock hazard, Corrosion, Equipment malfunction, animal related damage	Clean and seal all electrical components and enclosures. Replace all damaged wiring. Consider drip shield or water control.
Inadequate or inappropriate materials not intended for the usage	Personnel safety hazard, Fire hazard	Replace with appropriate materials designed and marked for the purpose.
Lack of fire extinguishers	Fire hazard	Place fire extinguishers rated for use on electrical equipment at easily accessible locations at entrances to main power/equipment rooms.
Grounding		
High neutral voltage	Feel tingling on equipment, measured voltage on neutral, Equipment failures, Shock hazard	Ensure the neutral is bonded to ground (following proper grounding scheme). Reduce resistance to ground (more ground rods, ring or mesh, ground enhancing materials, etc.)
Haphazard ground scheme	Shock hazard	Implement a uniform ground system (ex TN-C-S). See Section 2.4.4.1
Unmaintained or failed grounds	Ground resistance is too high	Add additional ground rods. Replace the grounding system.
Ungrounded sockets	Feel tingling on equipment, Shock hazard	Wire all circuits with ground wire to the main ground bar. Properly size ground wires.
Equipment malfunction/short lifespan		
Phase swap	Motors or other three-phase loads will not work	Call utility to fix it. Rewire the equipment. Consider phase-reversal relay. Color code wires to reduce occurrence.
120V (US) equipment on 220V system	Equipment malfunction or overheating	Install 220/120 transformer. Upgrade 120V-only equipment.
Power Quality		
High transient surges	Premature equipment failure	Surge Protective Devices (SPD). Lightning Protection System.
High inrush current	Nuisance tripping, Short dips in voltage, Motors not starting	Latching relays for offending appliances (e.g., ACs, water heaters, pumps, ...). Replace breaker with MOTOR STARTERS.

Issue	Effect or symptom	Potential Solutions
Voltage drop “brown out”, Over or under voltage (> ± 10%)	Dimming of lights, Audible change in fan noise/speed, Sensitive equipment shutting off frequently, Equipment failure	If <20%, may be addressed with Voltage Regulation (section 2.5.2). Add over/under voltage protector relay at point of use and motor protections. If culprit is utility: consider energy alternatives and storage (solar, generator, battery bank and inverter). If culprit is on site (e.g., large equipment start up): Create sub-system isolation and/or soft starters. Increase wire sizes so voltage drop is <4% from the utility to the building. Move the transformer/main distribution closer to the center of the loads.
Harmonic distortion	Excessive neutral current causing overheating, Buzzing sound as the panel vibrates at the harmonic frequency	Fully rated/oversized neutral conductor. Connect non-linear loads separate from other loads, and further upstream. Harmonic suppression reactors or filters.
Poor Power Factor (< 0.8)	High line current, loss of efficiency	Switch Fluorescent lighting for LED. Upgrade low power factor equipment. Voltage Regulation (section 2.5.2). (usually capacitors at the offending load).
Energy Sources		
Diesel generator “wet stacking”	Black, oozy exhaust, Reduced efficiency, Generator failure	Ensure the generator is loaded at least 30% periodically (per manufacturer). If paired with solar, ensure the controller is properly set with a minimum load. Install a smaller generator.
Transformer overloaded	Overheating, Increased noise, Fire hazard, Voltage drop	Upgrade the transformer. Reduce other issues with voltage regulation or fault protection. Add a new transformer if loads can be isolated into zones.
Unreliable grid	Power outages	Alternative energy sources like solar, generators, or battery storage.
High electricity cost	Economic impact on client	Investigate cost-benefit of solar or alternatives. Install energy-saving devices like LED lighting, more efficient equipment.

Appendix B Grounding Electrode Calculations

Option 1: Single Deep Ground Electrode

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.

Option 2: Multiple Ground Electrodes

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.

