The Circuit Designer's Companion: Grounding and wiring

Peter Wilson

http://www.edn.com/design/components-and-packaging/4429199/The-Circuit-Designer-s-Companion--Grounding-and-wiring

电路设计师指导手册(1)：接地与布线

作者：Peter Wilson

Adapted from The Circuit Designer's Companion, Third Ed., by Peter Wilson (Newnes).

摘录自 Peter Wilson 编写的《电路设计师指导手册》第三版（Newnes 出版社）

1.1 GROUNDING

A fundamental property of any electronic or electrical circuit is that the voltages present within it are referenced to a common point, conventionally called the ground. This term is derived from electrical engineering practice, when the reference point is often taken to a copper spike literally driven into the ground.

1.1 接地

任何电子或电气电路都有一个基本属性，即电路中呈现的电压都有一个公共的参考点，这个公共点习惯上被称为地。这个术语源自电气工程实践活动，在这些活动中参考点经常是指钉入大地的一颗铜钉。

This point may also be a connection point for the power to the circuit, and it is then called the 0 V (nought-volt) rail, and ground and 0 V are frequently (and confusingly) synonymous. Then, when we talk about a five-volt supply or a minus-twelve-volt supply or a two-and-a-half-volt reference, each of these are referred to the 0 V rail.

这个点也可能是电源与电路之间的的一个连接点，此时这个点被称为 0V(零伏)轨，而地和 0V 通常是同义词(有些令人困惑)。这样，当我们谈到 5V 电源或-12V 电源或 2.5V 参考电压时，这些电压的参考点都是 0V 轨。

At the same time, ground is *not* the same as 0 V. A ground wire connects equipment to earth for safety reasons, and does not carry a current in normal operation. However, in this chapter the word "grounding" will be used in its usual sense, to include both safety earths and signal and power return paths.

而实际地并不等同于 0V。基于安全的原因，需要用地线将设备连接到大地，在正常工作中地线是不承载电流的。然而，本文中的“接地”一词是按通常的意义使用的，包括安全地以及信号与电源返回路径。

Perhaps the greatest single cause of problems in electronic circuits is that 0 V and ground are taken for granted. The fact is that in a working circuit there can only ever be one point which is truly at 0 V; the concept of a "0 V rail" is in fact a contradiction in terms. This is because any practical conductor has a finite non-zero resistance and inductance, and Ohm's law tells us that a current flowing through anything other than a zero impedance will develop a voltage across it.

电路中出现问题的最大一个原因也许是将 0V 和地想当然认为是一样的。事实上，在一个工作电路中只有一个点是真正的 0V。“0V 轨”的概念实际上是一种自相矛盾的说法。这是因为任何实际导体都有有限的非零电阻和电感，欧姆定律告诉我们，在非零阻抗的任何物体上流过的电流都将在这个物体两端产生一个电压。

A working circuit will have current flowing through those conductors that are designated as the 0 V rail and therefore, if any one point of the rail is actually at 0 V (say, the power supply connection) the rest of the rail will not be at 0 V. This can be illustrated with the example in Figure 1.1.

一个工作中的电路将在指定为 0V 轨的这些导体中形成电流流动，因此如果轨的任何一点处于真正的 0V(比方电源连线)，那么轨的其它部分将不等于 0V。这种情况可以用图 1.1 中的例子来解释。

