Part 1 Analysis: Foreword & Chapter B

Foreword Overview

This section, authored by Dr. Khaled Y. Al-Khalaf of SASO (Saudi Standards, Metrology and Quality Organization), introduces the "Electrical Installation Guide according to IEC International Standards," originally compiled by Schneider Electric.

The foreword emphasizes the guide's importance as a reference for engineers and specialists in electrical installation design. It highlights the guide's focus on the IEC 60364 series of international standards, which cover safety, control, performance, and protection of electrical circuits.

A key point is that SASO has adopted the IEC 60364 series as Saudi standards and is developing national regulations based on them. This guide is presented as an essential tool for applying these standards in Saudi Arabia. SASO has also translated the guide into Arabic to broaden its accessibility.

Chapter B: General - Installed Power

Overview

This chapter provides the foundational methodology for designing an electrical installation. It outlines the process of determining power requirements, from listing individual loads to calculating the final supply demand. It covers the rules, regulations, and standards governing installations, methods for assessing different load types (motors, heating, lighting), and procedures for estimating the total power loading of an installation, including factors for utilization and simultaneity.

Key Standards and Codes Referenced

This chapter is fundamentally based on the IEC 60364 series and makes direct or indirect reference to numerous other IEC standards that are detailed in section 2.3 of the chapter.

- IEC 38-1983: Standard Voltages.
- IEC 439: Low-voltage switchgear and controlgear assemblies.
- IEC 364: Electrical installations of buildings (the core standard for the guide).
- IEC 364-3: Assessment of general characteristics.

- IEC 364-4-41: Protection for safety - Protection against electrical shock.
- IEC 364-4-42: Protection for safety - Protection against thermal effects.
- IEC 364-4-43: Protection for safety - Protection against overcurrent.
- IEC 364-4-47: Application of protective measures for safety - Measures of protection against electrical shock.
- IEC 364-5-51: Selection and erection of electrical equipment - Common rules.
- IEC 364-5-52: Selection and erection of electrical equipment - Wiring systems.
- IEC 364-5-53: Selection and erection of electrical equipment - Switchgear and controlgear.
- IEC 364-6: Verification.
- IEC 364-7-701: Requirements for special installations or locations - Electrical installations in bathrooms.
- IEC 479-1: Effects of current on human beings and livestock - Part 1: General aspects.
- IEC 76: Power transformers.
- ISO 9000 (EN 29000): Quality assurance standards for manufacturing processes.

Technical Specifications

1. Methodology

- Process: The study of an electrical installation follows a sequence:
    i. Listing of Power Demands: Compile a list of all loads, including total installed power and an estimation of actual loads based on operating modes (steady-state, starting, non-simultaneous operation).
    ii. Service Connection: Determine if the connection to the power-supply network will be at High Voltage (requiring a consumer substation) or Low Voltage (metered by LV tariffs).
    iii. Reactive Energy: Plan for power factor improvement (compensation).
    iv. LV Distribution: Design the distribution network, including standby sources, earthing arrangements, and hardware components based on building plans.
    v. Protection Against Electric Shock: Based on the determined earthing system (TT, IT, or TN), choose an appropriate protection scheme.
    vi. Circuits and Switchgear: Study each circuit to determine conductor size based on rated currents, short-circuit levels, and protective device types, ensuring compliance with voltage drop and motor starting requirements.
    vii. Special Loads/Sources: Study particular items like alternators, inverters, motors, and DC systems.

viii. Special Locations: Apply stricter regulations for locations like domestic dwellings.

2. Rules and Statutory Regulations

- Voltage Ranges (Low Voltage):
    - Specification: Low-voltage installations are defined as those operating between 100 V and 1000 V.
    - Standard Evolution: Existing 220/380 V and 240/415 V systems are to evolve to the recommended value of 230/400 V. The transition period should not exceed 20 years from the publication of IEC 38-1983.
    - Transition Tolerances:
        - For 220/380 V systems, the voltage should be brought to 230/400 V +6% / -10%.
        - For 240/415 V systems, the voltage should be brought to 230/400 V +10% / -6%.
        - The final tolerance after the transition period should be 230/400 V ±10%.
- Voltage Ranges (High Voltage):
    - Specification: Standard voltages above 1 kV and not exceeding 35 kV.
    - Non-preferred Values: Values in parentheses in Table B2 are non-preferred and not recommended for new systems.
    - System Type: Systems are generally three-wire unless indicated as four-wire.
- Installation Testing:
    - Initial Testing: Pre-commissioning tests are mandatory before a power authority connects an installation. Tests typically include:
        - Insulation tests of all cables (phase-to-phase and phase-to-earth).
        - Continuity and conductivity tests of all protective, equipotential, and earth-bonding conductors.
        - Resistance tests of earthing electrodes.
        - Checks on conductor cross-sectional-area for short-circuit level adequacy.
        - Verification of earthing for all exposed and extraneous metallic parts.
    - Periodic Check-Testing: Industrial and commercial installations require periodic re-testing.
        - Annually: For locations with a risk of degradation, fire, or explosion; temporary worksites; HV installations.
        - Every 3 years: For other general industrial/commercial cases.

        - 1 to 3 years: For buildings used for public gatherings, depending on the establishment type.
- Equipment Conformity:
    - Attestation: Conformity can be attested by an official mark, a certificate from a laboratory, or a declaration from the manufacturer.
    - Quality Assurance: Certification based on ISO 9000 / EN 29000 is used to verify the quality of the manufacturing process itself. Three models exist:
        - Model 3: Inspection and checking of final products.
        - Model 2: Includes final product checking and verification of the manufacturing process.
        - Model 1: Includes Model 2 requirements plus rigorous scrutiny of the design process.

3. Motor, Heating, and Lighting Loads

- Induction Motors:
    - Starting Current (Id):
        - Direct-on-line squirrel-cage motors: Id = 4.2 to 9 In (mean value = 6 In).
        - Wound-rotor motors: Id = 1.5 to 3 In (mean value = 2.5 In).
    - Power Factor Correction: Shunt-connected capacitors are used to reduce the input kVA and current.
- Resistive Heating and Incandescent Lamps:
    - Power Factor: Assumed to be cos ø = 1.
    - In-rush Current: At switch-on, the cold filament causes a brief but intense peak of current.
- Fluorescent Lamps:
    - Power Consumption: The power indicated on the tube (Pn) does not include power dissipated in the ballast. A figure of 25% of Pn can be used to estimate ballast loss if not specified.
    - Power Factor (cos ø):
        - Without PF correction: cos ø ≈ 0.6
        - With PF correction: cos ø ≈ 0.86
        - With electronic ballast: cos ø ≈ 0.96
- Discharge Lamps:
    - Start-up Time: These lamps have a long start-up time during which the current is greater than the nominal current.
    - Voltage Sensitivity: Lamps extinguish if the voltage falls below 50% of nominal voltage and require approximately 4 minutes to cool before re-igniting.

Visual Elements Analysis

Figure B5: diagram of a low-power speed controller.

- Description: This is a simplified circuit diagram illustrating how a DC motor is powered from an AC source via a controller. The diagram shows a "V power-supply network" (AC source) feeding into a rectifier bridge circuit. The output of the rectifier provides a DC supply (labeled 'In') to the motor (labeled 'M'). The motor current is labeled 'Im'.
- Technical Details: The diagram represents a speed-control converter for a DC motor. The input is an AC power supply, and the output is a controlled DC supply for the motor.
- Construction Notes: The controller is designed for specific applications requiring high torque or variable speed, such as machine tools. The operating principle does not allow for heavy overloading.
- Relationship to Text: This figure visually represents the DC motor power supply discussed in section 3.2. It clarifies the relationship between the AC input current (In) and the DC motor current (Im), which is essential for understanding the data in the accompanying Tables B6 and B7.

Calculations and Formulas

1. Current Demand for Induction Motors

- Formula (3-phase motor): `Ia = (Pn * 1000) / (√3 * U * η * cos ϕ)`
- Formula (1-phase motor): `Ia = (Pn * 1000) / (U * η * cos ϕ)`
- Variables:
    - `Ia` = Current demand (Amps)
    - `Pn` = Nominal mechanical power output (kW)
    - `U` = Voltage (Volts). Between phases for 3-phase, between terminals for 1-phase.
    - `η` = Per-unit efficiency (output kW / input kW)
    - `cos ϕ` = Power factor (kW input / kVA input)

2. Apparent Power (kVA) for Induction Motors

- Formula: `Pa = Pn / (η * cos ϕ)`
- Variables:
    - `Pa` = Apparent power supplied to the motor (kVA)
    - `Pn` = Nominal mechanical power output (kW)
    - `η` = Per-unit efficiency
    - `cos ϕ` = Power factor

3. Current Demand after Power Factor Correction

- Formula: `Ia' = Ia * (cos ϕ / cos ϕ')`
- Variables:
  - `Ia'` = Current after compensation (Amps)
  - `Ia` = Original current (Amps)
  - `cos ϕ` = Original power factor
  - `cos ϕ'` = Power factor after compensation

4. Current Demand for Resistive/Incandescent Loads

- Formula (3-phase): `Ia = Pn / (√3 * U)`
- Formula (1-phase): `Ia = Pn / U` *(Note: Pn is in Watts. If Pn is in kW, multiply formula by 1,000)*
- Variables:
  - `Ia` = Current demand (Amps)
  - `Pn` = Nominal power (Watts)
  - `U` = Voltage between terminals (Volts)

5. Current Demand for Fluorescent Lamps

- Formula: `Ia = (Pballast + Pn) / (U * cos ø)`
- Variables:
  - `Ia` = Current demand (Amps)
  - `Pballast` = Power dissipated in ballast (Watts)
  - `Pn` = Nominal power of the tube (Watts)
  - `U` = Applied voltage (Volts)
  - `cos ø` = Power factor of the complete circuit

6. Installed Apparent Power (kVA) Estimation

- Formula: `Pa = Pn / (η * cos ø)`
- Variables:
  - `Pa` = Apparent-power demand of the load (kVA)
  - `Pn` = Nominal power rating (kW)
  - `η` = Per-unit efficiency
  - `cos ø` = Power factor

7. Full-Load Current from kVA

- Formula (1-phase): `Ia = (Pa * 1000) / V`
- Formula (3-phase balanced): `Ia = (Pa * 1000) / (√3 * U)`
- Variables:
  - `Ia` = Full-load current (Amps)
  - `Pa` = Apparent Power (kVA)

- `V` = Phase-to-neutral voltage (Volts)
- `U` = Phase-to-phase voltage (Volts)

8. Transformer Nominal Full-Load Current

- Formula (3-phase): `In = (Pa * 1000) / (√3 * U)`
- Formula (Simplified for 400V): `In ≈ kVA * 1.4`
- Variables:
  - `In` = Nominal full-load current (Amps)
  - `Pa` = kVA rating of the transformer
  - `U` = Phase-to-phase no-load voltage (Volts)

Data Tables Analysis

- Table B1: Lists standard low voltages (100 V to 1000 V) as per IEC 38-1983, including 3-phase (230/400 V, 400/690 V) and single-phase (120/240 V) systems.
- Table B2: Lists standard voltages above 1 kV up to 35 kV (IEC 38-1983) for both 50/60 Hz (Series I) and 60 Hz North American practice (Series II), distinguishing between nominal system voltage and highest voltage for equipment.
- Table B3: Provides recommended frequencies for periodic check-tests based on installation type (e.g., annually for high-risk areas, every 3 years for other cases).
- Table B4: A comprehensive table showing power and current values for typical induction motors from 0.37 kW to 1100 kW. It provides uncompensated and compensated (to cos ϕ = 0.93) current values at various 1-phase and 3-phase voltages. A critical note indicates a 0.95 multiplication factor to convert 220/380V values to the modern 230/400V standard.
- Table B6 & B7: Provide motor power ratings, current ratings (In, Ith), catalogue numbers, and weights for DC motor progressive starters (Table B6: with voltage ramp; Table B7: with current limitation) for various voltages (220V, 380V, 415V, 440V).
- Table B8: Details the current demand for resistive heating and incandescent lighting for power ratings from 0.1 kW to 10 kW at different 1-phase and 3-phase voltages.
- Table B10 & B11: Show current demands and power consumption for standard and compact fluorescent lamps, respectively, at 220V/240V. They distinguish between power-factor corrected and uncorrected scenarios and note the effect of electronic ballasts.
- Table B12: Gives detailed demand characteristics for discharge lamps (high/low-pressure sodium, mercury vapour). It includes total power demand, current (corrected and uncorrected), starting current ratio (Ia/In), start-up time, luminous efficiency, and average lamp life.

- Table B13: Provides very approximate VA/m² estimates for installed apparent power for different types of applications (e.g., lighting for offices at 24 VA/m², machine shops at 300 VA/m²).
- Table B14: Lists simultaneity factors (ks) for apartment blocks based on the number of downstream consumers. The factor ranges from 1 for 2-4 consumers down to 0.40 for 50+ consumers.
- Table B16: Specifies the simultaneity factor (ks) for distribution boards based on the number of outgoing circuits, ranging from 0.9 for 2-3 circuits to 0.6 for 10 or more.
- Table B17: Gives simultaneity factors (ks) based on the function of the circuit (e.g., lighting = 1, socket-outlets = 0.1-0.2, motors for lifts = 1 for the most powerful, 0.75 for the second).
- Table B18: This is a worked example demonstrating the application of utilization (ku) and simultaneity (ks) factors to estimate the maximum predicted loading at three levels of an installation, reducing a total installed load of 126.6 kVA to a final demand of 65 kVA.
- Table B19: Lists IEC-standardized kVA ratings for HV/LV 3-phase distribution transformers (from 50 kVA to 2500 kVA) and their corresponding nominal full-load currents at various LV voltages (400V, 420V, 433V, 480V).

BOQ Implications

- Quantity Calculation Methods: The chapter provides the fundamental formulas for calculating load currents (Amps) from equipment power ratings (kW). These currents are the basis for sizing cables, busbars, and protective devices, which are key items in a BOQ.
- Cost Estimation Factors:
    - The concept of applying utilization (`ku`) and simultaneity (`ks`) factors is critical for cost-effective design. Basing a design on the simple sum of all loads would lead to oversized, unnecessarily expensive transformers, switchgear, and cabling. The example in Table B18 shows how a 126.6 kVA installed load can realistically be served by a system designed for 65 kVA, a significant cost saving.
    - Power factor correction is introduced as a method to reduce electricity bills and potentially avoid the cost of upgrading a transformer.
- Material Sizing:
    - Tables B4 through B12 provide the current demands for various equipment, which directly informs the required ampacity and cross-sectional area (c.s.a.) of cables in the BOQ.
    - Table B19 directly links the required kVA of an installation to standard transformer sizes, a primary capital equipment item.

Critical Notes and Warnings

- Voltage Standards: The guide emphasizes the transition from older 220/380V and 240/415V systems to the IEC recommended 230/400V standard. A conversion factor of 0.95 is provided to adjust current values for motors from the old to the new standard voltage. This is critical for correct calculations.
- Safety and Regulations: It is repeatedly stated that all designs must comply with local regulations and standards, which may impose constraints beyond the IEC guidelines presented.
- Discharge Lamps: A critical operational note warns that certain discharge lamps are sensitive to voltage dips (<50% nominal) and require a significant cooling-down period (approx. 4 minutes) before they can re-ignite. This has implications for applications requiring continuous lighting.
- Power Factors (`ku`, `ks`): The determination of these factors requires detailed knowledge of the installation and its operational patterns. The values provided are typical, and the ultimate responsibility lies with the designer. For example, for socket-outlets, the `ku` factor depends entirely on the appliances being used.