Option 3: Strip Conductor Electrode Mesh or Ground Plate

If a satisfactory solution cannot be found for the space allowed, the designer must consider a mesh of bare strip conductors (also called an Earth Grid) or ground plate system. Short ground rods may be added around the perimeter of the grid to further decrease resistance. For a mesh system the resistance can be calculated by

$$R_s = \rho\left(\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right)$$

Source: IEEE Std. 80-2013, section 14.2, equation 57

where:
ρ is the soil resistivity, as calculated above
L_T is the total buried length of conductors, in meters
A is the area occupied by the ground grid in m^2
h is the depth of the grid in meters

Appendix C Grounding Schemes

C.1 TN-C-S Grounding System

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 to create the separate conductors. This type of grounding, shown in Figure 22, 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 certain countries; consult the country-specific guidance for those projects.

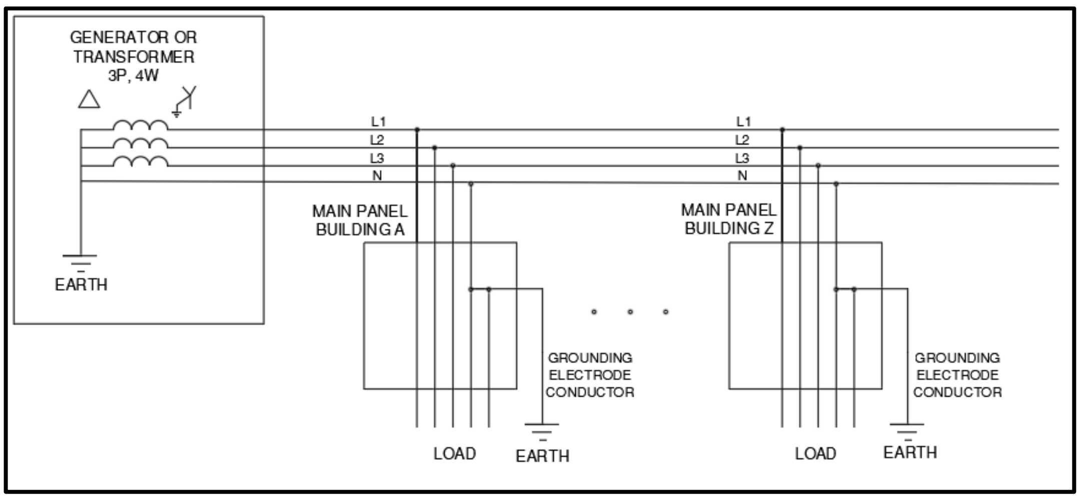


Figure 22: Site Grounding Layout for TN-C-S

C.2 TN-S Grounding System

In the TN-S grounding system, the source ground is connected to the grounds of the main distribution panel and subpanels through a separate wire from the neutral. If the wire is armored and of sufficient size the armoring can be used as this conductor.