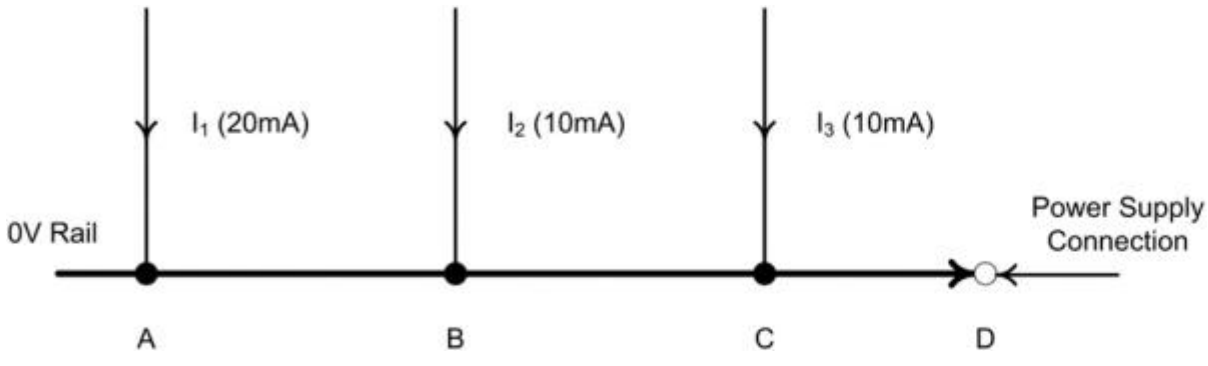

FIGURE 1.1 Voltages along the 0 V rail

图 1.1 0V 轨沿线的电压。

Assume the 0 V conductor has a resistance of 10mΩ/inch and that points A, B, C and D are each one inch apart. The voltages at points A, B and C referred to D are:

假设 0V 导体具有 10mΩ/英寸的电阻，A、B、C 和 D 点分别间隔一英寸。那么 A、B 和 C 点相对于 D 点的电压是：

V_C = (I1 + I2 + I3) × 10 mΩ = 400 μV
V_B = V_C + (I1 + I2) × 10mΩ = 700 μV
V_A = V_B + (I1) × 10mΩ = 900 μV

Now, after such a trenchant introduction, you might be tempted to say well, there are millions of electronic circuits in existence, they must all have 0 V rails, they seem to work well enough, so what's the problem? Most of the time there is no problem. The impedance of the 0 V conductor is in the region of milliohms, the current levels are milliamps, and the resulting few hundred microvolts drop doesn't offend the circuit at all; 0 V plus 500 μV is close enough to 0 V for nobody to worry.

现在，经过上述深入浅出的介绍后，你可能会说，世界上存在成千上万的电路，它们必定都有 0V 轨，但它们的工作看起来好得很，因此有什么问题呢？大多数情况下确实没有问题。0V 导体的阻抗是毫欧级别，电流是毫安，因此形成的几百微伏的压降根据不会损害到电路。0V 加上 500μV 还是非常接近 0V，没有人会担心。

The difficulty with this answer is that it is then easy to forget about the 0 V rail and assume that it is 0 V under all conditions, and subsequently be surprised when a circuit oscillates or otherwise doesn't work. Those conditions where trouble is likely to arise are:

这样的回答问题在于，很容易让人忘记 0V 轨，并认为在所有条件下都是 0V，但当电路发生振荡或不能工作时会让人大吃一惊。可能发生问题的那些条件是：

- where current flows are measured in amps rather than milli- or microamps;
- here the 0 V conductor impedance is measured in ohms rather than milliohms;
- here the resultant voltage drop, whatever its value, is of a magnitude or in such a configuration as to affect the circuit operation.

- 当测得的流动电流单位为安培而不是毫安或微安时；
- 0V 导体阻抗的测量值单位为欧姆而不是毫欧时；
- 最终压降不管值是多少，其数量级或配置情况都将影响到电路正常工作。

When to consider grounding

One of the attributes of a good circuit designer is to know when these conditions need to be carefully considered and when they may be safely ignored. A frequent complication is that you as circuit designer may not be responsible for the circuit's layout, which is handed over to a layout draughtsman (who may in turn delegate many routing decisions to a software package). Grounding is always sensitive to layout, whether of discrete wiring or of printed circuits, and the designer must have some knowledge of and control over this if the design is not to be compromised.

什么时候考虑接地
优秀的电路设计师的优秀品质之一是，知道何时需要慎重考虑这些条件，何时可以安全地忽略这些条件。通常的复杂性在于，你作为电路设计师可能不负责电路版图，版图设计要交给专门的版图人员完成(他们又可能会将许多布线策略交给软件包)。接地对版图来说总是敏感的，不管是分立的布线还是印刷电路板，如果设计要求比较高，设计师就必须在这方面具备一定的知识，并进行有效控制。

The trick is always to be sure that you know where ground return currents are flowing, and what their consequences will be; or, if this is too complicated, to make sure that wherever they flow, the consequences will be minimal. Although the above comments are aimed at 0 V and ground connections, because they are the ones most taken for granted, the nature of the problem is universal and applies to any conductor through which current flows. The power supply rail (or rails) is another special case where conductor impedance can create difficulties.