Cross-References

- The methodology section (pages B1, B14) acts as a roadmap, cross-referencing the logical steps of installation design to the corresponding chapters in the guide (B, C, D, E, F, G, H, J, L).
- Section 2.3 (B4) lists numerous IEC standards that are fundamental to the entire guide.
- Section 3.1 (B8) on power factor correction for motors explicitly cross-references to Chapter E for a detailed discussion.
- Section 4.6 (B18) on transformer selection cross-references to Chapter E for improving power factor.

Chapter C: HV/LV Distribution Substations (Sections 1-3)

Overview

This chapter details the characteristics of high-voltage (HV) power supplies for consumer substations, typically up to 36.5 kV. It covers the fundamental parameters of an HV supply, including voltage levels, short-circuit currents, and earthing methods. The chapter explains different types of HV service connections, the procedures for establishing a new consumer substation, and the critical protection schemes required. These schemes are designed to protect against electric shocks, overvoltages, overloads, and short-circuits, ensuring both personnel safety and equipment integrity. The importance of interlocks and proper operational procedures is also heavily emphasized.

Key Standards and Codes Referenced

- IEC 38: Standard Voltages.
- IEC 56: High-voltage alternating-current circuit breakers.
- IEC 71: Insulation co-ordination.
- IEC 76-3: Power transformers - Part 3: Insulation levels and dielectric tests.
- IEC 282-1: High-voltage fuses - Part 1: Current-limiting fuses.
- IEC 364: Electrical installations of buildings (and its various sub-parts).
- IEC 420: High-voltage alternating-current switch-fuse combinations.
- IEC 644 (1991): Specification for high-voltage fuse-links for motor circuit applications (referenced for withstand voltage formula).
- IEC 694: Common clauses for high-voltage switchgear and controlgear standards.
- IEC 787: Application guide for selection of fuse-links of high-voltage fuses for transformer circuit application.

Technical Specifications

Section 1: Supply of Power at High Voltage

- Voltage Levels:
    - Nominal Voltage: The voltage by which a system is designated (e.g., 20 kV).
    - Highest Voltage for Equipment: The maximum voltage at which equipment can operate under normal conditions, excluding transients. This is specified for systems > 1,000 V.
    - Standard Voltage Ratios: In any country, the ratio between two adjacent nominal voltages should be not less than two.
    - Voltage Tolerance: For Series I (50/60 Hz) systems, voltage does not differ by more than ±10% from nominal. For Series II (North American), it's +5% / -10%.
- Insulation Levels:
    - Rated Lightning Impulse Withstand Voltage (Peak): Equipment must withstand specific peak impulse voltages to protect against atmospheric surges. Values are given for different rated voltages (e.g., for a 12 kV system, a 75 kV peak impulse withstand is standard).

    - Rated Power-Frequency Withstand Voltage (RMS): Equipment must withstand specified RMS overvoltages for 1 minute (e.g., 28 kV for a 12 kV system).
- Short-Circuit Current:
    - Rated Breaking Capacity (Icu): The maximum short-circuit current a circuit breaker can interrupt. Standard values for HV systems include 8, 12.5, 16, 25, 40, 50 kA.
    - Rated Making Capacity (Icm): The maximum peak current a circuit breaker can close onto. This is typically 2.5 times the RMS value of its rated breaking capacity (Icu). This factor accounts for the DC component in an asymmetrical fault.
    - Thermal Withstand: All HV equipment must withstand the thermal and mechanical stresses of the maximum short-circuit current for 1 second (or 3 seconds depending on specifications).
- Rated Normal Current:
    - Specification: The RMS value of current that can be carried continuously without exceeding specified temperature rises.
    - Common Ratings: For general-purpose HV distribution switchgear, the most common rating is 400 A. Ratings of 630 A, 800 A, 1250 A, etc., are used for higher-load-density areas and bulk-supply substations.
- Earthing Connections:
    - Transferred Potential: A primary hazard where an HV earth fault raises the potential of the entire substation earthing system. This dangerous potential can be "transferred" to the consumer's LV installation via the LV neutral conductor.
    - Solutions:
        a. Restrict HV Earth-Fault Current: Done at the source substation by earthing the HV system through resistors or reactors. A typical limit for overhead lines is 300 A; for underground systems, 1,000 A.
        b. Low-Resistance Earthing: Ensure the substation earthing resistance (Rs) is low enough to limit the touch voltage.
        c. Equipotential Bonding: Create an equipotential "cage" at the substation to ensure all conductive parts are at the same potential during a fault.
        d. System Type: The choice of LV earthing system (TN, TT, IT) is critical in managing this risk.
- HV Service Connections:
    - Single-Line Service: A single tee-off from an HV distributor, common for rural areas and transformers up to 160 kVA.

    - Ring-Main Service: Uses a Ring-Main Unit (RMU) with two incoming switches and one outgoing protective device, providing a secure two-source supply. Common in urban underground networks.
    - Parallel Feeders: Two incoming lines from the same substation busbar, with interlocked switches to ensure only one is closed at a time, providing a backup supply.
- Operational Aspects:
    - Overhead Lines: Subject to frequent, temporary, self-clearing faults. Automatic reclosing schemes are used on circuit breakers to restore supply after such faults, typically with 1 to 3 reclose attempts before locking out for a permanent fault.
    - Underground Cables: Faults are less frequent but almost always permanent, requiring longer repair times.
    - Remote Control: SCADA systems are increasingly used for remote control of HV networks.

Section 2: Consumers HV Substations

- Establishment Procedure:
    i. Preliminary Information: The consumer must provide the supply authority with:
        - Maximum anticipated power (kVA) demand.
        - Layout plans showing the proposed substation location and access.
        - Required degree of supply continuity.
    ii. Project Studies: The supply authority provides:
        - Type of power supply (overhead/underground, single-line/ring-main, etc.).
        - Nominal and rated voltages.
        - Metering details and tariff structure.
    iii. Implementation: Consumer obtains official approval for equipment and installation methods.
    iv. Commissioning: Rigorous tests (earth resistance, continuity, HV component tests, interlocks) are performed before the installation is energized.

Section 3: Substation Protection Schemes

- Protection against Electric Shock:
    - Direct Contact: Prevented by containing live parts in housings (enclosures) or placing them out of reach.
    - Indirect Contact: Occurs when touching a conductive part that has become live due to an insulation failure. Protection is achieved by creating an equipotential environment and ensuring rapid disconnection. In HV

systems, limiting touch voltage to 50V may not be possible; therefore, creating an equipotential zone is the primary solution.

- Protection against Overvoltages:
  - Atmospheric Origin: Lightning arresters are used, connected between phase conductors and the earthing system.
  - Ferro-Resonance: A spontaneous condition in IT-earthed systems involving interaction between system capacitance and non-linear transformer inductance, which can cause severe overvoltages. It is countered by specific transformer core designs and damping resistors in VTs.
- Electrical Protection (Overcurrents):
  - Overload Protection: Provided by time-delayed relays (thermal or electronic) that trip a circuit breaker.
  - Transformer Internal Faults:
    - Buchholz Relay: Used on conservator-type transformers to detect gas accumulation (incipient faults) and oil surges (heavy internal faults).
    - DGPT (Detection of Gas, Pressure, and Temperature): A modern equivalent for "totally-filled" transformers.
  - Short-Circuit Protection:
    - Fuses: Used for smaller transformers (<45 A primary current). Require careful coordination.
    - Circuit Breakers: Used for larger transformers.
    - Restricted Earth-Fault (REF) Protection: A highly sensitive and rapid scheme that detects earth faults only within the transformer's HV windings, providing excellent protection against transferred potential hazards.
- Interlocks and Conditioned Manœuvres:
  - Purpose: To prevent incorrect operational sequences that could endanger personnel or damage equipment.
  - Method: Primarily uses key-transfer interlocking. A key is trapped or freed depending on the state of the equipment, forcing the operator to follow a strict, safe sequence of operations (e.g., cannot access fuses until the circuit is isolated and earthed).

Visual Elements Analysis

Figure C5: Determination of short-circuit making and breaking currents...

- Description: A waveform diagram of a fully-offset short-circuit current. It shows the asymmetrical current wave (envelope AA'-BB') and its components over time.

- Technical Details:
  - I_{MC}: Making current, the peak value of the first half-cycle.
  - I_{AC}: Peak value of the A.C. component of the current.
  - I_{DC}: Value of the D.C. component of the current.
  - EE': Instant of contact separation (arc initiation).
  - The diagram illustrates how the total current is a sum of the decaying DC component and the symmetrical AC component. The peak making current is shown to be approximately 1.8 times the peak AC component, which standardizes to the 2.5 x RMS value used for ratings.
- Relationship to Text: This figure visually explains the concept of asymmetrical short-circuit current and the derivation of the $2.5 \times I_{cu}$ factor for a circuit breaker's making capacity (Icm).

Figure C6: Transferred potential.

- Description: A circuit diagram showing an HV/LV transformer with an earth fault on the HV side. The fault current I_f flows to earth via the substation earth resistance R_s, creating a voltage rise $V = I_f * R_s$.
- Technical Details: The diagram clearly shows that the LV neutral is connected to the same earth point R_s. This means the entire LV system (neutral and phases) is raised to the potential V relative to remote earth. This voltage is then "transferred" to the consumer's installation.
- Relationship to Text: This is a critical diagram that visually explains the dangerous phenomenon of "Transferred Potential" discussed in the text, which is a key driver for many protection and earthing requirements.

Figure C7: Maximum earthing resistance Rs at a HV/LV substation...

- Description: A set of six diagrams (A-F) illustrating different standard LV earthing schemes (TN, TT, IT) and their variations, showing the connection of HV and LV earths.
- Technical Details:
  - Schemes A/B (TN/IT): HV and LV earths are interconnected (denoted by (R)). No specific value for Rs is imposed.
  - Schemes C/D (TT/IT): HV and LV earths are interconnected, but the consumer's installation has a separate earth. A formula is given to calculate the maximum permissible R_s to limit transferred potential. $R_s \leq (U_w - U_o) / I_m$.
  - Schemes E/F (TT/IT): The LV neutral is earthed separately from the substation equipment earth (denoted by (S)). The formula for R_s here protects the substation equipment itself. $R_s \leq (U_{ws} - U) / I_m$.

- Relationship to Text: This figure provides the visual context for the different earthing systems and is directly linked to the formulas and discussion on limiting overvoltages and ensuring safety during HV earth faults.

Figure C11: Automatic reclosing cycles of a circuit breaker...

- Description: A set of three current-vs-time graphs showing the automatic reclosing sequences of a circuit breaker on an HV overhead line.
- Technical Details:
  - 1-cycle RR + 1SR: Shows one rapid reclose (RR) attempt. If the fault persists, a slow reclose (SR) is attempted before lockout.
  - a-fault on main distributor: Shows a sequence with two slow reclose attempts (SR1, SR2).
  - b-fault on section supplied through IACT: Shows a sequence where an automatic isolating switch (IACT) operates after the first two trips, isolating the faulted section before the final reclose attempt.
- Relationship to Text: This figure illustrates the operational principles of auto-reclosing schemes described in the text, a key feature for improving supply continuity on overhead HV networks.

Figure C12 & C13: Vector diagrams for IT systems

- Description: Figure C12 shows the vector relationship of voltages and currents during a first earth fault in an IT system. Figure C13 shows the vector diagram of a displaced neutral due to ferro-resonance.
- Technical Details:
  - Fig C12: Shows that during a fault on one phase, the other two phases rise to $\sqrt{3}$ times the phase-to-neutral voltage with respect to earth.
  - Fig C13: Shows the neutral point 'N' displaced significantly from the earth potential 'E', resulting in severe overvoltages on the phase-to-earth connections (V1E, V2E, V3E).
- Relationship to Text: These diagrams are essential for understanding the behavior of IT systems under fault conditions and the specific, dangerous phenomenon of ferro-resonance.

Figure C17: Protection against earth fault on the HV winding.

- Description: A circuit diagram showing the principle of Restricted Earth-Fault (REF) protection. It shows a set of three current transformers (CTs) on the HV phase conductors, with their secondaries connected in parallel to an earth-fault relay (E/F relay).
- Technical Details: In normal operation or for faults outside the protected zone, the sum of the currents is zero, and the relay is stable. For an earth fault within the

zone (between the CTs and the transformer winding), the currents become unbalanced, causing the relay to operate.

- Relationship to Text: This diagram visually explains the REF protection scheme, described as a high-speed, sensitive, and recommended method for protecting against HV winding earth faults.

Figure C21: Discrimination between HV fuse operation and LV circuit breaker tripping...

- Description: A time-current characteristic curve graph showing the operating curve for an HV fuse and an LV circuit breaker.
- Technical Details: To ensure discrimination, the LV breaker's curve must be entirely to the left of and below the fuse's minimum pre-arcing time curve. Two criteria are given: $B/A \geq 1.35$ (current margin) and $D/C \geq 2$ (time margin).
- Relationship to Text: This figure graphically represents the principle of time-current discrimination, which is a critical concept for ensuring that the correct protective device operates during a fault.

Figure C24: Example of HV/LV/TR interlocking.

- Description: A sequence of four diagrams illustrating a key-interlocking procedure for safely isolating a transformer. It uses symbols for keys being free, trapped, or absent.
- Technical Details:
    i. Initial State: HV switch and LV CB are closed. Key 'O' is trapped in the LV CB.
    ii. Step 1-3: Operator opens LV CB, releasing key 'O'. Key 'O' is used to unlock and then close the HV earthing switch, which traps key 'O'.
    iii. Step 4: Closing the earthing switch releases key 'S' from the fuse access panel.
    iv. Step 5: Key 'S' is used to remove the transformer terminal shrouds, at which point key 'S' becomes trapped.
- Relationship to Text: This provides a clear, practical, step-by-step visual guide to the key-interlocking safety procedure described in the text, making a complex but vital process easy to understand.

Calculations and Formulas

- Maximum Peak Current: $Ipeak = 2.5 * Irms$ (where Irms is the symmetrical breaking capacity).
- Substation Earth Resistance (Rs) for TT/IT Systems (Fig C7):
    - $Rs \leq (Uw - Uo) / Im$
    - $Rs \leq (Uws - U) / Im$

- Withstand Voltage (Uw): $Uw = 1.5 * Uo + 750\ V$ (as per IEC 644).
- Transformer Impedance (Ztr): $Ztr = (Uo^2 * Usc) / (Pn * 100)$ (in milli-ohms).
- Upstream HV Network Impedance (Zs): $Zs = Uo^2 / Psc$ (in milli-ohms).