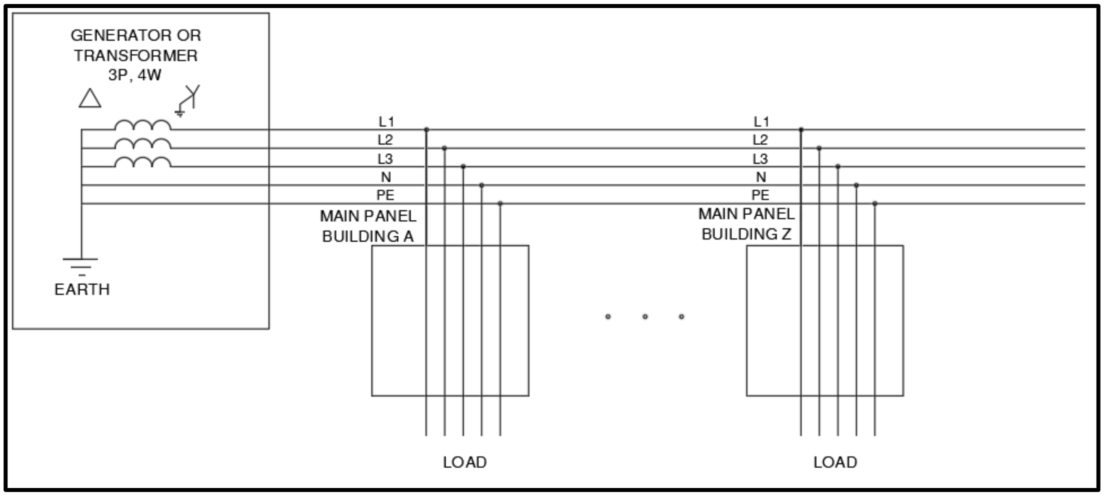


Figure 23: Site Grounding Layout for TN-S

C.3 TT Grounding System

In the T-T grounding system, all the buildings will have their own grounding electrode that is electrically independent of the source earth (i.e. not bonded to the neutral coming from the supply). The mass of earth is the only return path to the source earth. Thus, this relies on a low-impedance earth both at the source transformer and at every installation, and in impractical in locations with high soil resistivity. This scheme is common in India.

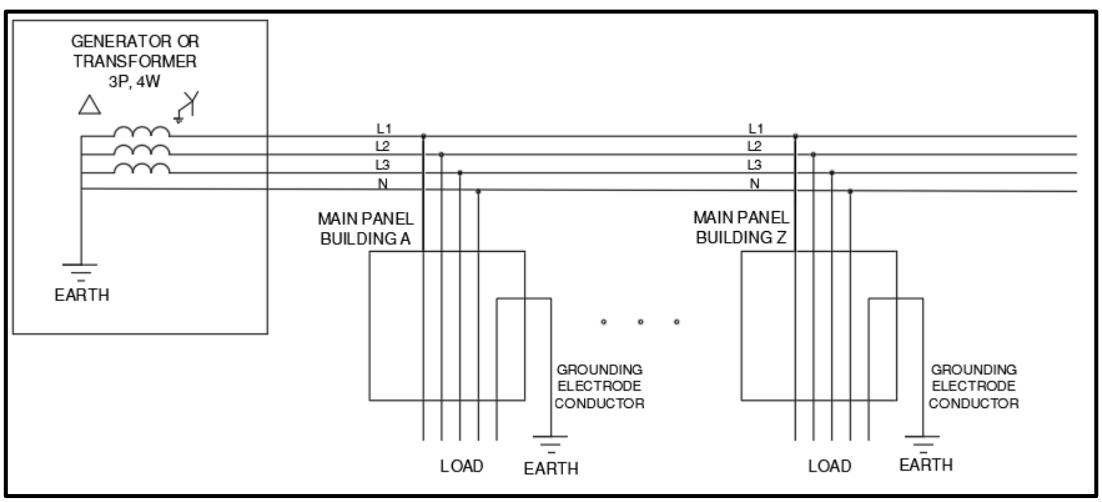


Figure 24: Site Grounding Layout for TT

C.4 TN-C Grounding System

In the TN-C system, all the grounds are combined with the neutral wire. If a fault occurs, the wire must carry both the phase imbalance current and the fault current with its harmonics. The loss of this conductor can result in the appliance becoming live and the earth protection no longer operates, so it is considered the least safe and is not allowed in many countries.