这里的技巧是要确保你知道哪里有地返回电流在流动，这种流动有什么后果。或者如果这太复杂的话，确保不管这些电流在哪里流动，造成的不良后果最小。虽然上述评论的对象是 0V 和地线，因为它们是最被认可的，但问题的实质是普遍性的，适用于电流流经的任何导体。电源轨(或轨)是另外一种特殊情况，此时的导体阻抗可能会产生问题。

1.1.1 Grounding within one unit

In this context, "unit" can refer to a single circuit board or a group of boards and other wiring connected together within an enclosure such that you can identify a "local" ground point, for instance the point of entry of the mains earth. An example might be as shown in Figure 1.2.

1.1.1 在一个单元内的接地

本文中提到的“单元”可以指单个电路板或一组电路板以及在同一个外壳内与之相连的其它线缆，因此你可以确定一个“局部”的接地点，比如主电源地的接入点。图 1.2 给出了一个例子。

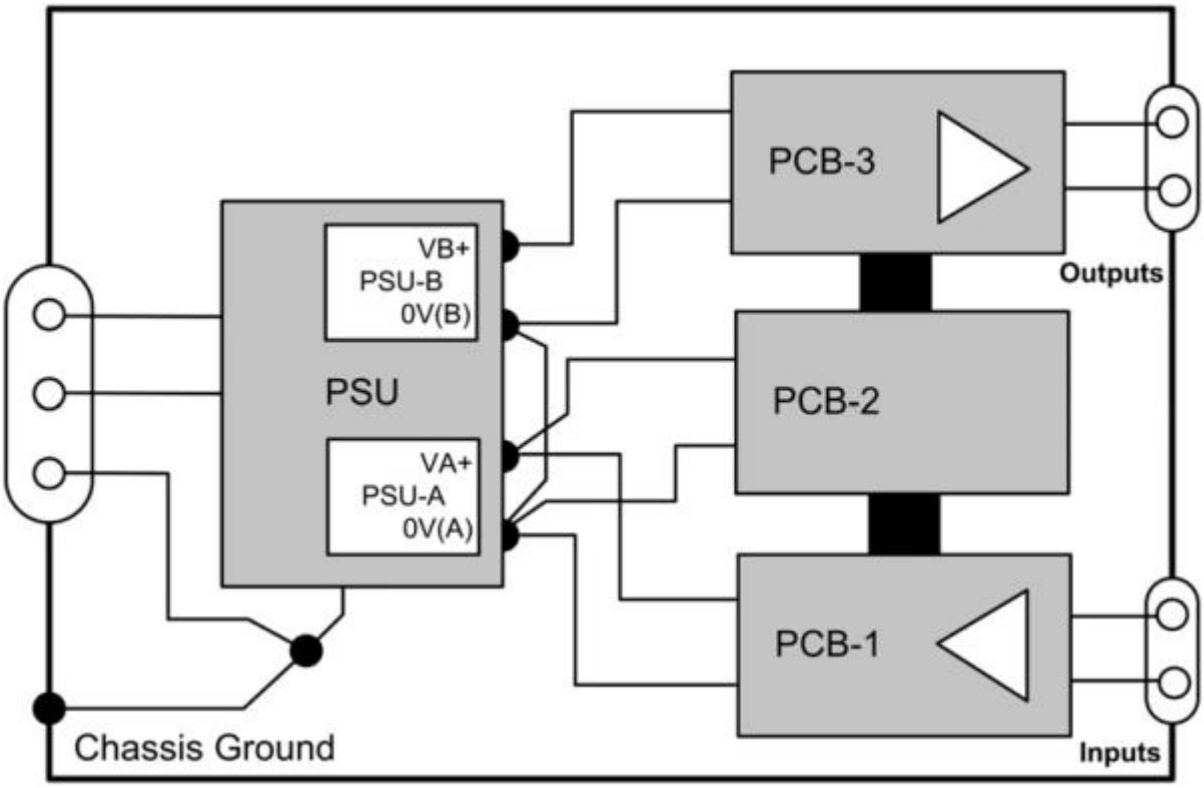

FIGURE 1.2 Typical intra-unit wiring scheme

图 1.2 典型的单元内部走线机制。

Let us say that printed circuit board (PCB) 1 contains input signal conditioning circuitry, PCB2 contains a microprocessor for signal processing and PCB3 contains high-current output drivers, such as for relays and for lamps. You may not place all these functions on separate boards, but the principles are easier to outline and understand if they are considered separately.

