14.1 Types of Ground

In EMC, a distinction is made between these types of ground:

- **Safety ground.** Safety ground means the ground of an electrically conductive chassis or electric circuit, which protects humans against shock hazards and the electric circuit from ESD pulses.
- **Functional ground.** A ground for other purposes than electrical safety, e.g., for mitigating EMC and EMI issues.
- **Chassis ground.** A chassis ground refers to the connection that establishes an electrical link to a metallic enclosure. For example, cable shields are usually connected to chassis ground.
- **Signal ground.** Signal ground means the return current path of a signal current back to its source.

More ground types and their symbols are mentioned in Sect. 14.2.

14.2 Ground Symbols

As mentioned above in Sect. 14.3, a distinction is made between different ground types. The standard IEC 60417 [1] defines the symbols for safety, functional, and chassis ground. These ground symbols are presented in Fig. 14.1.
Fig. 14.1 Earth and ground symbols according to IEC 60417. (a) No. 5017. Earth, ground. To identify an earth (ground) terminal in cases where neither the symbol 5018 nor 5019 is explicitly required [1]. (b) No. 5018. Functional earthing/grounding (US). To identify a functional earthing (grounding) terminal, for example, of a specially designed earthing (grounding) system to avoid causing malfunction of the equipment [1]. (c) No. 5019. Protective earth/ground (US). To identify any terminal which is intended for connection to an external conductor for protection against electric shock in case of a fault or the terminal of a protective earth (ground) electrode [1]. (d) No. 5020. Frame or chassis. To identify the frame or chassis terminal [1]. (e) No. 5021. Equipotentiality. To identify the terminals which, when connected together, bring the various parts of an equipment or of a system to the same potential, not necessarily being the earth (ground) potential, e.g., for local bonding [1]. (f) No. 6032. Do not connect to protective earth/ground (US). To indicate that conductive parts shall not be connected to protective earth (ground), e.g., on electrical equipment with conductive parts inside an insulating enclosure [1]. (g) No. 6092. Class II equipment with functional earthing/grounding (US). To identify class II equipment (appliances with double insulation and no protective conductor) with functional earthing (grounding) [1]

14.3 EMC Grounding Philosophy

A ground is often thought to be equipotential, meaning there is no voltage difference along a ground conductor or a ground plane. However, this is not true and there is a voltage drop across the $Z_g$ [Ω] when current flows along a ground conductor or a ground plane. This voltage drop could lead to common impedance coupling (see Sect. 12.1.1). The ground impedance can be written as (Fig. 14.2):

$$Z_g = R_g + j \omega L_g$$  \hspace{1cm} (14.1)
**14.4 Return Current Path on PCB Ground Planes**

Current does always take the path of the least impedance $Z \ [\Omega]$. Therefore, in case of a PCB signal trace above a solid ground plane (see Fig. 14.3), we can state the following:

- **At low frequencies** (around $f < 100 \text{kHz}$), the signal return current path in the *ground plane* flows more or less straight from via 2 back to via 1. This is because at low frequencies, the resistance $R_g \ [\Omega]$ dominates the impedance $Z_g = R_g + j \omega L_g$ of the *return current path*, and the lowest resistance from via 2 to via 1 is a direct line.
Fig. 14.3  Signal return currents in a solid PCB ground plane. (a) At low frequencies (around \( f < 100 \text{ kHz} \)). (b) At high frequencies (around \( f > 1 \text{ MHz} \)).

- **At high frequencies** (around \( f > 1 \text{ MHz} \)), the signal return current in the ground plane flows directly below the respective PCB trace. This is because the inductive reactance \( X = 2\pi f L_g \) starts to dominate the impedance \( Z_g = R_g + j\omega L_g \) of the return current path at high frequencies and the inductive reactance is lowest when the return current flows directly underneath the forward current PCB trace.

The points above lead to the conclusion that a solid ground plane should not be split up underneath a high-speed data line because in such a case, the signal return current would have to flow around that gap in the ground plane. This would lead to increased differential current loop area and therefore unintended emissions (see Sect. 9.9.1). Generally speaking, a solid ground plane without any gaps does often lead to the lowest unintended emissions.

Bear in mind that a digital signal—like a clock or data signal—consists of many harmonics where the amplitudes of the high-frequency harmonics primarily depend on the signal’s rise- and fall-time (see Sect. 5.2). Given this, the return current path of a digital signal on a PCB is not identical for all its harmonics: the higher the frequency, the closer does the harmonic signal follow the line underneath the forward current path of the digital signal.