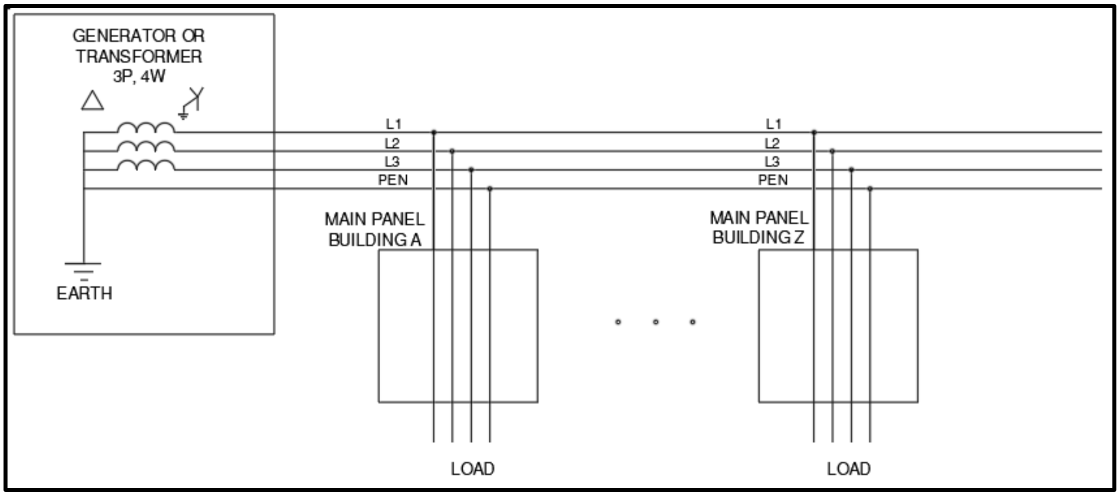


Figure 25: Site Grounding Layout for TN-C

C.5 IT GROUNDING SYSTEM

In the IT method, the source is either isolated from earth or connected through a deliberate high impedance, typically more than 1,000 Ω. The consumer side is directly connected to an earth electrode. This is a special application where isolation is needed such as on ships or in some medical locations.

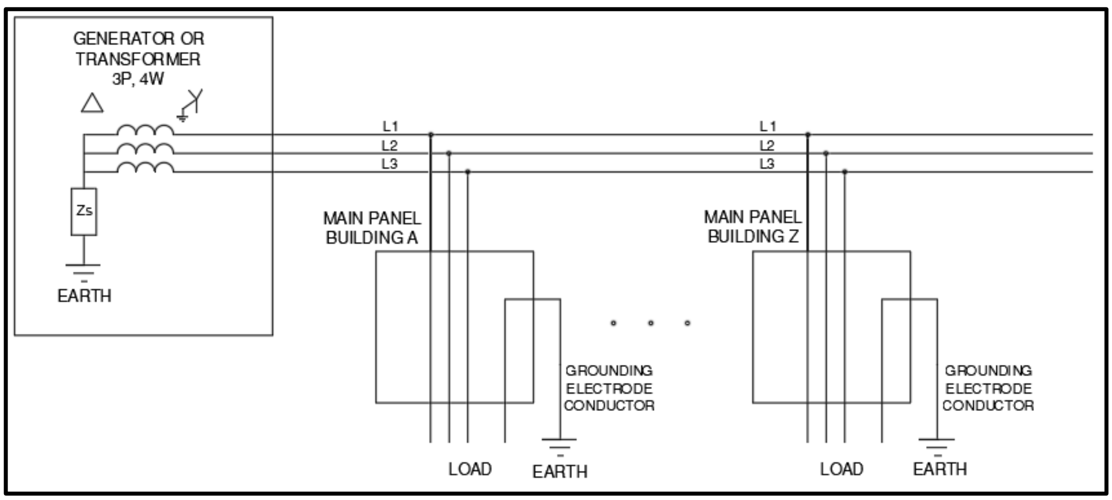


Figure 26: Site Grounding Layout for IT

Appendix D Power Quality Equipment

D.1 MOV Based Surge Protective Device

A surge protective device (SPD) is a protective device for limiting transient voltages by diverting or limiting surge current and is capable of repeating these functions as specified. SPDs were previously known as Transient Voltage Surge Suppressors (TVSS) or secondary surge arrestors (SSA). Secondary surge arrestor is a legacy term (often used by utilities) and is used most commonly for a device that has not been certified to ANSI/UL 1449. In 2009, after the adoption of ANSI/UL 1449 (3rd Edition), the term Transient Voltage Surge Suppressor was replaced by Surge Protective Device.

A Metal Oxide Varistor (MOV) is a semiconductor device composed mainly of Zinc Oxide (ZnO). A MOV functions similarly to two Zener diodes in series, and so has the V-I characteristics of Figure 27. However, as the entire bulk of the device functions as a junction, (and not just a thin interface), its energy absorbing ability is far greater than that of a Zener diode.