假设如印刷电路板(PCB)1 包含输入信号调节电路，PCB2 包含用于信号处理的微处理器，PCB3 包含大电流输出驱动器，比如用于继电器或灯的驱动器。你可能不会把所有这些功能放在分开的板上,但如果按分开的方式考虑可以更容易描述和理解其中的原理。

The power supply unit (PSU) provides a low-voltage supply for the first two boards, and a higher-power supply for the output board. This is a fairly common system layout and Figure 1.2 will serve as a starting point to illustrate good and bad practice.

电源单元(PSU)为前两块电路板提供低压电源，为输出电路板提供较高的电源。这是一种相当普遍的系统版图，图 1.2 可以用作说明好坏实践的起点。

1.1.2 Chassis ground

First of all, note that connections are only made to the metal chassis or enclosure at one point. All wires that need to come to the chassis are brought to this point, which should be a metal stud dedicated to the purpose.

1.1.2 机箱地

首先需要注意的是，地线只连接到金属机箱或外壳的一个点。所有需要连到机箱的地线都被引到这个点，这个点应该是专用于此目的的金属螺柱。

Such connections are the mains safety earth (about which more later), the 0 V power rail, and any possible screening and filtering connections that may be required in the power supply itself, such as an electrostatic screen in the transformer. (The topic of power supply design is itself dealt with in much greater detail in Chapter 7.)

这些连线有主电源安全地(后面会有更详细的讨论)、0V 电源轨以及电源本身可能要求的任何屏蔽与滤波连接(如变压器中的静电屏蔽)。(有关电源设计的主题本身将在第 7 章中作更详细的讨论)

The purpose of a single-point chassis ground is to prevent circulating currents in the chassis.[1] If multiple ground points are used, even if there is another return path for the current to take, a proportion of it will flow in the chassis (Figure 1.3); the proportion is determined by the ratio of impedances which depends on frequency.

机箱单点接地的目的是为了防止在机箱中形成循环电流[1]。如果使用多个接地点，即使存在另外一条电流返回路径，机箱中也会有与之成比例的电流流动(图 1.3)。具体比例则取决于阻抗比，而阻抗又取决于频率。