BOQ Implications

- Equipment Selection: The chapter provides specific criteria for selecting major equipment, which directly impacts the BOQ.
  - Transformers: Selection based on kVA rating, but also on type (conservator vs. total-fill, oil-immersed vs. cast-resin) which have different costs and protection requirements (Buchholz vs. DGPT).
  - Switchgear: Choice between fuses and circuit breakers for transformer protection is determined by primary current (< 45 A). This has a significant cost implication.
  - Protective Relays: The need for specific, high-performance relays like REF protection or voltage-controlled overcurrent relays adds cost but is critical for safety and reliability.
  - Lightning Arresters: Required for overhead-line-fed substations, adding to the material list.
- Civil Works: The choice of substation type (e.g., pole-mounted vs. indoor prefabricated housing) has major implications for civil works costs. Indoor substations require foundations, fire-rated walls, and potentially oil sumps.
- Cabling: The requirement for specific earthing conductor sizes and the recommendation to keep PE conductors close to phase conductors in TN/IT systems affects cable tray/conduit planning and costs.

Critical Notes and Warnings

- Personnel Safety: The entire chapter places a very high emphasis on safety, particularly the dangers of Transferred Potential from HV earth faults and the absolute necessity of following strict interlocking procedures before performing any maintenance.
- System Compatibility: It is critical to ensure that the LV earthing scheme (TN, TT, IT) is compatible with the protection philosophy and the equipment being installed. The behavior of IT systems during first and second faults is complex and requires special attention.
- Ferro-Resonance: This is highlighted as a specific and dangerous phenomenon in IT systems that can lead to destructive overvoltages if not properly addressed in the design of the VTs and protection.

- Discrimination: Failure to correctly coordinate protective devices (fuses, circuit breakers) can lead to widespread outages instead of isolating a local fault. The time-current characteristics must be carefully compared.

Chapter C: HV/LV Distribution Substations (continued)

Overview

This part of the chapter focuses on the practical implementation of consumer substations, distinguishing between those with Low Voltage (LV) and High Voltage (HV) metering. It delves into the choice of key equipment like switchgear and transformers, detailing their technical specifications, insulation methods, and safety features. The physical constitution of substations, both indoor and outdoor (pole-mounted, prefabricated), is described, including critical requirements for earthing, lighting, and safety. The appendices provide in-depth examples on protection coordination, the physics of ground-potential gradients, and the calculation of ferro-resonance phenomena.

Key Standards and Codes Referenced

- IEC 56-1, 129, 265-1, 298, 694: International standards for HV switchgear.
- IEC 76-2: Power transformer - Temperature rise.
- IEC 76-4: Guide to the lightning impulse and switching impulse testing of power transformers and reactors.
- IEC 296: Specification for unused mineral insulating oils for transformers and switchgear.
- IEC 947-1, 947-2, 947-3: Standards for LV switchgear, circuit breakers, and switches.
- IEC 420, 787: Standards related to HV switch-fuse combinations and fuse selection.
- CENELEC HD 46451: Standard for dry-type transformers.
- National Standards: French (UTE, EDF), British (BS), German (VDE), American (ANSI).

Technical Specifications

Section 4: The Consumer Substation with LV Metering

- Function: A substation with LV metering is an installation connected to a public HV supply (1 kV - 35 kV) with a single transformer, generally not exceeding 1,250 kVA.

- Switchgear Panels:
    - Technology: Modern switchgear is often modular, compartmented, and uses SF6 (Sulphur hexafluoride) as an insulating medium. This allows for compact, safe, and flexible switchboard arrangements.
    - Compartments: Panels are divided into four compartments: switchgear, connections, busbars, and control/indication.
    - Interlocks: Mechanical and electrical interlocks are critical for safety. They ensure:
        - Switch cannot be closed unless the access panel is closed and the earth switch is open.
        - Earth switch cannot be closed unless the main switch is open.
        - Access to cable terminations or fuses is only possible after the circuit is earthed.
- HV/LV Transformer Technology:
    - Dry-Type (Cast Resin): Windings are insulated by vacuum-cast epoxy resin. Classified as non-flammable and self-extinguishing. Ideal for indoor locations and high-rise buildings due to high fire safety. Environment class E2 (high condensation/pollution), climatic class C2 (operable down to -25°C).
    - Liquid-Filled (Oil-Immersed): Use mineral oil (IEC 296) for insulation and cooling.
        - Hermetically-Sealed Totally-Filled Tank: Used up to 10 MVA. Expansion of oil is compensated by the elastic deformation of cooling fins. Requires no air-drying device and is very low maintenance.
        - Air-Breathing Conservator-Type Tank: Used for transformers > 10 MVA. An expansion tank (conservator) above the main tank accommodates oil volume changes. Air breathes in and out through a silica-gel desiccator.
- Dielectric Fluids Categories (Table C31):
    - O1: Mineral oil (< 300°C flash-point).
    - K1, K2, K3: High-density hydrocarbons, esters, silicones (> 300°C flash-point).
    - L3: Insulating halogen liquids (non-flammable). Note: PCBs are prohibited.
- Safety for Liquid-Filled Transformers (Table C32):
    - Containment: A liquid-tight sump or sill must contain any potential leaks.
    - Fire Extinguishing: A pebble bed in the sump helps extinguish burning liquid.
    - Fire Detection: Automatic devices are required to cut power and give an alarm.

- Ventilation of Transformer Chambers:
  - Purpose: To dissipate heat from transformer losses and prevent overheating.
  - Natural Ventilation: Requires an air inlet orifice (S) at floor level and an outlet orifice (S') on the opposite wall at a height (H) above the inlet.
  - Forced Ventilation: Required for ambient temperatures > 20°C or where natural ventilation is inadequate. Uses thermostat-controlled fans.

Section 5: The Consumer Substation with HV Metering

- Function: Used for larger installations (>1,250 kVA) or where required by the utility. Metering equipment (CTs and VTs) is installed on the HV side.
- Parallel Operation of Transformers:
  - Conditions: To avoid damaging circulating currents, paralleled transformers must have:
    a. The same winding configuration and phase change (e.g., all Dyn 11).
    b. The same (or <10% difference) short-circuit percentage impedances (Zsc%).
    c. The same open-circuit voltage ratios (phase-to-phase voltages must not differ by more than 0.4%).
  - Rating Ratio: It is not recommended to operate transformers in parallel if their kVA ratings differ by more than a factor of 2:1.
- Power-Supply Changeover: For critical loads, automatic changeover schemes between the main supply and a standby generator are used. Interlocking must prevent parallel operation of the generator with the public supply unless a specific de-coupling scheme is agreed upon with the utility.

Section 6: Constitution of HV/LV Distribution Substations

- Indoor Substations:
  - Earthing Circuits: Must include separate earth electrodes for HV equipment, LV neutral, and the installation itself, unless space limitations require a common earthing system. Removable links must be provided for testing.
  - Safety Materials: Substations must be equipped with insulating mats/stools, insulated gloves, a voltage detector, fire extinguishers (powder or CO2), and clear DANGER/first-aid signage.
- Outdoor Substations:
  - Pole-Mounted: For rural areas, typically ≤ 160 kVA. Protected by lightning arresters on the HV side and two series LV circuit breakers (D1 at the transformer for overload, D2 at the consumer for main protection). Requires separated earth electrodes for safety.

    - Prefabricated Housings: Compact, weatherproof, and vermin-proof units mounted on a concrete base. Offer a rapid and cost-effective solution for both urban and rural settings.
    - Fenced Outdoor Substations: Weatherproof equipment is mounted on concrete plinths within a fenced area. Less common now due to high cost and visual impact.

Visual Elements Analysis

Figure C25 & C34: One-Line Diagrams for LV and HV Metering

- Description: These figures show one-line diagrams for four types of HV service connections: single-line, single-line with extension capability, duplicate (parallel) feeders, and ring-main. Figure C25 shows LV metering, while C34 shows HV metering.
- Technical Details: The diagrams clearly delineate the zones of access and responsibility for the power-supply authority, the consumer, and the testing authority. The key difference is the location of the metering CTs/VTs and the main protection, which shifts from the LV side (C25) to the HV side (C34).
- Construction Notes: Illustrates the electrical topology that the physical installation must follow. The choice between these service types depends on the required level of supply security.

Figure C33: Natural Ventilation

- Description: A cross-section of a transformer room showing the principle of natural convection cooling.
- Technical Details: Cool air enters through a low-level orifice of area `S`. It absorbs heat from the transformer, rises, and exits through a high-level orifice of area `S'` on the opposite wall. The height difference `H` drives the airflow.
- Relationship to Text: This diagram visually explains the variables `S`, `S'`, and `H` used in the ventilation calculation formulas provided in the text.

Figure C37: Phase change through a Dyn 11 Transformer

- Description: Shows the winding connections and corresponding voltage vector diagram for a Delta-star (Dyn 11) transformer.
- Technical Details: The primary is Delta connected. The secondary is Star connected with the neutral brought out. The "11" signifies a +30° phase shift of the LV voltage relative to the HV voltage (LV leads HV).
- Relationship to Text: This is the most common configuration for distribution transformers and is essential for understanding the conditions required for parallel operation.

Figure C42: Separated earth electrodes.

- Description: A diagram illustrating the safety principle of using separated earth electrodes for a pole-mounted substation.
- Technical Details: It shows three distinct earth electrodes: `RA` for the HV lightning arresters, `RB` for the transformer frame/tank and other metallic parts (the installation earth), and `Rp` for the LV neutral.
- Construction Notes: The text notes that `RB` must be < 3 ohms to limit voltage rise at the consumer's premises during a fault. This separation prevents HV fault potentials from being directly transferred to the LV system.

Appendix Figures (AC1-1, AC2-1, AC3-1, etc.)

- Description: These figures provide detailed graphical and mathematical explanations for advanced concepts.
    - AC1-1: Shows the time-current curves for an HV fuse and an overload relay, defining the "transfer current" where protection responsibility is handed from one to the other.
    - AC2-1 & AC2-3: Illustrate the physics of how current flowing from an earth rod into the soil creates potential gradients on the ground surface, defining the dangerous concepts of "step voltage" and "touch voltage".
    - AC3-1 & AC3-2: Show the circuit and vector diagrams used in the mathematical derivation of the neutral voltage displacement during ferro-resonance.

Calculations and Formulas

Natural Ventilation Orifice Area

- Formula: `S = 0.18 * P / √H` and `S' = 1.1 * S`
- Variables:
    - `S` = Sectional area of incoming-air orifice (m^2).
    - `S'` = Sectional area of outgoing-air orifice (m^2).
    - `P` = Total transformer losses (no-load + full-load) in kW.
    - `H` = Height difference between orifice centers (m).

Forced Ventilation Air-Flow Rate

- Formula:
    - `0.081 * P` (for totally-filled transformer)
    - `0.05 * P` (for dry-type Class F transformer)
- Variables:
    - Air-flow rate is in cubic meters per second at 20°C.
    - `P` = Total losses in kW.

Appendix 3: Ferro-Resonance Calculation (Per-Unit Method)

- Procedure: A step-by-step calculation using per-unit values for voltage and impedance to determine the neutral-to-earth voltage (`VNE`) during a ferro-resonant condition.
    - Step 1: Calculate phase currents (`I1`, `I2`, `I3`) based on the saturated and unsaturated reactances.
    - Step 2: Vectorially sum the phase currents to find the neutral current (`IN`).
    - Step 3: Calculate the equivalent parallel impedance of the network (`ZNE`).
    - Step 4: Calculate `VNE = IN * ZNE`.
- Example: The worked example shows how a `VNE` of 1.375 per-unit (or 137.5% of the normal phase-to-neutral voltage) is derived, confirming the danger of this phenomenon.

BOQ Implications

- Equipment Costs: The choice between LV and HV metering significantly impacts cost. HV metering requires expensive high-voltage CTs and VTs.
- Transformer Selection: Dry-type transformers are more expensive than oil-filled ones but may reduce civil works costs (no sump, less stringent fire separation).
- Switchgear: The need for specific switchgear (e.g., 4-pole breakers for switched neutrals, interlocked changeover panels, SF6 insulated units) must be reflected in the BOQ.
- Safety and Civil Works:
    - The cost of providing required safety materials (mats, gloves, signs, extinguishers) must be included.
    - For liquid-filled transformers, the BOQ must account for the construction of a containment sump and pebble bed.
    - Ventilation louvres (for natural) or fans and thermostats (for forced) are required items.
    - Earthing systems, including copper conductors, earth rods, and removable test links, are a key part of the materials list.

Critical Notes and Warnings

- Parallel Operation: The conditions for paralleling transformers are strict and non-negotiable. Failure to match winding configurations, voltage ratios, and impedances will lead to large circulating currents, overheating, and potential equipment failure.
- Interlocking: Safety interlocks on HV switchgear are not optional. They are a fundamental safety requirement to prevent catastrophic operator error. The procedure shown in Fig. C24 must be followed precisely.

- Separated Earthing: For pole-mounted substations, the separation of the HV arrester earth from the LV system earth is a critical safety measure to prevent the transfer of dangerous lightning-induced potentials.
- Ventilation: Inadequate ventilation will cause a transformer to overheat, reducing its lifespan and available power output. The calculation formulas must be correctly applied.

Part 4 Analysis: Chapter D - Low-voltage service connections

Overview

This chapter provides a detailed examination of low-voltage (LV) public distribution networks and how consumers connect to them. It begins by surveying the diverse electricity supply characteristics (voltages, frequencies, tolerances) found around the world. The chapter then describes the common topologies of LV distribution networks, such as radial and tapered systems, and contrasts European and North American practices. It details the components and modern arrangements for a consumer's service connection, emphasizing the move towards external, weatherproof enclosures. Finally, it addresses the critical issues of supply quality, particularly maintaining voltage levels within statutory limits, and explains the principles behind tariff structures and metering, including kVA maximum-demand billing.

Key Standards and Codes Referenced

- IEC 38-1983: Standard Voltages (referenced for the recommended 230/400 V standard).
- IEC 287 (1982): Calculation of the continuous current rating of cables (referenced for cable ampacity calculations).
- IEC 364: Electrical Installations of Buildings (implicit foundation for safety and earthing system requirements like TT and TN).
- IEC 1000-3-3 and 1000-4-15: Referenced for flicker meter standards and parameter limits (from Appendix EMC, relevant context).

Technical Specifications

1. Low-Voltage Consumers and Networks

- LV Supply Range: Most common LV supplies are within the range of 120 V single-phase to 240/415 V 3-phase, 4-wire.
- LV Supply Limit: Power-supply organizations can typically supply loads up to 250 kVA at LV, but often propose an HV service for loads above this level, or where the existing LV network is marginally adequate.
- LV Network Topologies:
    - European Urban Practice: Standard-sized LV distribution cables form a network through 4-way link boxes located in manholes at street corners. By removing phase links, the network is operated as a series of branched, open-ended radial systems. This provides high flexibility for maintenance and fault isolation.
    - Tapered Radial Distribution: Used in less-densely loaded areas. The conductor cross-sectional area is reduced as the distance from the substation increases and the number of downstream consumers decreases. This is a more economical design.
    - Overhead Lines: Traditionally bare copper conductors on poles. Modern practice favors insulated twisted conductors (aerial bundled cables), which are safer and more visually acceptable.
- North American vs. European Practice:
    - European: LV networks are extensive. Large HV/LV transformers in substations (approx. 500-600 meters apart) feed numerous consumers via a robust 3-phase, 4-wire LV network.
    - North American: LV networks are minimal. The distribution is effectively done at HV (as a 3-phase, 4-wire system). This HV network feeds numerous small, single-phase transformers which then supply one or a few premises directly with 120/240 V single-phase, 3-wire.