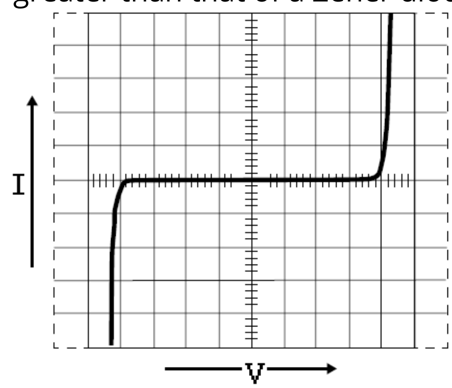


Figure 27: Typical MOV Current Voltage (I-V) Curve

Until the applied voltage reaches the threshold value, minimal current flows. Above that voltage the current increases exponentially with further increases in voltage. Hence for a surge voltage in excess of the threshold value, the voltage will be clamped at a value somewhat above the threshold value, with the rest of the surge voltage dropped across the line impedance between the source of the surge and the MOV.

Per the National Electrical Code® (NEC) and ANSI/UL 1449, SPDs are designated as follows:

Type 1: Permanently connected, intended for installation between the secondary of the service transformer and the line side of the service disconnect overcurrent device (service equipment). Their main purpose is to protect insulation levels of the electrical system against external surges caused by lightning or utility capacitor bank switching.

Type 2: Permanently connected, intended for installation on the load side of the service disconnect overcurrent device (service equipment), including brand panel locations. Their main purpose is to protect the sensitive electronics and microprocessor based loads against residual lightning energy, motor generated surges and other internally generated surge events.

Type 3: Point-of-utilization SPDs installed at a minimum conductor length of 10 meters (30 feet) from the electrical service panel to the point-of-utilization. Examples include cord connected, direct plug-in and receptacle type SPDs

This document will focus primarily on Type 2 devices that should be installed at the main panel for each building.

MOV Based SPDs have FIVE important characteristics that need to be carefully considered:

1. For best operation, the voltage rating must match that of the utility.
2. The peak current rating chosen must be suitable for the location; closer to the utility transformer requires a larger peak current rating.
3. For best operation, the unit must be connected to a low resistance ground.
4. The internal MOV element degrades with use and eventually fails short. So a series fuse is typically integrated into the unit. Hence occasional replacement will be required.
5. The nature of the MOV element means that the peak voltage that the device clamps at can be 2-3 times the peak of the device's voltage rating; so this will be INADEQUATE protection for sensitive medical type equipment.

Multiple manufacturers, device ratings and form factors are available, and Figure 28 is just one example.

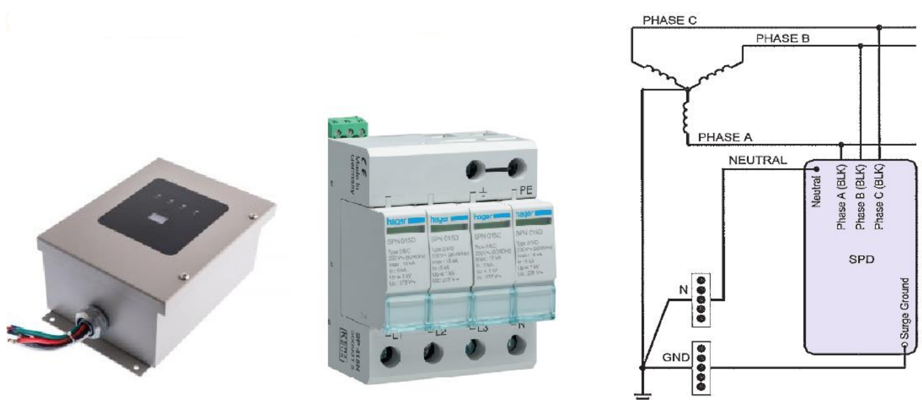


Figure 28: Typical 3-Phase Type-2 SPDs and corresponding connection diagram

NOTE that a system cannot be "Hi-Pot" tested with MOV based SPDs in place. The connection to ground has to be temporarily removed.