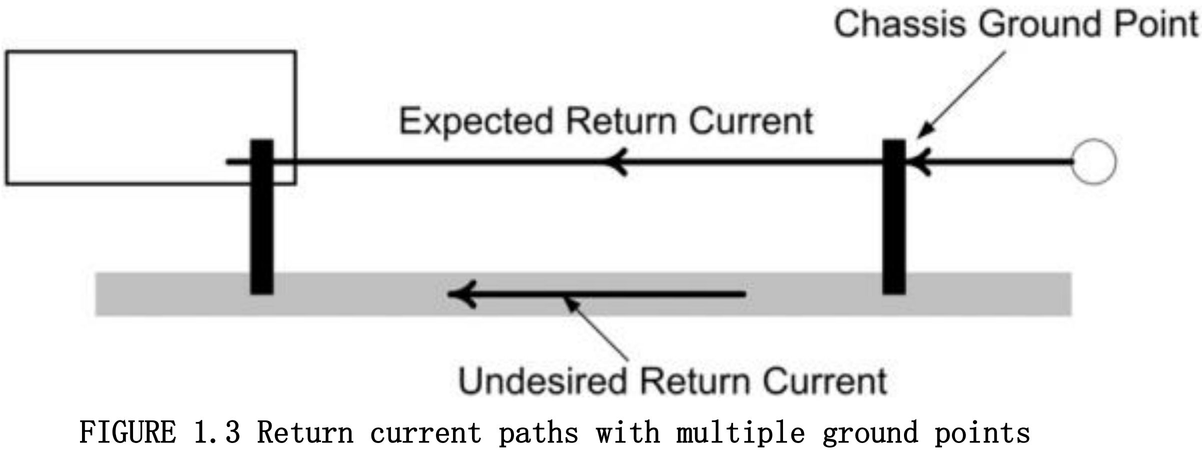

FIGURE 1.3 Return current paths with multiple ground points

图 1.3 具有多个接地点的返回电流路径。

Such currents are very hard to predict and may be affected by changes in construction, so that they can give quite unexpected and annoying effects: it is not unknown for hours to be devoted to tracking down an oscillation or interference problem, only to find that it disappears when an inoffensive-looking screw is tightened against the chassis plate.

这种电流很难预测，而且可能受到结构变化的影响，因此它们会产生极其意外又令人恼火的效应：可能花了很长时间去跟踪振荡或干扰问题，最后发现当机箱板上一颗不起眼的螺钉经过紧固后问题消失了。

Joints in the chassis are affected by corrosion, so that the unit performance may degrade with time, and they are affected by surface oxidation of the chassis material. If you use multi-point chassis grounding then it is necessary to be much more careful about the electrical construction of the chassis.

机箱连接处会受腐蚀的影响，因此单元性能可能随时间推移而劣化，而且会受机箱材料表面氧化的影响。如果你使用多点机箱接地，那么更加仔细地考虑机箱电气结构就很有必要。

[1]But, when RF shielding and/or a low-inductance ground is required, multiple ground points may be essential. This is covered in Chapter 8.

但是，当要求射频屏蔽和/或低电感接地时，多点接地也许是必须的。这一点将在第 8 章中讨论。

1.1.3 The conductivity of aluminum

Aluminum is used throughout the electronics industry as a light, strong and highly conductive chassis material - only silver, copper and gold have a higher conductivity. You would expect an aluminum chassis to exhibit a decently low bulk resistance, and so it does, and is very suitable as a conductive ground as a result.

1.1.3 铝的导电特性

由于铝是一种轻量、坚固和高导电性的机箱材料，在整个电子行业中有着广泛的应用——只有银、铜和金具有更高的导电率。铝机箱具有相当低的体电阻，因此非常适合用作导电接地端。

Unfortunately, another property of aluminum (which is useful in other contexts) is that it oxidizes very readily on its surface, to the extent that all real-life samples of aluminum are covered by a thin surface film of aluminum oxide (Al_2O_3). Aluminum oxide is an insulator. In fact, it is such a good insulator that anodized aluminum, on which a thick coating of oxide is deliberately grown by chemical treatment, is used for insulating washers on heatsinks.

遗憾的是，铝的另外一种属性(在其它情况下非常有用)是它的表面很容易氧化，以致于所有实际使用的铝材都覆盖有一层氧化铝(Al_2O_3)薄膜。氧化铝是一种绝缘物质。事实上，它的绝缘性能相当好，以致于阳极电镀铝常用作散热器上的绝缘垫圈，因为在这种铝材表面通过化学处理方法专门生成了一层很厚的氧化膜。

The practical consequence of this quality of aluminum oxide is that the contact resistance of two sheets of aluminum joined together is unpredictably high. Actual electrical contact will only be made where the oxide film is breached. Therefore, whenever you want to maintain continuity through a chassis made of separate pieces of aluminum, you must ensure that the plates are tightly bonded together, preferably with welding or by fixings which incorporate shakeproof serrated washers to dig actively into the surface.

这种品质的氧化铝的实用结果是，连接在一起的两层铝之间的接触电阻异常高。实际电气接触只是在氧化膜破裂的地方。因此无论何时只要你想保持由多片铝板做成的机箱的导电连续性，你必须确保铝板紧密地绑定在一起，最好采用焊接或紧固的方法，后者可以使用防震锯齿形垫圈并使之深入铝材表面。

The same applies to ground connection points. The best connection (since aluminum cannot easily be soldered) is a force-fit or welded stud (Figure 1.4), but if this is not available then a shakeproof serrated washer should be used underneath the nut which is in contact with the aluminum.