2. The Consumer-Service Connection

- Modern Practice: Service components (fuses, meters) are now typically located outside the consumer's building in a weatherproof cabinet for ease of access for meter reading and maintenance.
- Components: A typical service connection includes:
    - Service cable tee-joint from the main distributor.
    - Supply authority fuses (sealed and inaccessible to the consumer).
    - Metering equipment (kWh meter, possibly kVA demand meter).
    - Installation main circuit breaker (accessible to the consumer).
- Earthing Systems:
    - TT System: The installation's main circuit breaker must include a residual-current device (RCD) for protection against indirect contact.

    - TN System: Protection is provided by a standard overcurrent circuit breaker or switch-fuse.

3. Quality of Supply Voltage

- Statutory Limits: Supply authorities must typically maintain the voltage at the service position within ±5% of the declared nominal value (though some jurisdictions allow ±6% or more).
- Appliance Tolerance: IEC standards require LV appliances to operate satisfactorily within ±10% of their nominal voltage. This leaves a margin of at least 5% for voltage drop within the consumer's installation.
- Sources of Voltage Drop:
    - HV Network: Maintained within ±2% by on-load tap-changers at the bulk-supply substation.
    - HV/LV Transformer: Has an internal voltage drop under load. A typical transformer with 5% reactance will have a voltage drop of ~3.4% at full load with a 0.8 power factor.
    - LV Distributor: The remaining allowable voltage drop occurs along the final distribution cable.
- Transformer Tapping: Off-circuit tap changers on distribution transformers are used to adjust the output voltage to compensate for the transformer's position on the HV network (e.g., a +2.5% tap for a location close to the bulk supply, a -5% tap for a remote location).

4. Tariffs and Metering

- Tariff Principles: Tariffs are designed to encourage consumers to:
    - Reduce I^2R losses in the network by improving their power factor. This is often achieved by billing based on kVA maximum demand in addition to kWh consumption.
    - Reduce peak power demand by offering cheaper electricity rates during off-peak hours (e.g., night) and seasons.
- kVA Maximum-Demand Metering:
    - The meter measures the average kVA demand over fixed, successive periods (typically 10, 30, or 60 minutes).
    - The billing is based on the single highest average value recorded during the entire billing period (e.g., 3 months).
- Remote Control: Ripple control systems, which inject a coded voice-frequency signal (e.g., 175 Hz) onto the LV mains, are used by utilities for remote meter reading and changing of tariff periods.

Visual Elements Analysis

Figure D3: LV Distribution Network with Link Boxes

- Description: A plan view of an urban LV network. An HV/LV substation feeds multiple 4-core distribution cables. These cables are interconnected at street corners via 4-way link boxes.
- Technical Details: The diagram shows that some "phase links" within the link boxes are removed. This breaks the network into a series of open-ended radial branches. This configuration allows a section of cable between two link boxes to be isolated for repair without interrupting supply to most consumers, who can be back-fed from an adjacent distributor.
- Relationship to Text: This figure provides a clear visual representation of the flexible, interconnected radial network common in European cities, as described in section 1.2.

Figure D4: Widely-used American and European-type systems.

- Description: A comparative schematic of the two main distribution philosophies.
- Technical Details:
    - European side: Shows a single, large 3-phase HV/LV transformer feeding an extensive LV distribution network that supplies many consumers.
    - American side: Shows a 3-phase HV distributor line from which numerous small, single-phase transformers are tapped off. Each of these transformers then provides a 120/240V 3-wire supply to a small number of consumers.
- Relationship to Text: This diagram is critical for understanding the fundamental differences in network topology discussed in section 1.2.

Figure D5: Typical service arrangement for TT-earthed systems.

- Description: An isometric view of a service connection to a building. The diagram shows the main LV distributor cable, a service cable tee-joint (A), a weatherproof cabinet on the exterior wall containing fuses (F) and a meter (C), and the installation main circuit breaker (DB) inside the building.
- Technical Details: The diagram identifies the components and shows the supply-authority/consumer interface point is after the meter. The presence of a TT-earthing system mandates that the consumer's main circuit breaker (DB) includes RCD protection.
- Relationship to Text: This figure illustrates the modern practice of locating service equipment externally and clarifies the typical components of a service connection.

Figures D6, D7, D8: Installation Types

- Description: Three sketches showing typical service connection arrangements in different environments.
  - D6 (Rural): Shows the meter and main CB located in a weatherproof pillar some distance from the main building (e.g., a sawmill).
  - D7 (Semi-urban): Shows the service termination and meter in an external cabinet, with the main CB located inside the consumer's premises (e.g., a shop).
  - D8 (Town Centre): Shows the service cable terminating in a flush-mounted wall cabinet accessible from the public way, containing the utility fuses. This is preferred for aesthetic reasons.

Calculations and Formulas

Transformer Voltage Drop

- Formula: `V% drop = R% cos ø + X% sin ø`
- Variables:
  - `V% drop`: Percentage voltage drop within the transformer.
  - `R%`: Percentage resistance voltage of the transformer.
  - `X%`: Percentage reactance voltage of the transformer.
  - `cos ø`: Power factor of the load.
- Example: For a typical transformer with R%=0.5 and X%=5.0, at a power factor of 0.8 lagging (cos ø = 0.8, sin ø = 0.6): `V% drop = (0.5 * 0.8) + (5.0 * 0.6) = 0.4 + 3.0 = 3.4%`

kVA Maximum-Demand Metering Principle

- Formula: `Average kVA = (Total kVAh consumed in period) / (Period length in hours)`
- Example: If a meter registers 5 kVAh over a 10-minute period (1/6 of an hour): `Average kVA = 5 / (1/6) = 5 * 6 = 30 kVA`. The dial on the meter is marked to show this final `Average kVA` value directly.

Data Tables Analysis

- Table D1: A comprehensive multi-page survey of electricity supplies in various countries. It details for each country: frequency, domestic voltage/system type, commercial voltage/system type, industrial voltage, and LV tolerance. The bracketed letters (A, B, C, etc.) refer to the circuit diagrams on page D5, providing a visual key to the system configuration (e.g., 3-phase star earthed-neutral). This table is an invaluable reference for international projects.
- Table D2: Provides typical maximum permitted service currents and corresponding kVA loads for different LV systems. For example, for a 230/400 V,

3-phase, 4-wire system, a typical maximum permitted service current is 120 A, corresponding to a load of 83 kVA.

BOQ Implications

- Cable Sizing: The chapter highlights that LV distributor cable sizes are limited by voltage drop considerations. The example calculation shows that a 240 mm² copper cable can supply a 292 kVA load over 306 meters before exceeding a 3.6% voltage drop. This calculation is essential for correctly specifying cable quantities and sizes in the BOQ.
- Equipment Selection: The choice of network topology (e.g., underground cables with link boxes vs. overhead lines) and service connection type (e.g., external pillars vs. flush-mounted cabinets) dictates the primary materials for the BOQ.
- Metering Costs: The discussion on tariffs reveals that the metering equipment required can range from simple kWh meters to complex kVA maximum-demand meters with time-of-use registers and remote communication capabilities, which have significantly different costs.

Critical Notes and Warnings

- Voltage Drop is Critical: The guide explicitly warns that while a standard might permit a high voltage drop (e.g., 8%), this can be detrimental to the operation of motors and represents a significant waste of energy. Designs should aim for lower voltage drops on circuits supplying sensitive or heavy equipment.
- System Differences: The stark contrast between European and North American distribution philosophies is a major warning. An engineer cannot apply design principles or assumptions from one system to the other without risking major design flaws.
- Safety and Earthing: The requirement for an RCD on all TT-earthed systems is a critical safety rule that is emphasized. The choice of earthing system has direct consequences for the required protective devices.

Part 5 Analysis: Chapter E - Power factor improvement and harmonic filtering

Overview

This chapter provides a comprehensive guide to understanding, calculating, and implementing power factor correction and harmonic filtering in low-voltage installations. It begins by defining active, reactive, and apparent power, explaining why reactive power is necessary for inductive equipment but detrimental to the overall efficiency of the power system. The chapter details the economic and technical benefits of improving the power factor, such as reduced electricity costs, lower system losses, and increased available power. It presents various methods and strategies for installing capacitor banks (global, by sector, individual) and for calculating the optimal level of compensation. A significant portion is dedicated to the practical challenges, including the risk of motor self-excitation and the adverse effects of system harmonics on capacitor banks, providing solutions like oversizing and the use of harmonic-suppression reactors.

Key Standards and Codes Referenced

- IEC 831-1: Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1000 V - Part 1: General - Performance, testing and rating - Safety requirements - Guide for installation and operation.
- IEC 1000 series (now IEC 61000): Standards on Electromagnetic Compatibility (EMC), implicitly relevant to the discussion on harmonics.
- IEC 269: Low-voltage fuses (relevant to protection of capacitor banks).
- IEC 947-2: Low-voltage switchgear and controlgear - Part 2: Circuit-breakers (relevant to protection).

Technical Specifications

1. Power Factor Fundamentals

- Active Power (P): The "working" power, converted into mechanical work, heat, or light. Measured in watts (W) or kilowatts (kW).
- Reactive Power (Q): The power required to create and sustain magnetic fields in inductive equipment (motors, transformers). It is exchanged cyclically between the source and the load. Measured in volt-amperes reactive (var) or kilovar (kvar).
- Apparent Power (S): The vector sum of active and reactive power; it represents the total power that must be supplied by the network. Measured in volt-amperes (VA) or kilovolt-amperes (kVA).
- Power Factor (PF or cos ϕ): The ratio of active power to apparent power (`PF = P / S`). It is a measure of efficiency. A value of 1.0 is ideal; a low value indicates poor efficiency.
- Typical Power Factors (uncompensated):
  - Induction motors (full load): 0.85
  - Fluorescent lamps (uncompensated): 0.5

- Discharge lamps: 0.4 to 0.6
- Welding set (arc): 0.5

2. Power Factor Correction Principles

- Objective: To improve the power factor of an installation by installing a bank of capacitors, which act as a local source of reactive energy. This reduces the reactive power drawn from the supply network.
- Benefit: Reduces the total apparent power (kVA) demand for the same amount of active power (kW), leading to:
  - Economic: Lower electricity bills by avoiding penalties for low power factor (e.g., for `tan φ > 0.4`).
  - Technical:
    - Reduced current in upstream conductors.
    - Reduced I^2R losses in cables and transformers.
    - Reduced voltage drop.
    - Increased available active power from existing transformers and switchgear.
- Installation Strategies:
  - Global Compensation: One large capacitor bank at the main LV distribution board.
  - Compensation by Sector: Banks installed at local distribution boards.
  - Individual Compensation: Capacitors connected directly to the terminals of large individual motors. This is the most technically effective method.

3. Capacitor Bank Implementation & Harmonics

- Fixed vs. Automatic Banks:
  - Fixed: Used for constant loads or individual motor compensation.
  - Automatic: Used for variable loads. A control relay monitors the power factor and switches capacitor "steps" in or out via contactors to match the required compensation level.
- Harmonics:
  - Problem: Non-linear loads (VSDs, rectifiers, electronic ballasts) create harmonic currents, which distort the voltage waveform. Capacitors are very sensitive to harmonics, as their impedance decreases with frequency, leading to high harmonic currents that can cause overheating and failure.
  - Resonance: A critical issue where the natural resonant frequency of the system inductance and the capacitor bank (`ho = √(Ssc / Q)`) aligns with a system harmonic (e.g., 5th or 7th), causing massive amplification of current and voltage.
  - Solution:

a. Oversizing: Use capacitors rated for a higher voltage (e.g., 440 V capacitors on a 400 V system) to handle increased voltage and thermal stress.
b. Harmonic-Suppression Reactors: Add an inductor in series with the capacitor bank to shift the resonant frequency to a safe, non-harmonic value (e.g., 190 Hz on a 50 Hz system).

- Capacitor Technology:
  - Type: Dry-type, metallized polypropylene, self-healing film.
  - Protection: Internal overpressure disconnector and an external HPC fuse.
  - Tolerances: Capacitance tolerance is 0 to +5%. All components (cables, switchgear) must be sized for 1.5 times the capacitor's nominal rated current to account for harmonics, overvoltage, and capacitance tolerance.

4. Motor Compensation Specifics

- Protection Settings: When a capacitor is connected to a motor's terminals, the total current drawn from the supply decreases. The motor's overcurrent protection relay setting must be reduced accordingly (typically by a factor of 0.9).
- Self-Excitation: A critical risk. If a large capacitor bank remains connected to a motor after it is switched off, the motor's rotor can act as a generator, using the capacitor to self-excite. This can produce dangerously high overvoltages.
- Prevention: The kvar rating of a capacitor connected directly to a motor's terminals must be limited. The recommended maximum is given by the formula $Qc \leq 0.9 * Io * Un * \sqrt{3}$. Table E28 provides pre-calculated maximum kvar values for standard motors.

Visual Elements Analysis

Figure E1, E3, E4, E6: Power Diagrams

- Description: These figures illustrate the fundamental relationship between Active Power (P, kW), Reactive Power (Q, kvar), and Apparent Power (S, kVA) as a right-angled triangle. P is the horizontal side, Q is the vertical side, and S is the hypotenuse. The angle between P and S is ϕ.
- Technical Details: The diagrams visually represent the Pythagorean relationship $S^2 = P^2 + Q^2$ and the trigonometric definitions $\cos \phi = P/S$ and $\tan \phi = Q/P$. Figure E4 shows the underlying vector relationship between voltage and current that gives rise to the power triangle.

Figure E9: Showing the essential features of power-factor correction

- Description: A set of three circuit diagrams showing reactive current flow.
- Technical Details:

- (a) Shows reactive current I_L flowing from the source to the load R.
- (b) A capacitor C is added. It generates reactive current I_C that is equal and opposite to I_L. The net reactive current from the source becomes zero.
- (c) The active current I_R is added, showing that the source now only supplies I_R, and the installation appears to have a power factor of 1.

- Relationship to Text: This perfectly illustrates the principle of local reactive energy compensation.

Figure E10: Diagram showing the principle of compensation

- Description: A power triangle diagram showing how compensation works.
- Technical Details: The original apparent power is S, with a large reactive component Q. A capacitor bank provides reactive power Q_c. This reduces the net reactive power to $Q' = Q - Q_c$. The new, smaller apparent power is S'.
- Relationship to Text: This diagram visually represents the formula $Q_c = P * (\tan \phi - \tan \phi')$ used for calculating the required capacitor bank size.

Figure E13: The principle of automatic-compensation control

- Description: A circuit diagram of an automatic power factor correction bank.
- Technical Details: A current transformer (CT) on the main incoming supply feeds a "varmetric relay". The relay measures the power factor and operates a series of contactors, which switch individual capacitor steps in or out of the circuit to match the load's reactive power demand.
- Relationship to Text: This shows the practical implementation of the automatic capacitor banks described in the text.

Figure E29: Technical-economic comparison of an installation before and after power-factor correction.