D.2 Constant Voltage Transformer

A Constant Voltage Transformer (CVT) is a very simple "old school" device consisting of just a special transformer and a capacitor; no electronics at all are involved,

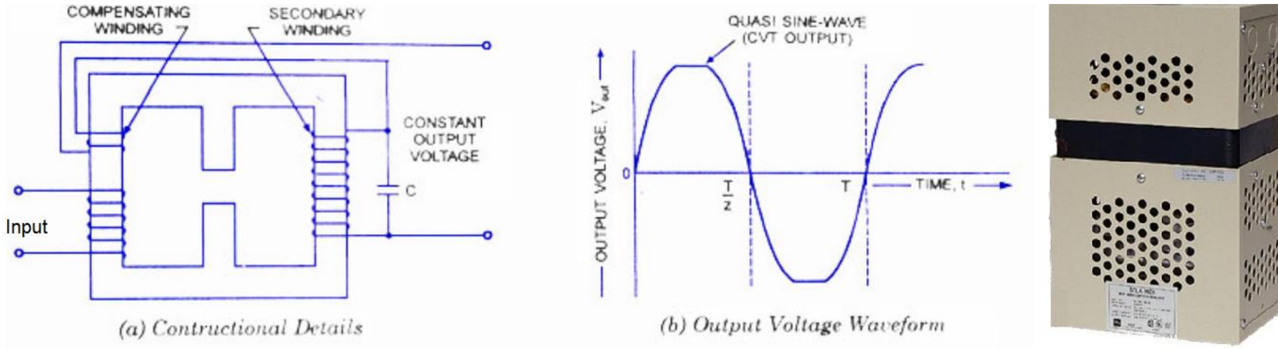


Figure 29. The transformer is operated so that its magnetic circuit is somewhat saturated, and this provides the near constant voltage at the output.

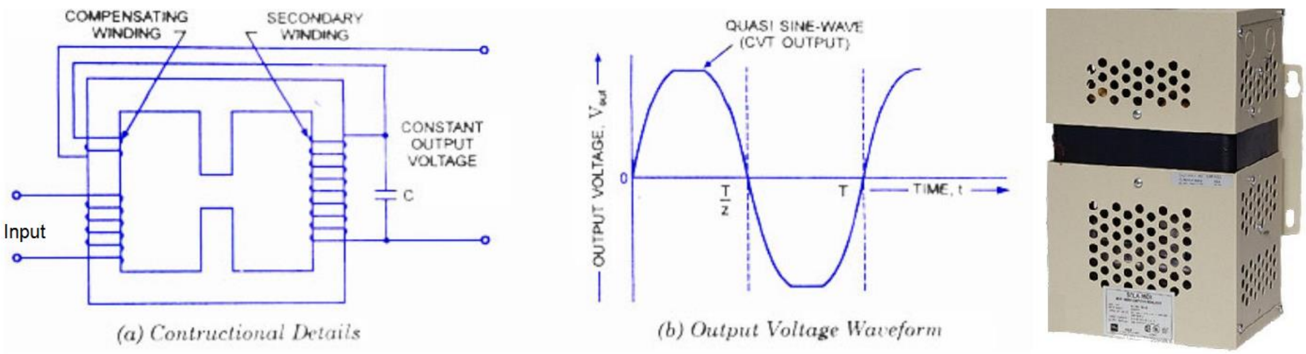


Figure 29: Constant Voltage Transformer; Typical schematic, waveform, and packaging

The CVT has many unattractive features as summarized in Table 8, (large, heavy, noisy, runs hot, limited kVA, expensive if sourced in the US, etc.), that appear to make it less attractive than other more modern choices, such as a UPS. But the CVT has three compelling features that still give it a very useful niche application where it excels (for medical equipment); zero maintenance, long life and excellent suppression of voltage transients. However, EMI has experienced issues with the capacitors failing on several projects and the capacitors had to be replaced with a better quality component.