接地点可以采用同样的方法。最好的连接方式是压接或焊接螺柱(因为铝焊接起来比较困难)(图 1.4)，但如果这种方式不可用的话，可以在与铝材接触的螺母下面使用防震锯齿形垫圈。

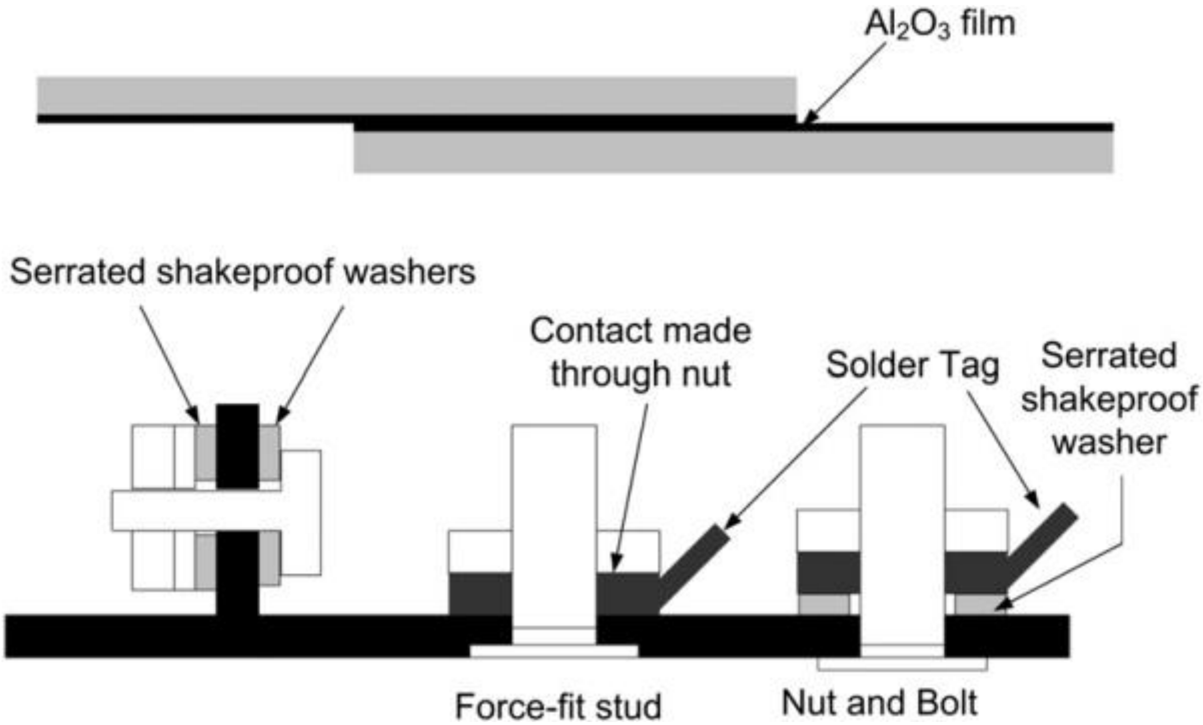

FIGURE 1.4 Electrical connections to aluminum

图 1.4：到铝材的电气连接。

Other materials
Another common chassis material is cadmium- or tin-plated steel, which does not suffer from the oxidation problem. Mild steel has about three times the bulk resistance of aluminum so does not make such a good conductor, but it has better magnetic shielding properties and it is cheaper.

其它材料
另外一种常用的机箱材料是镀镉或镀锡的钢材，这种材料不存在氧化的问题。低碳钢的体电阻是铝材的三倍，因此导电性不是太好，但它具有更好的磁屏蔽属性，并且价格较低。

Die-cast zinc is popular for its light weight and strength, and ease of creating complex shapes through the casting process; zinc's conductivity is 28% that of copper. Other metals, particularly silver-plated copper, can be used where the ultimate in conductivity is needed and cost is secondary, as in RF circuits. The advantage of silver oxide (which forms on the silver-plated surface) is that it is conductive and can be soldered through easily. Table 1.1 shows the conductivities and temperature coefficients of several metals.