- Description: A "before and after" one-line diagram showing the impact of installing a 250 kvar capacitor bank on a 630 kVA transformer supplying a 500 kW load.
- Technical Details:
  - Before: $\cos \phi = 0.75$, Demand $S = 665$ kVA (overloaded), Current $I = 960$ A.
  - After: $\cos \phi = 0.928$, Demand $S = 539$ kVA (14% spare capacity), Current $I = 778$ A. Cable losses are reduced to $(778/960)^2 = 65\%$ of the former value.
- Relationship to Text: This is a powerful summary diagram that quantifies the significant technical and economic benefits of power factor correction discussed throughout the chapter.

Calculations and Formulas

1. Basic Power Formulas

- Power Factor: $PF = \cos\phi = P / S$
- Tangent Phi: $\tan\phi = Q / P$
- Apparent Power: $S = \sqrt{P^2 + Q^2}$

2. Capacitor Bank Sizing (kvar)

- General Formula: $Qc = P * (\tan\phi - \tan\phi')$
  - Qc = Required rating of capacitor bank (kvar).
  - P = Active power of the load (kW).
  - $\tan\phi$ = Tangent of the angle of the original power factor.
  - $\tan\phi'$ = Tangent of the angle of the target power factor.
- From Billed kvarh: `Qc (kvar) = kvarh_billed / number_of_hours_of_operation`

3. Harmonic Resonance

- Formula: $ho = \sqrt{Ssc / Q}$
- Variables:
  - ho = Harmonic order of the natural resonant frequency.
  - Ssc = System short-circuit level at the point of connection (kVA).
  - Q = Capacitor bank rating (kvar).

4. Capacitor Current and Sizing

- Nominal Current: $In = Q / (\sqrt{3} * Un)$
- Component Sizing: All components (cables, circuit breakers) must be sized for a current of 1.5 x In.

Data Tables Analysis

- Table E7: Provides typical $\cos\phi$ and $\tan\phi$ values for common equipment, essential for initial load assessment.
- Table E8: Shows the multiplying factor for cable c.s.a. as power factor decreases. A cable for a load at PF=0.4 must have a c.s.a. 2.5 times larger than for the same kW load at PF=1.0.
- Table E17: A comprehensive lookup table to find the required "kvar per kW of load" to improve from an initial $\cos\phi$ to a target $\cos\phi$. This is a very practical tool for quick calculations.
- Table E20: Shows the available active power (kW) from fully-loaded transformers at different power factors. For example, a 1000 kVA transformer can deliver 700 kW at PF=0.7 but 960 kW at PF=0.96.

- Table E24: Lists the reactive power (kvar) consumed by transformers themselves (no-load and full-load losses) for various sizes. This is important for precise compensation calculations where metering is on the HV side.
- Table E28: A critical safety table providing the maximum kvar of PF correction that can be applied directly to motor terminals without risking self-excitation.

BOQ Implications

- Primary Equipment: The main items for the BOQ are the capacitor banks themselves, specified by their kvar rating and voltage.
- Control Gear: For automatic banks, the BOQ must include the power factor controller (varmetric relay) and the appropriately rated contactors for each capacitor step.
- Protective Devices: Fuses or circuit breakers specifically designed for capacitor switching (to handle high in-rush currents) are required.
- Cabling: As per the 1.5x rule, cables feeding capacitor banks must be oversized compared to what their nominal current would suggest.
- Cost Savings (Negative Costs): The analysis performed in this chapter leads to significant cost reductions in other areas of the BOQ. By improving the power factor, the required kVA rating of the main transformer may be smaller, and the cross-sectional area of main feeder cables can be reduced.

Critical Notes and Warnings

- Harmonics are a Major Risk: The guide strongly warns that installing capacitor banks in a network with significant harmonic distortion without proper analysis can be catastrophic. Resonance can destroy the capacitors and affect the entire installation.
- Motor Self-Excitation: Connecting an oversized capacitor bank directly to a motor is extremely dangerous. The maximum values in Table E28 must be respected. If more compensation is needed, it must be located upstream and switched separately.
- Overcompensation: Installing too much compensation can lead to a leading power factor and cause overvoltages, especially during low-load periods. This is why automatic, stepped banks are essential for variable loads.
- Component Sizing: The rule to size all associated switchgear and cabling for 1.5 times the capacitor's nominal current is a critical safety and reliability requirement.

Part 6 Analysis: Chapter F - Distribution within a low-voltage installation

Overview

This extensive chapter is the core of practical LV installation design. It details the physical and logical layout of distribution systems, from the main distribution board down to the final circuits. It covers the critical topics of ensuring supply continuity and quality for essential services, including the selection and integration of standby power sources. A major section is dedicated to a thorough explanation of the different standardized earthing schemes (TT, TN, IT), which are fundamental to electrical safety. The chapter also provides detailed guidance on the selection and construction of distribution boards, the sizing and designation of conductors and cables, and the classification of external influences using the IP code system.

Key Standards and Codes Referenced

- IEC 364: Electrical installations of buildings (the foundational standard for the entire chapter).
    - IEC 364-3: Assessment of general characteristics.
    - IEC 364-4-41: Protection against electrical shock.
    - IEC 364-5-52: Wiring systems.
    - IEC 364-7-701, 706, 710: Requirements for special locations (bathrooms, conductive locations, exhibitions).
- IEC 439-1: Low-voltage switchgear and controlgear assemblies - Part 1: Type-tested and partially type-tested assemblies (for distribution boards).
- IEC 446: Identification of conductors by colours or numerals.
- IEC 529 (1989): Degrees of protection provided by enclosures (IP Code).
- IEC 947: Low-voltage switchgear and controlgear standards.
- CENELEC: European Committee for Electrotechnical Standardization (referenced for harmonized cable designation codes).
- NFC 15-100: French national installation standard (referenced for some specific examples).

Technical Specifications

1. Principal Schemes of LV Distribution

- Radial Branched Distribution: The most common system. A main feeder supplies distribution boards, which in turn supply sub-distribution boards or final circuits. Conductor sizes are often tapered (reduced) as they get further from the source.
- Prefabricated Bus Channels (Busways): Offer flexibility for installations in large, non-partitioned spaces like industrial workshops. Tap-off units can be easily added along the busway.
- Simple (Unbranched) Radial Distribution: Used for centralized control where each load has a dedicated circuit from the main board. Offers high isolation but uses more copper.
- IT to TN Transition: In large industrial installations, an IT system might be used for power circuits while a separate, galvanically isolated TN system is created via an LV/LV transformer to supply lighting and socket-outlet circuits.

2. Essential Services and Standby Supplies

- Continuity: Achieved by dividing the installation into "essential" and "non-essential" loads. Essential loads are supplied via an automatic changeover scheme from a standby source (e.g., diesel generator, UPS).
- Quality of Supply (EMC):
    - Disturbances: Networks are subject to voltage dips, flicker, overvoltages, harmonics, and high-frequency phenomena.
    - Mitigation: Achieved through:
        - UPS: For the most sensitive equipment (computers, IT).
        - De-coupling: Supplying disturbing loads (e.g., large motors) and sensitive loads from separate transformers.
        - Harmonics Filters: To reduce harmonic distortion.
        - Lightning Arresters: For installations fed by overhead lines, especially where the keraunic level > 25.
- Choice of Reserve Power Source: Depends on application requirements and acceptable interruption times.
    - No break (zero time): Requires a battery/inverter system (UPS).
    - < 1 second: Can be achieved by a motor-generator set with a flywheel.
    - 1 to 10 minutes: Typical time for a cold-start diesel generator.

3. Earthing Schemes

- Purpose: To protect against electric shock by providing a low-impedance path for fault currents and by creating an equipotential zone.
- Definitions:
    - PE Conductor: Protective Earth conductor. Connects exposed-conductive-parts to the main earthing terminal.
    - PEN Conductor: A conductor combining the functions of Protective Earth and Neutral.

    - Exposed-Conductive-Part: A conductive part of equipment that can be touched and can become live under fault conditions (e.g., metal casing of a motor).
    - Extraneous-Conductive-Part: A conductive part not forming part of the electrical installation, liable to introduce a potential (e.g., metal water pipes, building's steel frame).
- Main Schemes:
    - TT (Terre-Terre): Source neutral is earthed. Installation's exposed parts are earthed to a separate, local earth electrode. Requires RCDs for protection.
    - TN (Terre-Neutre): Source neutral is earthed. Installation's exposed parts are connected directly to the source earth via the protective conductor.
        - TN-C (Combined): Neutral and PE functions are combined in a single PEN conductor. Prohibited for conductors < 10 mm^2 Cu / 16 mm^2 Al, for flexible conductors, and in high-fire-risk premises.
        - TN-S (Separated): Separate PE and N conductors are run throughout the installation.
        - TN-C-S: A TN-C supply is used, but the PE and N are separated at the origin of the installation. The TN-C scheme must not be used downstream of the TN-S part.
    - IT (Isolé-Terre): Source is isolated from earth (or earthed through a high impedance). Exposed parts are earthed to a local electrode. A first fault does not cause disconnection but must be detected by an Insulation Monitoring Device (IMD) and located. A second fault creates a short-circuit that must be cleared by overcurrent devices. Offers the highest supply continuity.

4. Distribution Boards (DBs)

- Technology:
    - Fixed Functional Units: Components are fixed. Maintenance or modification requires shutdown of the entire board.
    - Isolating/Disconnecting Units: Functional units are mounted on removable panels with upstream isolation.
    - Withdrawable Chassis-Mounted Units: Drawer-type units that can be completely withdrawn for servicing, offering the highest level of service continuity.
- Forms of Separation (IEC 439-1): Defines the degree of internal compartmentalization.
    - Form 1: No separation.
    - Form 2: Busbars separated from functional units.

    - Form 3: Form 2 + functional units separated from each other.
    - Form 4: Form 3 + outgoing terminals separated from each other. Higher forms offer greater safety during maintenance.

5. Distributors (Conductors and Cables)

- Conductor Identification (IEC 446):
    - Protective (PE/PEN): Green-and-yellow striped marking exclusively.
    - Neutral (N): Light-blue colour.
    - Phase: Any other colour except green, yellow, or light-blue.
- CENELEC Cable Designation Code (e.g., H07RN-F 3G1,5):
    - H: Harmonized cable.
    - 07: 450/750 V rated voltage.
    - R: Natural rubber insulation.
    - N: Neoprene sheath.
    - F: Flexible core.
    - 3: Number of conductors.
    - G: Includes a green/yellow conductor.
    - 1,5: Cross-sectional area in mm².

6. External Influences & IP Code (IEC 529)

- Codification: Designates environmental conditions with a two-letter, one-number code (e.g., `AD` for water, `AE` for foreign bodies).
- IP Code (e.g., IP54):
    - First Numeral (Solids): Protection against solid objects (0=no protection, 6=dust-tight).
    - Second Numeral (Liquids): Protection against water ingress (0=no protection, 8=continuous submersion).
    - Additional/Supplementary Letters: Provide extra information (e.g., `C`=tool access protection, `H`=high-voltage apparatus).

Visual Elements Analysis

Figure F6: Use of a LV/LV transformer to provide a 3-phase 3-wire TN system from a 3-phase 3-wire IT network.

- Description: A schematic showing a main IT power network and a Delta/Star LV/LV transformer.
- Technical Details: The primary of the transformer is connected to the IT system. The secondary is Star-connected, and its neutral point is earthed, creating a new, galvanically isolated TN system. This allows lighting and socket-outlet circuits

(which require a neutral) to be safely supplied without compromising the high continuity of the main IT system.
- Relationship to Text: Visually explains the "IT to TN transition" concept, a key strategy for mixed-use industrial facilities.

Figure F13 & F14: Neutral currents in a TN-S and TN-C system.

- Description: Comparative diagrams showing current flow in the PE/PEN conductors.
- Technical Details: In a TN-S system (F13), the PE conductor carries no current under normal conditions. In a TN-C system (F14), the PEN conductor carries the unbalanced neutral current (`I3`, `I4`). This stray current in the PEN conductor, which is bonded to equipment frames, can cause electromagnetic interference (EMI).
- Relationship to Text: These diagrams are critical for understanding the EMC advantages of TN-S over TN-C, as explained in section 4.3.

Figure F24: An example of a block of flats in which the main earthing terminal (6) provides the main equipotential connection.

- Description: A diagram showing the main earthing terminal in a building.
- Technical Details: It clearly shows extraneous conductive parts like water pipes (4) and heating pipes (5) being bonded by protective conductors (3) to the main earthing terminal (6). The terminal itself is connected via the earthing conductor (2) to the earth electrode (1). A removable link (7) allows for testing.
- Relationship to Text: This provides a clear, practical example of how the definitions in section 4.1 are applied to achieve equipotential bonding.

Figure F26-F29 & F31-F34: Earthing Scheme Diagrams

- Description: A set of simple, standardized diagrams showing the connection topology for TT, TN-C, TN-S, TN-C-S, and IT systems.
- Technical Details: Each diagram shows the connection of the source neutral (left side) and the installation's exposed parts (right side) to earth. They are the definitive visual reference for distinguishing the schemes.
- Relationship to Text: These are the key diagrams for understanding the definitions and characteristics described in section 4.2.

Figure F57: Representation of different forms of LV functional distribution boards.

- Description: Four diagrams illustrating the different levels of internal separation in a distribution board as per IEC 439-1.
- Technical Details:
    - Form 1: No barriers.

    - Form 2: Busbars are enclosed, separated from functional units.
    - Form 3: Busbars are enclosed, and each functional unit is in its own compartment.
    - Form 4: Same as Form 3, but the terminals for each unit are also in their own separate compartments.
- Relationship to Text: Visually clarifies the "Forms of separation," which is a key specification for the safety and maintainability of distribution boards.

Calculations and Formulas

- Earth Electrode Resistance (Closed Loop): $R \approx 2\rho / L$
- Earth Electrode Resistance (n Rods in parallel): $R \approx \rho / (n * L)$
    - R = Resistance (Ohms)
    - ρ = Soil resistivity (Ohm-metres)
    - L = Length of buried conductor or rod (metres)
    - n = Number of rods

BOQ Implications

- Material Specification: This chapter is central to the BOQ. It dictates:
    - Earthing System: The type of scheme (TT, TN, IT) determines the entire protection philosophy and the types of devices needed (RCDs vs. standard MCBs). This is a primary cost driver. The BOQ must specify quantities of earth rods, copper tape/cable for electrodes, and PE/PEN conductors of specific sizes.
    - Distribution Boards: The required "Form" of separation (1-4) is a key cost factor, with higher forms requiring more material and fabrication labor. The choice between fixed and withdrawable units also has a major impact on cost and must be specified.
    - Cabling: The chapter provides detailed codes (CENELEC) for specifying the exact type of cable required (insulation, sheath, flexibility, voltage rating). This level of detail is necessary for an accurate BOQ.
    - Conduits & Trunking: Selection of wiring systems (e.g., conduits, trays, busways) is a major material component of the BOQ.
- Labor Considerations:
    - Creating supplementary equipotential bonding is labor-intensive and must be factored in.
    - Installation of complex earthing grids or deep-driven earth rods requires specialized labor and equipment.
    - The assembly of high-form-rated distribution boards is more complex than for simpler types.