### 14.5 Grounding of Systems

A system in the context of *grounding of systems* means, e.g., a PCBA with multiple circuits placed on the PCB or an electric device which consists of several PCBAs and/or electronic modules and units. We call these circuits, PCBAs, modules, and units in the following just circuits. The grounds of these circuits can be connected in many different ways. Basically, there are three variants [2]:

- **Single-point ground systems.** See Sect. 14.5.1.
- **Multipoint ground systems.** See Sect. 14.5.2.
- **Hybrid ground systems.** See Sect. 14.5.3.
Fig. 14.4 Single-point ground systems. Ideally: $Z_{g1} = Z_{g2} = Z_{g3} = 0\,\Omega$, $C_{stray} = 0\,F$. (a) Daisy-chain ground system. (b) Star ground system

### 14.5.1 Single-Point Ground Systems

Single-point ground systems are only useful for low frequencies ($<100\,\text{kHz}$). It is nearly impossible to implement a single-point ground system at high frequencies ($<1\,\text{MHz}$) because high-frequency currents start to flow through the stray capacitances $C_{stray} \,[\text{F}]$, thus converting a single-ground system into an unintended and, therefore, not optimal multi-ground system.

Figure 14.4 shows two types of single-point ground systems:

- **Daisy-chain ground system.** The daisy-chain ground system is a simple way to implement a single-point ground system, but it is not recommended because of the common-impedance coupling.
- **Star ground system.** A star ground system is an improved way to implement a single-point ground system than the daisy-chain variant because it reduces the common-impedance noise coupling.

### 14.5.2 Multipoint Ground Systems

The concept of a multi-ground system —like shown in Fig. 14.5—is usually applied for high-frequency systems. At high frequencies ($>1\,\text{MHz}$), the ground impedance
Fig. 14.5 Multipoint ground system. Ideally: $Z_{g1} = Z_{g2} = Z_{g3} = 0\Omega$

Fig. 14.6 Hybrid ground system. Low-frequency (LF) signals flow to the left to the single-ground point and high-frequency (HF) signals through the capacitors $C_{g1}$, $C_{g2}$, and $C_{g3}$

$Z_g = R_g + j\omega L_g$ is primarily dominated by the ground inductance $L_g$ [H]. This means that the ground connections of the circuits to ground should be as short as possible with low impedance (e.g., with multiple vias). For PCBs, a multipoint ground system is best achieved with one or several solid and uninterrupted ground plane(s).

### 14.5.3 Hybrid Ground Systems

*Hybrid ground systems* provide different paths to ground for low-frequency currents $I_{LF}$ [A] and high-frequency currents $I_{HF}$ [A]. Figure 14.6 shows a typical hybrid ground system, which provides a single-point ground system for low-frequency signals and a multipoint ground system for high-frequency signals.

Hybrid grounding can also be applied to cable shields (see Sect. 13.7.4), where one end of the cable shield is connected to ground with low impedance and the other end is connected via a capacitor. A hybrid grounded cable shield could provide reasonable protection against inductive coupling of HF magnetic fields and at the same time prevent LF currents from flowing along the cable shield.
14.6 Ground Loops

A ground loop is a current loop formed by ground conductors and ground itself, like shown in Fig. 14.7. Ground loops could lead to the following interference problems:

- **Interference caused by ground voltage potential difference.** A voltage potential difference between the ground connection points of two circuits, which are interconnected via a ground conductor, could cause an unintended noise current $I_{sg}$ [A] along the signal ground wire between the two circuits. As a consequence, a noise voltage $V_n = I_{sg} \cdot Z_{sg}$ is introduced in the signal connection between the circuits, where $Z_{sg}$ [$\Omega$] is the impedance of the signal ground wire of the interconnection between the two circuits.

- **Interference caused by magnetic field coupling to ground loop.** A voltage $V_g$ [V] could be induced into the ground loop by a magnetic field (see magnetic field coupling in Sect. 12.1.3 on page 195). $V_g$ [V] causes a noise current $I_{sg}$ [A] through the signal ground wire, which introduces a noise voltage $V_n = I_{sg} \cdot Z_{sg}$ to the signal interconnection.

Figure 14.8 compares how ground loop interference does affect single-ended (unbalanced) and differential signal (balanced) interfaces. Well-balanced differential interfaces (e.g., LVDS) are more robust against ground loop coupling than single-ended interfaces (e.g., CMOS) because the noise voltage $V_n$ [V] affects both signal lines of a differential interface and is canceled out. A list of digital single-ended and differential signal interfaces can be found in Sect. 7.10 on page 90.