压铸型锌材也非常流行，因为它重量轻，强度大，并且通过压铸工艺很容易做成复杂的形状。锌的导电性是铜的 28%。在导电性为主、成本次要的场合(比如射频电路)，还可以使用其它金属，特别是镀银的铜。(在镀银层表面形成的)氧化银优点是具有导电性，并且很容易焊接。表 1.1 给出了几种金属的导电性和温度系数。

Metal	Relative conductivity (Cu = 1, at 20°C)	Temperature coefficient of resistance (/°C at 20°C)
Aluminum (pure)	0.59	0.0039
Aluminum alloy:		
Soft-annealed	0.45–0.50	0.0039
Heat-treated	0.30–0.45	0.0039
Brass	0.28	0.002–0.007
Cadmium	0.19	0.0038
Copper:		
Hard-drawn	0.895	0.00382
Annealed	1.0	0.00393
Gold	0.65	0.0034
Iron:		
Pure	0.177	0.005
Cast	0.02–0.12	0.005
Lead	0.7	0.0039
Nichrome	0.0145	0.0004
Nickel	0.12–0.16	0.006
Silver	1.06	0.0038
Steel	0.03–0.15	0.004–0.005
Tin	0.13	0.0042
Tungsten	0.289	0.0045
Zinc	0.282	0.0037

Table 1.1 Conductivity of Metals

表 1.1 几种金属的电导率。

1.1.4 Ground loops

Another reason for single-point chassis connection is that circulating chassis currents, when combined with other ground wiring, produce the so-called "ground loop," which is a fruitful source of low-frequency magnetically induced interference.

1.1.4 接地环路

机箱单点接地的另外一个理由是，循环的机箱电流与其它接地线结合在一起时会产生所谓的“接地环路”，这是低频磁感应干扰的一个重要来源。

A magnetic field can only induce a current to flow within a closed-loop circuit. Magnetic fields are common around power transformers - not only the conventional 50 Hz mains type (60 Hz in the US), but also high-frequency switching transformers and inductors in switched-mode power supplies - and also other electromagnetic devices: contactors, solenoids and fans. Extraneous magnetic fields may also be present. The mechanism of ground-loop induction is shown in Figure 1.5.