Critical Notes and Warnings

- TN-C Scheme Restrictions: The guide repeatedly warns that the TN-C scheme is prohibited in several key situations: for small conductors (<10mm² Cu), in high-fire-risk locations, and in installations with significant IT equipment due to EMI problems. This is a critical design constraint.
- PEN Conductor Rules: In a TN-C system, the PEN conductor must *always* be connected to the earth terminal of an appliance *first*, before being looped to the neutral terminal. The protective function takes priority.
- Earthing and Bonding: Efficient bonding to create an equipotential zone is presented as more critical for safety than simply achieving a low earth electrode resistance value. All extraneous metal parts must be bonded.
- Continuity of PE Conductors: Protective conductors must not contain any switching devices or removable links (except for dedicated testing links at the main terminal). They must be connected in parallel, not series, to avoid a single loose connection compromising the safety of all downstream equipment.

Part 7 Analysis: Chapter G - Protection against electric shocks

Overview

This chapter provides a detailed, practical guide to the principles and implementation of protection against electric shock in low-voltage installations. It builds upon the definitions from previous chapters to explain the specific measures required for both direct and indirect contact hazards. The core of the chapter is the implementation of "protection by automatic disconnection of supply (ADS)" for the three standardized earthing schemes: TT, TN, and IT. It details the rules, disconnection times, and calculation methods required for each system, emphasizing the roles of protective devices like fuses, circuit breakers (CBs), and residual current devices (RCDs). The chapter concludes with a thorough discussion on the characteristics and application of RCDs, including methods for achieving discriminative tripping.

Key Standards and Codes Referenced

This chapter is heavily based on IEC standards for electrical safety.

- IEC 479-1: Effects of current on human beings and livestock - Part 1: General aspects. This standard provides the fundamental data on the physiological effects of electric current, which underpins all safety rules.
- IEC 364: Electrical installations of buildings (the core standard).
  - IEC 364-4-41: Protection for safety - Section 41: Protection against electrical shock.
  - IEC 364-4-471: Part of the standard specifically recommending high-sensitivity RCDs.
- IEC 755: General requirements for residual current operated protective devices.
- IEC 1008: Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs).
- IEC 1009: Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBOs).
- IEC 947-2 Appendix B: Covers industrial-type circuit breakers with incorporated residual-current protection (CBRs).

Technical Specifications

1. General Concepts

- Electric Shock Hazard: The danger is a function of the current magnitude and its duration. The curve C1 in Figure G1, from IEC 479-1, shows that a current exceeding 30 mA is potentially lethal if not interrupted very quickly.
- Direct Contact: Contact with a conductor that is live in normal circumstances.
- Indirect Contact: Contact with an exposed-conductive-part (e.g., metal casing) that has become live accidentally due to an insulation failure.
- Protection against Direct Contact:
  - Primary Measure: Physical prevention through insulation of live parts or placing them inside enclosures with a protection rating of at least IP2X or IPXXB.
  - Additional Measure: Use of high-sensitivity RCDs with a rated operating current $I\Delta n \leq 30$ mA. This is mandatory in many countries for socket-outlet circuits and special locations (e.g., bathrooms, worksites).
- Protection against Indirect Contact:
  - Principle: Achieved by "Automatic Disconnection of Supply" (ADS), which requires proper earthing of all exposed conductive parts.
  - Touch Voltage (Uc): The voltage appearing between an exposed-conductive-part and other conductive parts during a fault.
  - Conventional Touch Voltage Limit (UL): The maximum touch voltage that can be tolerated indefinitely. Standard values are 50 V for normal dry

locations and 25 V for special locations (e.g., agricultural, construction sites).

2. Automatic Disconnection for TT-earthed Systems

- Principle: The fault loop impedance is high due to the inclusion of two earth electrode resistances (source and installation). Therefore, fault current is too low to operate overcurrent devices.
- Protection Method: Protection is exclusively provided by RCDs.
- Condition: The RCD sensitivity $I\Delta n$ must satisfy the formula: $I\Delta n \leq UL / RA$, where RA is the resistance of the installation's earth electrode.
- Discrimination: Selective tripping between upstream (time-delayed, "S" type) and downstream (instantaneous) RCDs is used to ensure only the faulty circuit is disconnected.

3. Automatic Disconnection for TN-earthed Systems

- Principle: An insulation fault to earth creates a low-impedance short-circuit loop through the PE or PEN conductor, resulting in a very high fault current.
- Protection Method: Protection is provided by overcurrent devices (fuses or circuit breakers).
- Condition: The fault current Id must be high enough to cause the protective device to operate within the specified time. This is verified by ensuring the calculated fault current is greater than the device's required operating current (Ia): $Id = Uo / Zs > Ia$.
- Maximum Disconnection Times (for UL = 50V):
  - `0.8 s` for 127 V
  - `0.4 s` for 230 V
  - `0.2 s` for 400 V
  - `0.1 s` for >400 V
- Circuit Length Limitation: The length of a circuit is limited by its impedance. If a circuit is too long, the impedance will be too high to guarantee sufficient fault current for the protective device to operate.

4. Automatic Disconnection for IT-earthed Systems

- First Fault: A single fault to earth results in a very small fault current (limited by the system's leakage impedance) which is not dangerous. The system continues to operate, but an Insulation Monitoring Device (IMD) must give an audible and/or visual alarm.
- Second Fault: If a second fault occurs on a different phase before the first is cleared, a high-current phase-to-phase short-circuit is created. This fault must be cleared by overcurrent devices.

- Protection Method:
  - If a common PE conductor is used: Protection is similar to the TN system, but calculations must account for a double-length fault loop (as the fault can be on two different final circuits).
  - If separate earth electrodes are used: The fault loop includes earth resistances, so RCDs are required for protection, similar to the TT system.

5. Residual Current Devices (RCDs)

- Types:
  - RCCB (IEC 1008): Residual Current CB (no overcurrent protection). Must be used with a series fuse or CB (SCPD).
  - RCBO (IEC 1009): Residual Current CB with Overcurrent protection.
  - CBR (IEC 947-2 App. B): Industrial CB with RCD functionality.
- Immunity: RCDs must be immune to nuisance tripping from transient leakage currents (e.g., from switching) and overvoltages (e.g., lightning). Special "S" type (time-delayed) or high-immunity RCDs are used for this.
- Discrimination:
  - Current-based: Using RCDs of different sensitivities (e.g., 300 mA upstream of 30 mA). Limited to two levels.
  - Time-based: Using time-delayed RCDs upstream of instantaneous ones. This allows for multi-level discrimination. A typical scheme might have a 500 mA 'S' type RCD at the origin, feeding a 300 mA instantaneous RCD on a distribution board, which in turn feeds a 30 mA RCD on a final circuit.

Visual Elements Analysis

Figure G1: Curve C1 of IEC 479-1

- Description: A log-log graph showing the pathophysiological effects of AC current on the human body versus the duration of exposure.
- Technical Details: The graph is divided into four zones: (1) Imperceptible, (2) Perceptible but no harmful effect, (3) Reversible effects (muscular contraction), (4) Irreversible effects (ventricular fibrillation). The key curves are:
  - `C1`: Represents a 0% probability of heart fibrillation.
  - `C2`: Represents a 5% probability of heart fibrillation.
  - `C3`: Represents a 50% probability of heart fibrillation.
- Relationship to Text: This graph is the scientific basis for all electrical safety limits, especially the 30 mA threshold for high-sensitivity RCDs and the maximum disconnection times.

Figure G10: Automatic disconnection for a TT-earthed installation.

- Description: A diagram showing a person touching a faulty appliance in a TT system.
- Technical Details: It clearly traces the fault current path: from the phase conductor, through the appliance, through the person (creating touch voltage U_c), to the installation earth electrode R_A, through the mass of earth, to the source earth electrode R_n, and back to the source neutral.
- Relationship to Text: This visually demonstrates why the fault loop impedance in a TT system is high (sum of R_A and R_n plus cable resistances) and why protection must rely on sensitive RCDs.

Figure G12: Automatic disconnection for a TN-earthed installation.

- Description: A diagram showing a fault in a TN-C system.
- Technical Details: The fault current path is shown from the phase conductor, through the appliance, and back to the source via the metallic PEN conductor. The touch voltage U_c is shown to be half the phase-to-neutral voltage ($U_c = 230/2 = 115\ V$) before disconnection.
- Relationship to Text: This illustrates why the fault current in a TN system is very high (a short-circuit) and can be cleared by overcurrent devices.

Figure G17: Fault-current paths for a first (earth) fault on an IT-earthed system.

- Description: A diagram of an IT system with a single phase-to-earth fault.
- Technical Details: It shows that the fault current I_{d1} is limited by the high neutral earthing impedance Z_{ct} (e.g., 1500 Ω). A separate, small capacitive leakage current I_{d2} also flows through the healthy phases. The resulting touch voltage U_c is extremely low (calculated as 0.99 V in the example).
- Relationship to Text: This perfectly illustrates why a first fault in an IT system is not dangerous and does not require disconnection, providing high service continuity.

Figure G39: Typical 3-level installation, showing the protection of distribution circuits in a TT-earthed system.

- Description: A detailed one-line diagram of a complete installation.
- Technical Details: It shows a main circuit breaker with a time-delayed RCD at the origin. This feeds several distribution circuits, including one for a motor protected by an instantaneous RCD, and another feeding a final distribution box. This box contains high-sensitivity (30 mA) RCDs for individual final circuits (lighting, sockets).
- Relationship to Text: This is an excellent practical summary, showing how the principles of multi-level RCD discrimination (both time and current based) are applied in a real-world installation to ensure both safety and selectivity.

Calculations and Formulas

1. RCD Sensitivity for TT Systems

- Formula: $I\Delta n \leq UL / RA$
- Variables:
  - $I\Delta n$ = Rated operating current of the RCD (Amps).
  - UL = Conventional touch voltage limit (50 V or 25 V).
  - RA = Resistance of the installation earth electrode (Ohms).

2. Maximum Circuit Length for TN Systems

- Formula: $Lmax = (0.8 * Uo * Sph) / (\rho * (1+m) * Ia)$
- Variables:
  - $Lmax$ = Maximum circuit length (metres).
  - Uo = Nominal phase-to-neutral voltage (e.g., 230 V).
  - Sph = Cross-sectional area (c.s.a.) of the phase conductor (mm²).
  - ρ = Resistivity of the conductor material (e.g., 22.5×10^{-3} Ω.mm²/m for copper).
  - m = Ratio of c.s.a. of phase to PE conductor ($m = Sph / SPE$).
  - Ia = Operating current of the protective device (Amps).
- Note: The 0.8 factor accounts for a 20% voltage drop during the fault.

BOQ Implications

- Device Specification: The choice of earthing system has a massive impact on the BOQ.
  - TT Systems: The BOQ will be dominated by RCDs of various sensitivities (e.g., 500mA, 300mA, 30mA) for main, distribution, and final circuits.
  - TN Systems: The BOQ will consist primarily of standard MCBs and fuses. The cost shifts from specialized RCDs to potentially larger cable sizes to manage fault loop impedance.
  - IT Systems: The BOQ must include a specialized and often expensive Insulation Monitoring Device (IMD) as a mandatory item.
- Cabling: For TN and IT systems, the maximum circuit length calculations are a critical part of the design process. If calculations show a standard cable size is too long, a larger and more expensive cable must be specified in the BOQ to ensure the fault loop impedance is low enough for protection to operate correctly.
- Labor and Testing: The requirement to measure earth electrode resistance (RA) for TT systems and fault loop impedance (Zs) for TN/IT systems implies specific testing procedures and associated labor costs during commissioning.

Critical Notes and Warnings

- IT System Complexity: The guide repeatedly emphasizes that while IT systems offer the best service continuity, they are complex. Protection relies on detecting the *first* fault with an IMD and ensuring disconnection on the *second* fault. This requires a high level of maintenance and trained personnel to locate and fix the first fault promptly.
- TN-C PEN Conductor: The use of a combined neutral and protective conductor (PEN) is fraught with risks (EMI, fire) and is prohibited in many circumstances. The guide strongly favors TN-S (separate conductors).
- RCDs are not a Panacea: While RCDs are essential for TT systems and provide excellent additional protection in all systems, they are not a substitute for proper earthing and overcurrent protection. They are part of an overall safety strategy.
- Calculation is Key: For TN and IT systems, protection is not guaranteed unless the fault loop impedance is calculated or measured to be low enough. Relying on a "rule of thumb" is not sufficient and can lead to an unsafe installation. The maximum circuit length tables are a critical design tool.

Part 8 Analysis: Chapter H1 - The protection of circuits

Overview

This chapter provides a comprehensive and practical methodology for designing the electrical protection of circuits in a low-voltage installation. It presents the fundamental rules and detailed procedures for selecting the appropriate cross-sectional area (c.s.a.) of cables and the ratings of their associated protective devices (circuit breakers or fuses). The chapter covers methods for both unburied and buried circuits, accounting for numerous derating factors like installation method, grouping, and ambient temperature. It also details the calculation of voltage drop and short-circuit currents (both maximum and minimum levels) at any point in an installation. Finally, it provides specific guidance on the dimensioning and protection of protective earthing (PE) and neutral conductors, which are critical for overall system safety and reliability.

Key Standards and Codes Referenced

- IEC 724 (1984): Guide to the short-circuit temperature limits of electrical cables with a rated voltage not exceeding 0.6/1.0 kV (referenced for adiabatic method).

- IEC 364-5-52: Electrical installations of buildings - Part 5: Selection and erection of electrical equipment - Chapter 52: Wiring systems. This is the core standard for the tables and methods presented.
- UTE C15-105: French guide from which many of the practical tables are derived.

Technical Specifications

1. General Principles of Overcurrent Protection

- Fundamental Conditions: A protective device (circuit breaker or fuse) is correctly chosen if it satisfies two conditions:
    i. Overload Protection: $I_B \le I_n \le I_Z$
        - I_B: The maximum load current of the circuit.
        - I_n: The nominal current of the protective device (or its setting I_r).
        - I_Z: The maximum permissible continuous current for the cable.
    ii. Short-Circuit Protection: $I^2 \le 1.45 * I_Z$
        - I^2: The "conventional" tripping current of the device (a standardized value that ensures tripping within 1 or 2 hours).
        - The factor 1.45 is a standard margin to ensure the cable is protected under all overload conditions.
- Short-Circuit Withstand: The protective device's breaking capacity (I_{cu} or I_{scf}) must be greater than the prospective short-circuit current (I_{sc}) at its point of installation.

2. Determining Conductor c.s.a. for Unburied Circuits

- Methodology: A three-step process using a "fictitious current" I'_z to simplify calculations.
    i. Determine Code Letter: Based on the conductor type and installation method (e.g., multicore cables on a perforated tray = Code E).
    ii. Determine Factor K: $K = K1 * K2 * K3$
        - $K1$: Correction for installation method (e.g., cables in thermal insulation).
        - $K2$: Correction for grouping (mutual heating from adjacent cables).
        - $K3$: Correction for ambient temperature different from the reference of 30°C.
    iii. Calculate Fictitious Current: $I'_z = I_Z / K$ (where I_Z is the required current-carrying capacity, typically equal to the protective device rating I_n).
    iv. Find Conductor Size: Use I'_z and the code letter to look up the required conductor c.s.a. in Table H1-17.