In many cases, ground loops do not lead to EMC problems. Meaning, the EMC design engineers should not avoid ground loops at any cost. However, EMC design engineers should be aware of ground loops and how to deal with them if they lead to an EMC issue. Ground loops are primarily a problem for low-frequency applications ($f < 100$ kHz) because the size of ground loops is usually large. Thus, they have a large inductance, which means that they represent a high impedance for HF signals. A typical example of an EMC issue due to a ground loop is the 50/60 Hz hum coupled into audio systems.

If ground loops are a problem, the following are options for minimizing their impact:

**Fig. 14.7** Example of a ground loop in case of a single-ended interface
Fig. 14.8  Ground loop noise coupling: single-ended vs. differential interfaces. $V_g$ [V] could be caused by a voltage potential difference between the ground connections of circuits 1 and 2, or $V_g$ [V] could be induced by a magnetic field. (a) Ground loop noise coupling in case of a single-ended (unbalanced) interface. The noise voltage $V_n$ [V] does directly interfere with the useful signal. (b) Ground loop noise coupling in case of a differential (balanced) interface. $V_n$ [V] does add to both differential signal lines likewise, and the noise voltage is canceled out

- **Use balanced transmission lines.** As mentioned above and shown in Fig. 14.8, differential interfaces with a balanced transmission line are very robust against interference caused by ground loops.

- **Applying single-point or hybrid grounding.** Single-point or hybrid ground systems (see Figs. 14.4 and 14.6) help avoid ground current loops caused by voltage potential differences in the ground system. However, they do not help to avoid ground loop currents induced by magnetic fields.

- **Reducing the ground impedance.** Reducing the ground impedance $Z_{sg}$ [$\Omega$] in the signal ground conductor—like shown in Fig. 14.8a—reduces the noise voltage $V_n$ [V] caused by the unintended ground loop current $I_{sg}$ [A] through the signal ground conductor.

- **Breaking the ground current loop:**
  - **Transformers, photocouplers.** If the interface between circuit 1 and 2 in Fig. 14.8 is realized with a transformer or a photocoupler (see Fig. 14.9a,b), the low-frequency ground current path is interrupted. However, HF currents may still flow through the stray capacitance of the transformer or photocoupler.
  - **Common-mode chokes.** If a common-mode choke is added to the interface between circuits 1 and 2 (see Fig. 14.9c), the HF ground loop currents through the signal ground conductor are attenuated. However, at very low frequencies of $f < 10$ kHz and very high frequencies of $f > 1$ GHz, the attenuation of the ground loop currents due to a common-mode choke is limited because of its relatively low inductance $L$ [H] and its stray capacitance $C$ [F].
  - **Fiberglass.** Using a fiberglass communication system between circuits 1 and 2—like shown in Fig. 14.9d—breaks the ground loop for currents of any frequency $f$ [Hz]. However, fiberglass communication systems are costly.
Fig. 14.9 How to break ground loops. (a) A transformer can be used to break the ground loop for low-frequency ground loop currents. (b) A photocoupler can be used to break the ground loop for low-frequency ground loop currents. (c) A common-mode choke can be used to break the ground loop for high-frequency ground loop currents. (d) A fiberglass communication system can be used to break the ground loop for noise currents for any frequency $f$ [Hz]

14.7 Summary

- **Types of ground.** There are safety, functional, chassis, and signal grounds.
- **EMC ground philosophy.**
  - Do always consider ground as a return current path.
  - Minimize current loop area between forward and return current path.
  - Consider and minimize common impedance coupling in the ground path.
- **Return current path on solid PCB ground planes.**
  - Signals with $f < 100$ kHz: the return current path takes the path of the least resistance and takes the shortest way possible through the ground plane.
  - Signals with $f > 1 $ MHz: the return current path takes the path of the least inductance and flows back to the source directly underneath the PCB signal trace of the forward current.
- **Grounding of systems.**
  - Single-point ground systems are typically used at LF ($f < 100$ kHz).
  - Multipoint ground systems are typically used at HF ($f > 1$ MHz).
  - Hybrid ground systems split ground return current paths for LF and HF.
• **Balanced vs. unbalanced transmission lines.** Balanced transmission lines are more robust against ground noise than unbalanced transmission lines.

• **Ground loops.**
  
  – Ground loop currents are typically caused by:
    
    - Voltage potential difference in the ground system.
    - Magnetic fields coupling to the ground current loop.
  
  – Reducing the ground impedance reduces the ground noise voltage caused by ground loop currents.
  
  – Single-point and hybrid ground systems help reduce ground loop currents.
  
  – Breaking the ground loop eliminates any ground noise current.

**References**


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