The main supplier in the US is SOLA HD. As the production of a CVT is quite labor intensive, CVTs sourced in a developing country such as India are far less expensive than in the US.

D.3 UNINTERRUPTABLE POWER SUPPLY (UPS)

There are two very different types of UPS, with very different capabilities, with simplified block diagrams as shown in Figure 30.

- For the **simple** type, if the grid is available it is routed directly to the output. Only if there is a black-out is the output fed power from the battery via the inverter.

- For the **double conversion** type, the inverter feeds power to the output at all times, except in the event of failure when the bypass is used.

Table 19 summarizes the differences in capabilities, where it must be emphasized that only the double-conversion type provides surge protection. The more common "simple" type, typically used with PCs, does NOT provide much in the way of surge protection.

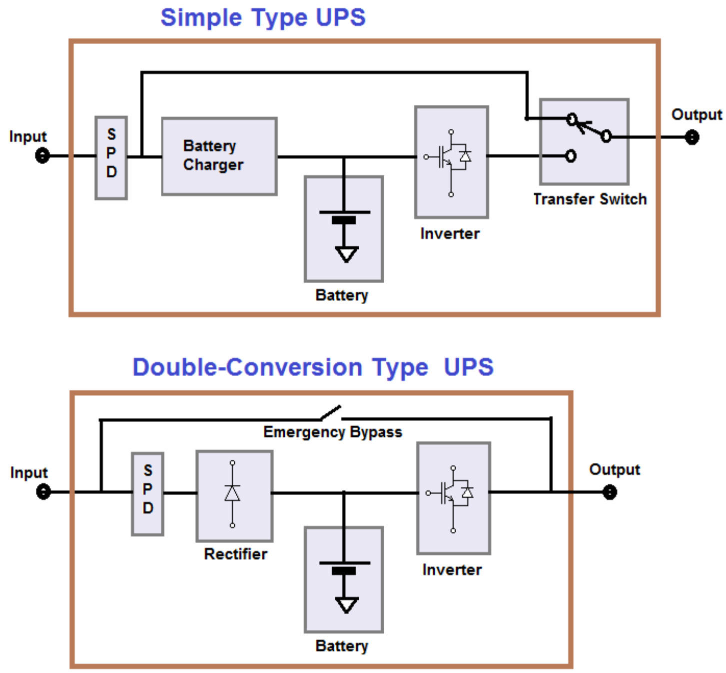


Figure 30: Block diagrams for the two UPS types

Table 19: UPS Capability for Surge Protection vs. Type

Parameters	"Simple" UPS	"Double Conversion" UPS
Continuous isolation of the output voltage from the effects of surges or transients on the input ?	No	Yes
During operation on battery, output voltage is approximately that of a sinewave ?	No, often a pseudo-square wave	Yes, more likely
Need for maintenance ?	Yes, especially batteries	Yes, especially batteries
Cost	Less	More
Likelihood of failure	Technically simpler but often built cheaply, so operating life of 5-10 years?	Technically more complicated but usually better designed and built, so an operating life of at least 10 years. ?
Best use	Won't work for surge protection. OK for riding thru short black-outs in a location with a stable grid.	Superior protection against surges and lightning transients.

D.4 MOTORIZED VARIABLE TRANSFORMER

In overly simple terms, a motorized variable transformer is the magnetic version of the resistive variable resistor or potentiometer.