3. Determining Conductor c.s.a. for Buried Circuits

- Methodology: Similar to unburied circuits, but with a different set of correction factors.
- Factor K Calculation: $K = K4 * K5 * K6 * K7$
  - $K4$: Correction for installation method (e.g., in earthenware ducts).
  - $K5$: Correction for grouping of buried cables.
  - $K6$: Correction for the nature of the soil (its thermal resistivity).
  - $K7$: Correction for soil temperature different from the reference of 20°C.
- Find Conductor Size: Use $I'z = IZ / K$ and look up the required conductor c.s.a. in Table H1-24.

4. Verification of Short-Circuit Conditions

- Thermal Withstand: The cable must withstand the thermal energy let through by the protective device during a short-circuit. This is verified by the condition: $I^2t \leq k^2S^2$
  - I^2t: The thermal energy let-through value of the protective device (obtained from manufacturer's data).
  - k: A constant that depends on the conductor material and insulation type (e.g., 115 for PVC/copper, 143 for XLPE/copper).
  - S: The cross-sectional area of the conductor in mm².
- Electrodynamic Constraints: For bus-trunking and prefabricated systems, the peak let-through current of the protective device must be less than the rated peak withstand current of the system.

5. Protective Earthing (PE) and Neutral (N) Conductors

- PE Conductor Sizing:
  - Simplified Method: The PE c.s.a. is based on the phase conductor c.s.a. (Sph):
    - If $Sph \leq 16\ mm^2$, then $SPE = Sph$.
    - If $16 < Sph \leq 35\ mm^2$, then $SPE = 16\ mm^2$.
    - If $Sph > 35\ mm^2$, then $SPE = Sph / 2$.
  - Adiabatic Method: Used for TT systems or where a smaller c.s.a. is desired. $SPE = (I * \sqrt{t}) / k$.
- PEN Conductor Sizing: A PEN conductor (combined PE and Neutral) must have a c.s.a. of at least 10 mm² copper or 16 mm² aluminium.
- Neutral Conductor Sizing:
  - The neutral c.s.a. must be equal to the phase c.s.a. for circuits ≤ 16 mm² (Cu) or 25 mm² (Al).
  - It can be smaller for larger circuits only if specific conditions are met (e.g., balanced load, low harmonic content, separate protection).

- Neutral Conductor Protection: The neutral must be protected and switched together with the phases in some cases (e.g., IT systems, or TT/TN systems where $SN < Sph$). Unprotected, unswitched neutrals are common where $SN = Sph$.

Visual Elements Analysis

Figure H1-1: Logigram for the selection of cable size and protective-device rating...

- Description: A flowchart that summarizes the entire design process for a circuit.
- Technical Details: It starts with the load current IB and upstream short-circuit current Isc. It shows the decision path for selecting a protective device (In), which determines the required cable ampacity (IZ). This leads to calculating the c.s.a. based on installation conditions. The process then loops back for verification checks: voltage drop, thermal withstand, and protection of persons (e.g., max length in TN/IT systems).
- Relationship to Text: This logigram is a visual table of contents for the entire chapter, mapping out the logical sequence of calculations.

Figure H1-6: Current levels for determining circuit breaker or fuse characteristics.

- Description: A diagram showing the relationship between the key current levels on a logarithmic scale.
- Technical Details: It clearly defines three zones:
  - Zone a (Normal Operation): $IB \le In \le IZ$.
  - Zone b (Overload): $I2 \le 1.45\ IZ$.
  - Zone c (Short-Circuit): $Isc \le Iscb$.
- Relationship to Text: This visually represents the two fundamental rules of overcurrent protection.

Figure H1-16 & H1-23: Examples for determining K factors.

- Description: These diagrams show sample installations with multiple circuits on a cable tray or buried in the ground.
- Technical Details: They provide concrete examples of how to determine the number of circuits for the grouping factor ($K2$ or $K5$) and how to identify the ambient temperature ($K3$ or $K7$) and installation method ($K1$ or $K4$).
- Relationship to Text: They make the abstract concept of applying correction factors tangible and easy to follow.

Figure H1-35: Impedance diagram.

- Description: A right-angled triangle showing the relationship between Resistance (R), Reactance (X), and Impedance (Z).

- Technical Details: It visually represents the formula $Z = \sqrt{R^2 + X^2}$, which is the foundation of the impedance method for short-circuit calculations.
- Relationship to Text: This diagram is fundamental to understanding section 4 on short-circuit calculations.

Figure H1-56: A poor connection in a series arrangement...

- Description: Shows two ways to connect PE conductors: "correct" (in parallel to a common bar) and "incorrect" (in series or "daisy-chained").
- Technical Details: The diagram warns that in a series connection, a single loose terminal will compromise the earth connection for all downstream equipment.
- Relationship to Text: This is a critical visual aid for the PE conductor connection rules in section 6.1.

Calculations and Formulas

- Fictitious Current $I'z$: $I'z = IZ / K$ where $K = K1 * K2 * K3$ (unburied) or $K = K4 * K5 * K6 * K7$ (buried).
- Voltage Drop (3-phase): $\Delta U = \sqrt{3} * IB * (R \cos \phi + X \sin \phi) * L$
- Short-Circuit Current (Impedance Method): $Isc = U20 / \sqrt{(\Sigma R)^2 + (\Sigma X)^2}$
- Cable Thermal Withstand: $t = (k^2 * S^2) / I^2$ or check $I^2t\_device \leq k^2S^2$
- PE Conductor Sizing (Adiabatic): $SPE = (I * \sqrt{t}) / k$
- Maximum Circuit Length (TN, Phase-Neutral Fault): $Lmax = (0.8 * Uo * Sph) / (\rho * (1 + m) * Ia)$
- Maximum Circuit Length (IT, Phase-Phase Fault): $Lmax = (0.8 * U * Sph) / (2 * \rho * (1 + m) * Ia)$

Data Tables Analysis

This chapter is extremely reliant on its data tables. Key tables include:

- H1-13 to H1-15 & H1-19 to H1-22: Provide the K factor values for all installation conditions (grouping, temperature, installation method, soil type).
- H1-17 & H1-24: The main sizing tables that link the calculated fictitious current $I'z$ and code letter to a required conductor c.s.a. for unburied and buried circuits, respectively.
- H1-29: A practical lookup table for quickly determining voltage drop in V/A/km for various cable sizes and load types.
- H1-33, H1-36, H1-37: Provide the impedance values (R and X) for upstream networks and transformers, needed for accurate short-circuit calculations.
- H1-40: A simplified table for estimating downstream short-circuit current based on the upstream value and the intervening circuit length and c.s.a.

- H1-49 to H1-52: A set of very practical tables giving the maximum circuit length for circuits protected by different types of circuit breakers (B, C, D type).
- H1-60 & H1-61: Define the sizing rules for PE conductors and provide the k factor values needed for thermal withstand calculations.
- H1-65: A crucial summary table showing the required protection and switching schemes for neutral conductors in all earthing systems (TT, TN-C, TN-S, IT).

BOQ Implications

- Cable Schedule Generation: This chapter provides the complete, detailed methodology for generating a cable schedule. For every circuit, the designer can determine the conductor material (Cu/Al), c.s.a. (mm^2), and insulation type (PVC/XLPE). This is a primary output for the BOQ.
- Protective Device Schedule: The methodology directly informs the selection of every fuse and circuit breaker, including its type (e.g., C-type MCB), rated current (In), and required breaking capacity (Icu). This is another primary output for the BOQ.
- Cost Optimization: The use of correction factors allows for precise, non-oversized cable selection, saving material costs. Conversely, it highlights where derating is necessary (e.g., for grouped cables in a hot environment), ensuring that the specified cable is technically adequate and avoiding future failures, which is also a cost consideration.
- Material Diversity: The tables detail a wide variety of materials (copper vs. aluminium, PVC vs. XLPE insulation), all of which have different costs that will be reflected in the final BOQ.

Critical Notes and Warnings

- Two Fundamental Rules: The conditions $IB \le In \le IZ$ and $I^2 \le 1.45\ IZ$ are the absolute foundation of overcurrent protection design and must always be satisfied.
- Minimum Isc is Critical: Protection must be verified against the *minimum* possible short-circuit current (which occurs at the end of the longest circuit run), not just the maximum. If the minimum fault current is too low, the protective device may not trip, creating a dangerous situation.
- Conductor Protection is Paramount: The primary role of a protective device is to protect the *cable* from damage. The selection of the device rating is therefore intrinsically linked to the cable's characteristics (IZ and thermal withstand k^2S^2).
- PE and Neutral Rules: The rules for sizing and protecting PE and Neutral conductors are not optional; they are critical for safety against electric shock and

for the correct functioning of the system, especially regarding harmonics and fault clearance. A PEN conductor, in particular, must never be switched.

Part 9 Analysis: Chapter H2 - The switchgear

Overview

This chapter provides a comprehensive technical overview of low-voltage (LV) switchgear, detailing the functions, standards, and characteristics of various components like disconnectors, switches, fuses, and circuit breakers. It explains the fundamental roles of switchgear: electrical protection, safe isolation, and control. The chapter classifies different devices based on their capabilities, such as their ability to make or break current under normal load or fault conditions. A significant focus is placed on circuit breakers, explaining their operational principles, tripping characteristics (thermal-magnetic, electronic), and key performance ratings like breaking capacity (Icu, Ics) and making capacity (Icm). The chapter concludes with a detailed discussion on the crucial techniques of discrimination (selectivity) and cascading, which are essential for designing safe, reliable, and cost-effective electrical distribution systems.

Key Standards and Codes Referenced

- IEC 947: The primary international standard for Low-voltage switchgear and controlgear.
    - IEC 947-1: General rules.
    - IEC 947-2: Circuit-breakers.
    - IEC 947-3: Switches, disconnectors, switch-disconnectors and fuse-combination units.
- IEC 898: Circuit-breakers for overcurrent protection for household and similar installations (domestic-type).
- IEC 269-1, 269-2-1, 269-3: Standards for LV fuses (industrial and domestic).
- IEC 617-7: Graphical symbols for diagrams.

Technical Specifications

1. Basic Functions of LV Switchgear

- Electrical Protection: To limit the destructive effects of overcurrents (overloads and short-circuits) and insulation failures. This is the primary function of circuit breakers and fuses.

- Isolation (Disconnection): To separate a circuit or apparatus from all energized parts to allow for safe maintenance. A key requirement is a visible break or a fail-proof position indicator. The device must be lockable in the open position.
- Control: To modify a load-carrying system, including functional (routine) switching, emergency switching/stopping, and switching for mechanical maintenance.

2. Elementary Switching Devices

- Disconnector (Isolator): A manually-operated switch for providing safe isolation. It is not designed to make or break current and must only be operated on a de-energized circuit. It has a rated short-time withstand current.
- Load-Breaking Switch: A control switch used to make and break normal load currents. It does not provide overcurrent protection. Its performance is defined by its utilization category (e.g., AC-23 for motor loads).
- Contactor: A solenoid-operated switch designed for a high number of close/open cycles, typically used for motor control and controlled remotely. It must be paired with a separate short-circuit protective device.
- Fuses:
  - Type gG/gI: General-purpose fuses for overload and short-circuit protection.
  - Type aM: Fuses for motor circuits. They provide short-circuit protection only and must be associated with an overload relay.
  - Current Limitation: Modern cartridge fuses are current-limiting; they melt and interrupt the current before the first major peak of a high short-circuit current is reached, significantly reducing thermal (I^2t) and electrodynamic stresses.

3. Circuit Breakers (CBs)

- Functions: Circuit breakers are multi-function devices that can provide control, isolation, and protection against both overloads and short-circuits.
- Fundamental Characteristics:
  - Rated Current (In): The maximum current the CB can carry continuously at a reference ambient temperature (typically 40°C for industrial, 30°C for domestic). The CB must be derated for higher temperatures.
  - Tripping Units:
    - Thermal-Magnetic: A bi-metal strip provides a time-delayed trip for overloads (`Ir` or `Irth`), and an electromagnet provides an instantaneous trip for short-circuits (`Im`).

        - Electronic: Uses current transformers and electronics to provide more precise and adjustable protection curves, including long-delay (overload), short-delay, and instantaneous trips.
    - Rated Short-Circuit Breaking Capacity (Icu): The maximum prospective fault current a CB can break without being damaged.
    - Rated Service Short-Circuit Breaking Capacity (Ics): A percentage of Icu (e.g., 25%, 50%, 75%, 100%) that a CB can break and remain immediately available for re-use. This is a more realistic measure of performance. In Europe, `Ics = 100% Icu` is common practice.
- Categories (IEC 947-2):
    - Category A: CBs without a deliberate short-time delay for tripping (e.g., most moulded-case circuit breakers).
    - Category B: CBs with a short-time delay capability, allowing them to remain closed during a downstream fault to achieve time-based discrimination. They have a rated short-time withstand current (Icw).

4. Coordination Between Protective Devices

- Discrimination (Selectivity):
    - Objective: To ensure that in the event of a fault, only the protective device immediately upstream of the fault operates, leaving the rest of the installation energized.
    - Methods:
        a. Current-based: Achieved by setting the trip current levels of series devices at stepped intervals. Simple but often provides only partial discrimination.
        b. Time-based: The upstream CB (Category B) is deliberately delayed, giving the downstream CB time to clear the fault first. Provides absolute discrimination up to the `Icw` rating of the upstream CB.
        c. Energy-based (Logic): A patented system (e.g., by Merlin Gerin) where CBs communicate via pilot wires. The upstream CB is set to trip instantaneously unless it receives a signal from the downstream CB indicating the fault is in the downstream zone, at which point it adds a delay.
- Cascading (Back-up Protection):
    - Objective: To use a current-limiting CB upstream to protect a downstream CB that has a lower breaking capacity (`Icu`) than the prospective short-circuit current at its location.
    - Principle: The upstream current-limiting CB operates so fast (< 0.01s) that it cuts off the fault current before it reaches its peak. The energy let

through is low enough that the downstream CB, despite its lower rating, can safely withstand it.
    - Benefit: Allows for the use of smaller, less expensive downstream CBs, significantly reducing the cost and size of switchboards.
    - Verification: Cascading combinations are not theoretical; they must be verified by laboratory tests performed by the manufacturer, who provides tables of approved combinations.

Visual Elements Analysis

Figure H2-21: Principal parts of a circuit breaker.

- Description: A schematic cross-section of a circuit breaker.
- Technical Details: It clearly identifies the four main functional parts:
    i. The power circuit terminals.
    ii. The contacts and arc-dividing chamber (where the arc is extinguished).
    iii. The trip mechanism and protective devices (thermal-magnetic or electronic).
    iv. The latching mechanism and operating handle.
- Relationship to Text: This provides a fundamental understanding of the physical components that enable a circuit breaker's functions.

Figure H2-15: Current limitation by a fuse.

- Description: A current-vs-time graph showing how a current-limiting fuse operates.
- Technical Details: The graph shows the "prospective fault-current peak" that *would* have occurred. The fuse, however, melts at `Tf` (pre-arcing time) and the arc is extinguished at `Ttc` (total clearance time). The actual "limited current peak" is much lower than the prospective peak.
- Relationship to Text: This is a key diagram for understanding the current-limiting principle, which is the basis for both modern fuses and current-limiting circuit breakers.

Figure H2-35: Prospective and actual currents.