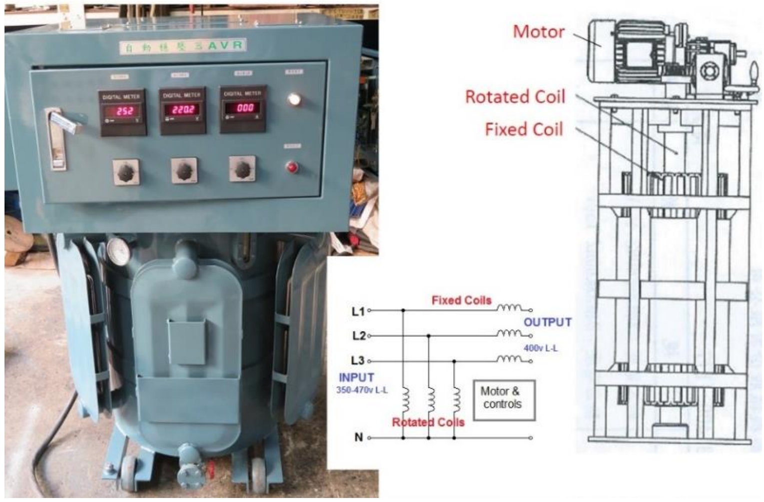


Figure 31: Example of motorized variable transformer, (200kVA from Opti-UPS – Taiwan)

In the example of Figure 31, an electric motor slowly rotates an armature having one coil per phase, which then affects the voltages developed across the fixed coils in series with the output, so adjusting the output voltage back to its required nominal value.

Hence it can be seen that:

- The response time is slow, ~1 second.
- Most of the components are fairly rugged and immune to voltage surges, with the exception being the control PCB.
- The operating life (~10 years) is limited mostly by mechanical components such as bearings and speed reducing gears.
- As the three rotating coils are all on the same shaft, the output phases cannot be independently controlled.

The unit shown in Figure 31 was about 1.3m tall and 1m in diameter and cost about $15,000;- so quite reasonable for the 200kVA rating.

Figure 31 is just one example of this type of voltage regulator. Others do actually have a sliding "wiper" picking off the required voltage from the exposed edges of the windings of an autotransformer, (so more like an actual potentiometer), and so have much lower operating lifetimes.

D.5 Solid-Sate Tap Changer

This type of voltage regulator can be thought of as an electronic version of the motorized variable tap changer, in that there is:

- An isolation transformer with a ratio of 1 to ~1.2.
- 6 to 8 taps on the secondary that correspond to voltages of (for example) -15%, -10%, -5%, 0%, +5%, +10%, and +15%.
- Back to back SCRs that are used to electronically select the most appropriate tap to give an output voltage as close as possible to the required nominal value.

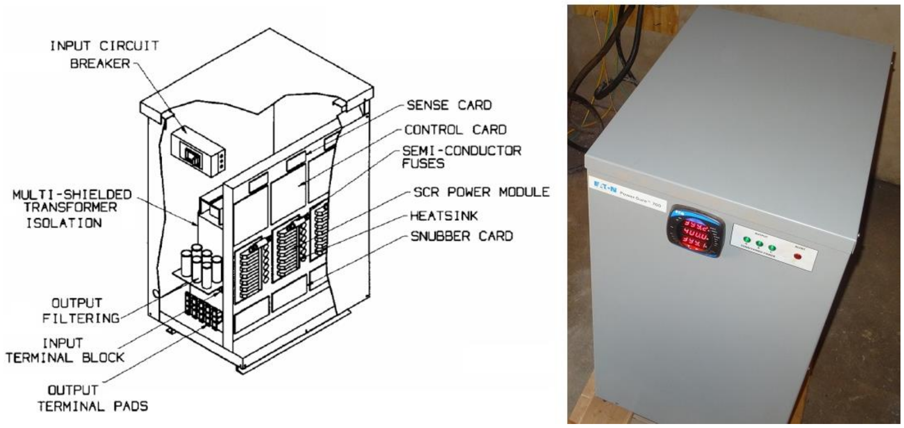


Figure 32: Example of a Solid-state voltage regulator, (30kVA from Eaton)

It can therefore be seen that this has at least three advantages over a motorized variable transformer:

- very fast (~1 cycle)
- each phase is regulated independently
- fewer mechanical components to wear out

But of course the disadvantages are greater complexity and greater cost. The 30kVA unit shown in Figure 32 was approximately 1m tall and cost ~$15k.