- Description: A simplified version of the current-limitation graph, clearly contrasting the high prospective fault-current waveform with the much smaller, "cut-off" actual current waveform let through by a current-limiting CB.
- Relationship to Text: This visually summarizes the benefit of current limitation, which is the foundation for the cascading technique.

Figure H2-46: Absolute and partial discrimination.

- Description: A simple one-line diagram and corresponding graph showing two CBs (A and B) in series.
- Technical Details:
  - Absolute Discrimination: If the fault current at B (I_{scB}) is less than the magnetic trip setting of A (I_{rmA}), only B will trip.
  - Partial Discrimination: If I_{scB} is greater than I_{rmA}, both A and B will trip.
- Relationship to Text: This provides the fundamental definition of discrimination, which is the goal of all coordination studies.

Figure H2-47 to H2-52 & Table H2-49: Methods for discriminative tripping.

- Description: A series of graphs and a summary table illustrating the different methods of achieving discrimination.
- Technical Details: The graphs show the time-current curves for CBs A and B.
  - H2-47/48 (Current-based): Shows how stepping the trip settings $I_{rmA} > I_{rmB}$ can provide absolute or partial discrimination.
  - H2-51/52 (Time-based): Shows that by adding a time delay (Δt) to the trip curve of the upstream breaker A, it will wait for the downstream breaker B to clear the fault, ensuring absolute discrimination.
- Relationship to Text: These figures provide the visual explanation for the principles of current-based and time-based discrimination, which are critical design techniques.

Calculations and Formulas

- Rated Making Capacity (Icm): $I_{cm} = k * I_{cu}$. The factor k depends on the power factor of the fault circuit (from Table H2-34). For $I_{cu} > 50$ kA, $k = 2.2$.
- Overload Trip Setting (Ir or Irth): A value adjustable between 0.4 to 1.0 times the CB's rated current I_n. $I_r > I_B$ (load current).

BOQ Implications

- Device Specification: This chapter is critical for the detailed specification of all protective devices in the BOQ. A specification must include:
  - Type (e.g., MCB, MCCB, fuse).
  - Rated Current I_n (Amps).
  - Rated Breaking Capacity I_{cu} (kA).
  - Rated Service Breaking Capacity I_{cs} (% of Icu).
  - Tripping Curve Type (e.g., B, C, D for domestic; adjustable electronic for industrial).
- Cost Optimization through Cascading: The principle of cascading is a major cost-saving tool. By specifying a current-limiting CB at the head of a distribution

board, the designer can specify cheaper, lower-`Icu` rated CBs for all downstream circuits in the BOQ, leading to substantial savings.

- Cost vs. Performance with Discrimination: Achieving absolute discrimination often requires more sophisticated (and expensive) Category B circuit breakers with time-delay features. The BOQ must reflect the trade-off between the cost of the switchgear and the required level of supply continuity for the installation.

Critical Notes and Warnings

- Disconnector vs. Switch: A disconnector/isolator cannot break load current. Attempting to do so is extremely dangerous. A load-breaking switch is required for this function.
- Fuse Types: `aM` fuses are for short-circuit protection only and must be paired with a separate overload relay. Using an `aM` fuse alone provides no overload protection for a motor.
- Cascading is Not Guesswork: The use of cascading is only permissible if the specific combination of upstream and downstream circuit breakers has been tested and certified by the manufacturer. A designer cannot simply assume a combination will work. Manufacturer's tables are essential.
- Discrimination is a System Property: Achieving selectivity requires a coordinated study of all protective devices in series. Simply selecting individual devices without considering their interaction will likely result in a lack of discrimination and nuisance tripping of upstream breakers.

Part 10 Analysis: Chapters J & L - Particular Supply Sources/Loads & Special Locations

Overview

This final part of the analysis covers two distinct but related topics. Chapter J focuses on the specific protection and operational requirements for non-standard power sources, such as alternators (generators) and Uninterruptible Power Supply (UPS) units, and for particular types of loads like LV/LV transformers, lighting circuits, and asynchronous motors. It addresses the unique challenges these systems present, such as low fault currents from generators and high in-rush currents from transformers and lamps. Chapter L applies many of the general principles from the guide to the specific context of domestic premises and other special locations (e.g., bathrooms, showers). It outlines the mandatory safety rules, circuit division practices, and equipment specifications required for these high-risk or commonly regulated environments.

Key Standards and Codes Referenced

- IEC 947-2, 947-4-1, 947-6-2: Standards for circuit breakers, contactors, and motor-starters.
- IEC 146-4: Standard for semiconductor converters, relevant to UPS systems.
- IEC 60742: Standard for safety isolating transformers.
- IEC 364-7-701: Specific requirements for electrical installations in bathrooms and showers.
- IEC 364-7-702: Specific requirements for swimming pools and fountains.

Technical Specifications

Chapter J: Particular Supply Sources and Loads

1. Protection of Circuits Supplied by an Alternator (Generator)

- Problem: The short-circuit current from an alternator is significantly lower (5-6 times less) than from a transformer of the same kVA rating. This creates a challenge for overcurrent protection, as the fault current may not be high enough to trip a standard circuit breaker set for transformer-fed fault levels.
- Short-Circuit Current Behavior:
    - Sub-transient period (10-20 ms): Initial fault current is `3 to 5 * In`.
    - Transient period (80-280 ms): Current decays.
    - Steady-state: Current stabilizes at `2.5 to 4 * In` with an Automatic Voltage Regulator (AVR), but can be as low as `0.3 * In` with manual control.
- Protection Solution:
    - Low-setting Tripping Units: Use circuit breakers with low and adjustable magnetic trip settings (e.g., `1.5 to 10 * Ir` for an STR type, or curve B `3-5 * In` for an MCB).
    - RCDs: Where fault current is insufficient to trip overcurrent devices for indirect contact protection (in IT/TN systems), RCDs must be used.

2. Inverters and UPS (Uninterruptible Power Supply) Units

- Types of UPS:
    - Off-line: The load is normally supplied directly from the mains. The UPS (inverter + battery) switches on only when the mains fails. Transfer time is < 10 ms.
    - On-line: The load is continuously supplied through the rectifier and inverter, providing a perfectly clean, stable, and truly uninterruptible supply.

- Protection Schemes:
  - TT/TT Scheme: The inverter output is temporarily earthed via a contactor when the mains supply (which provides the primary earth reference) is lost.
  - TN/TN Scheme: Protection relies on overcurrent devices. The very limited short-circuit current from the inverter must be sufficient to trip the downstream CBs.
  - IT/IT Scheme: Requires two separate Insulation Monitoring Devices (IMDs), one for the mains side and one for the inverter side, with an automatic changeover between them.

3. Protection of LV/LV Transformers

- In-rush Current: Energizing a transformer causes a high transient current peak, which can be 10 to 25 times the nominal full-load current.
- Protection: The primary-side protective device must be chosen to withstand this in-rush current without nuisance tripping.
  - Circuit Breakers: Use time-delayed types (e.g., Compact NS STR) or types with high magnetic trip settings (e.g., Type D, `10-14 * In`).
  - Fuses: Type `aM` fuses are often used, but they must be significantly oversized (e.g., 4 times `In`) and only provide short-circuit protection.

4. Lighting Circuits

- Disturbances:
  - Fluorescent Lamps: High current peak on startup to charge capacitors. Multiple lamps on one circuit can cause nuisance tripping. Limit of ~8 tubes per contactor is suggested.
  - Incandescent Lamps: Very high in-rush current (up to 15 times `In`) due to the low resistance of the cold filament.
- Protection: Circuit breaker ratings are chosen based on the total power of the lamps and their type. Tables J4-2, J4-3, and J4-4 provide direct selection of CB ratings for incandescent, discharge, and fluorescent lamps.

5. Asynchronous Motors

- Protection Functions: A complete motor circuit requires:
  - Short-Circuit Protection: Provided by the instantaneous magnetic trip of a circuit breaker or by `aM` or `gM` type fuses.
  - Overload Protection: Provided by a thermal relay (often integrated into a contactor, forming a "discontactor").

    - Isolation: Provided by the circuit breaker or a separate switch-disconnector.
- Coordination: The tripping curve of the CB/fuse must be above the motor's starting current curve, while the thermal relay's curve must be below it. This ensures the motor can start without tripping, but is protected from sustained overloads.
- Preventive Protection:
    - Thermal Sensors (Thermistors): Embedded in motor windings to detect overheating directly.
    - Insulation Monitoring: For stationary motors, an IMD can monitor the insulation resistance before start-up to prevent a fault on energization.

Chapter L: Domestic and Similar Premises and Special Locations

1. Domestic Premises

- Circuit Subdivision: National standards recommend a minimum number of circuits for comfort and fault isolation.
    - At least one circuit for lighting (max 8 points).
    - At least one circuit for socket-outlets (max 8 sockets).
    - Dedicated circuits for major appliances (cooker, water heater, washing machine).
- Protective Conductors: A PE conductor is required in all circuits.
- Socket-Outlets: Must be of a shuttered type for safety.
- Cabling and Protection: Table L1-11 provides standard c.s.a. and protective device ratings for common domestic circuits (e.g., Lighting: 1.5 mm² Cu, 16A CB; Sockets: 2.5 mm² Cu, 25A CB).

2. Bathrooms and Showers (IEC 364-7-701)

- Principle: Protection is based on defining zones with increasing restrictions.
- Zones:
    - Zone 0: The interior of the bath-tub or shower basin. Only SELV at 12 V is permitted, with the source outside Zone 2.
    - Zone 1: The area directly above the bath/shower to a height of 2.25 m. Only SELV at 12 V or specific fixed water heaters are permitted.
    - Zone 2: The area extending 0.60 m horizontally from Zone 1 and to a height of 2.25 m. SELV or Class II equipment is permitted. A single socket-outlet fed by a separating transformer is allowed.
    - Zone 3: The area extending 2.40 m horizontally from Zone 2. Standard wiring is permitted, but socket-outlets must be protected by a 30 mA RCD, a separating transformer, or be SELV.

- Equipotential Bonding: A supplementary equipotential bonding conductor must connect the PE conductors of all circuits to all extraneous conductive parts (metal pipes, drains, etc.) within the zones.

3. Recommendations for Other Special Installations

- Data Processing: TN-S scheme is recommended.
- Marinas, Fairs, Balneotherapy: Protection by 30 mA RCDs is mandatory.
- Motor Vehicles: Protection by RCDs or electrical separation.

Visual Elements Analysis

Figure J1-2: Establishment of short-circuit current for a three-phase short circuit at the terminals of an alternator.

- Description: A graph of the alternator fault current (RMS) vs. time.
- Technical Details: It clearly shows the three distinct periods: a high initial "sub-transient" current, a decaying "transient" current, and a lower "steady-state" current. It also contrasts the much higher steady-state current achieved with an AVR compared to manual excitation control.
- Relationship to Text: This is the key diagram for understanding why protecting alternator-fed circuits is challenging and requires special consideration of the time-varying fault current.

Figure J2-2 & J2-3: Off-line and On-line UPS systems.

- Description: Simplified block diagrams of the two main UPS topologies.
- Technical Details:
  - Off-line (J2-2): Shows the load normally fed from the mains via a filter, with the rectifier/battery/inverter path only engaged by a changeover switch upon mains failure.
  - On-line (J2-3): Shows the load always being fed through the rectifier/inverter path, completely isolating it from mains disturbances.
- Relationship to Text: These diagrams are essential for understanding the fundamental operational differences between the two UPS types.

Figure J5-3: Tripping characteristics of a circuit breaker (type MA) and thermal-relay / contactor combination.

- Description: A time-current graph showing the coordination between a motor's starting curve, a thermal overload relay's trip curve, and a magnetic-only circuit breaker's trip curve.

- Technical Details: The graph perfectly illustrates the protection "window". The CB provides instantaneous protection for high short-circuit currents. The thermal relay provides slow, inverse-time protection for overloads. The space between these two curves allows the motor's high starting current to flow for the required time without causing a trip.
- Relationship to Text: This is the definitive visual explanation of motor protection coordination.

Figure L2-1: Zones 0, 1, 2, 3 in proximity to a bath-tub.

- Description: A plan view and vertical cross-section of a bathroom, clearly delineating the four safety zones around a bathtub.
- Technical Details: The diagram provides the exact dimensions for each zone: Zone 1 is the footprint of the tub up to 2.25m high; Zone 2 extends 0.60m horizontally from Zone 1; Zone 3 extends 2.40m horizontally from Zone 2.
- Relationship to Text: This is the key reference diagram for applying the strict safety rules for bathrooms as mandated by IEC 364-7-701.

Figure L2-8: Supplementary equipotential bonding in a bathroom.

- Description: A diagram showing the metallic parts in a bathroom all connected by PE conductors.
- Technical Details: It shows the metal bath, radiator, water pipes, gas pipes, and even the metal door frame all being bonded together.
- Relationship to Text: This visually demonstrates the practical application of the mandatory supplementary equipotential bonding rule for bathrooms.

Calculations and Formulas

- Alternator Short-Circuit Current: `Isc = Ig * (100 / x'd)`
  - `Ig`: Rated full-load current of the alternator.
  - `x'd`: Transient reactance of the alternator in %.
- Primary Current of an LV/LV Transformer (In-rush calculation):
  - `Isc2 = (Pn * 100) / (Us * Usc%)` (Secondary short-circuit current)
  - `Isc1 = Isc2 * (Us / Up)` (Primary short-circuit current)
- Maximum Secondary Circuit Resistance (ELV Lighting):
  - `Rc = U2/Im2 - U2/Isc2`
  - This formula calculates the maximum permissible resistance of the ELV circuit cabling to ensure the primary-side CB will trip on a secondary-side fault.

BOQ Implications

- Specialized Equipment: The need for specific equipment must be detailed in the BOQ.
    - Generators/UPS: Specified by kVA rating, autonomy time (for UPS batteries), and required accessories (e.g., changeover panels, external fuel tanks).
    - Motor Starters: The BOQ must list the combination of circuit breaker, contactor, and thermal relay for each motor circuit.
    - LV/LV Transformers: Specified by kVA rating, primary/secondary voltage, and winding configuration (e.g., Delta/Star).
- Domestic Installations: The BOQ for a domestic project is directly informed by Table L1-11, which provides a "shopping list" of required conductor sizes and protective device ratings for standard circuits.
- Special Locations: For bathrooms, the BOQ must include supplementary equipotential bonding conductors and specialized equipment like SELV transformers or separating transformers for sockets, which adds cost compared to a standard room.

Critical Notes and Warnings

- Alternator Protection is Difficult: The low and decaying fault current from a generator is a major challenge. Standard protection schemes designed for transformer supplies will not work without careful re-evaluation and the use of specialized low-setting or voltage-controlled protective devices.
- UPS Protection is Unique: The short-circuit current from a UPS is very limited. Standard overcurrent discrimination is often not possible. Protection relies on manufacturer-tested combinations and specific rules for different earthing systems.
- In-rush Currents: The high transient currents from transformers and lamps are a primary cause of nuisance tripping. Protective devices must be selected specifically to withstand these phenomena.
- Bathroom Safety is Non-Negotiable: The rules for zones and equipotential bonding in bathrooms are among the strictest in electrical installation practice and are absolutely mandatory for safety. There is no room for interpretation or deviation.