磁场感应出的电流只能在闭环电路中流动。磁场广泛存在于电源变压器周围——不仅是传统的 50Hz 主变(美国是 60Hz)，还有开关电源中使用的高频开关变压器

和电感——以及其它电磁设备周围，如电流接触器、螺线管和风扇。同时还可能存在外部磁场。接地环路的感应机制如图 1.5 所示。

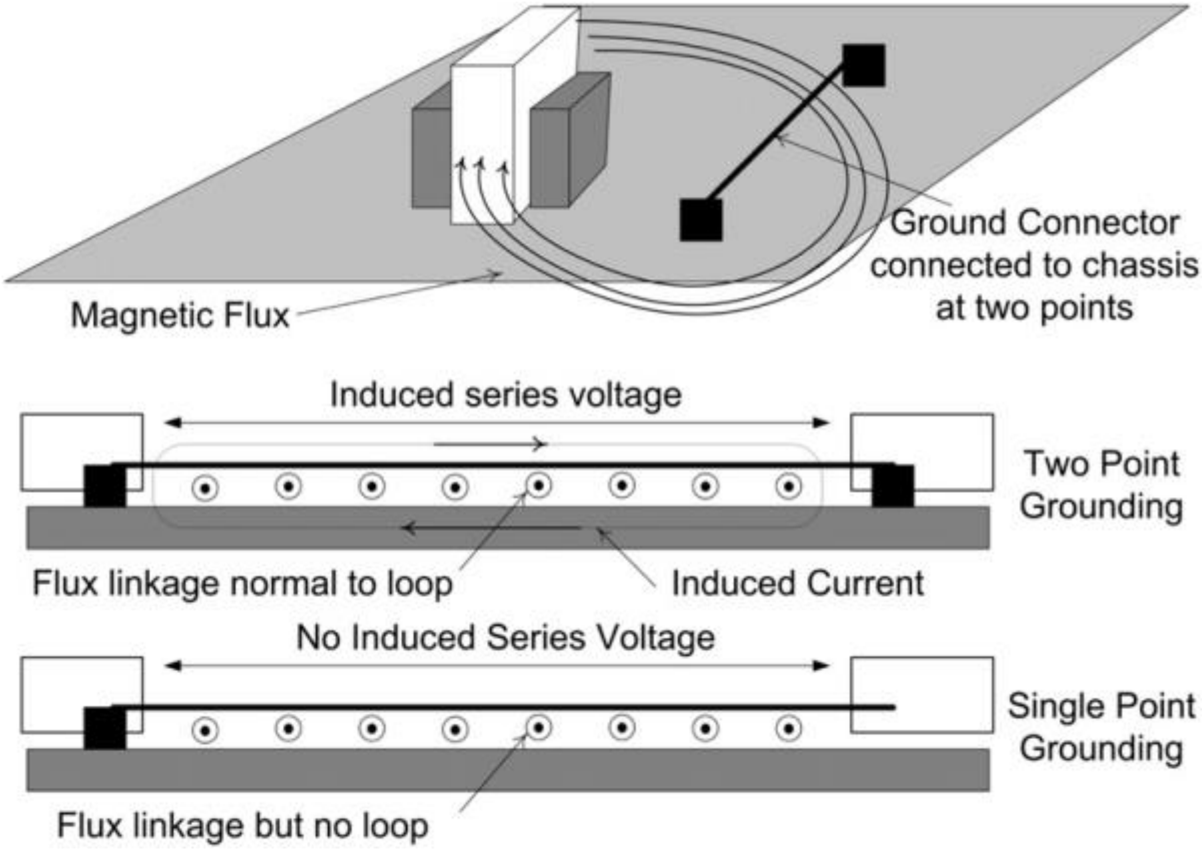

FIGURE 1.5 The ground loop

图 1.5：接地环路。

Lenz's law tells us that the EMF induced in the loop is:

$$V = -10^{-8} \times A \times n \times dB/dt$$

where A is the area of the loop in cm^2, B is the flux density normal to it in microTesla (μT) assuming a uniform field, and n is the number of turns (n = 1 for a single-turn loop).

楞次定律告诉我们，环路中感应的电动势(EMF)是：

$$V = -10^{-8} \times A \times n \times dB/dt$$

其中 A 是单位为 cm^2 的环路面积，B 是假设均匀磁场条件下单位为 μT 的归一化通量密度，n 是匝数(单匝环路时 n=1)。

As an example, take a 10 μT 50-Hz field as might be found near a reasonable-sized mains transformer, contactor or motor, acting at right angles through the plane of a 10-cm^2 loop that would be created by running a conductor 1 cm above a chassis for 10 cm and grounding it at both ends. The induced EMF is given by

$V = -10^{-8} \times 10 \times d/dt(10 \times \sin 2\pi \times 50 \times t)$
$= -10^{-8} \times 10 \times 1000\pi \times \cos \omega t$
$= 314\ \mu V$ peak

举个例子，在合理尺寸的主变压器、电流接触器或电机附近通常有一个 10 μT 50Hz 的磁场，它们以合适的角度穿过一个面积为 $10cm^2$ 的环路平面(这个平面是在长 10cm 的机箱上方 1cm 处安装一段导体并在两端接地的情况下形成的)，这时感应到的电动势是：
$V = -10^{-8} \times 10 \times d/dt(10 \times \sin 2\pi \times 50 \times t)$
$= -10^{-8} \times 10 \times 1000\pi \times \cos \omega t$
$= 314\ \mu V$ peak

Magnetic field induction is usually a low-frequency phenomenon (unless you happen to be very close to a high-power radio transmitter) and you can see from this example that in most circumstances the induced voltages are low. But in low-level applications, particularly audio and precision instrumentation, they are far from insignificant. If the input circuit includes a ground loop, the interference voltage is injected directly in series with the wanted signal and cannot then be separated from it. The cures are:

磁场感应通常是一种低频现象(除非你刚好非常靠近一台大功率的无线发射器)，从这个例子可以看出，在大多数情况下感应到的电压是很低的。但在低电平应用中，特别是音频和精密仪器，这些电压就变得相当显著。如果输入电路包含一个接地环路，干扰电压将与有害信号一起直接注入进来，并且无法分离。解决这个问题的方法有：

- open the loop by grounding only at one point;
- reduce the area of the loop (A in the equation above) by routing the offending wire(s) right next to the ground plane or chassis, or shortening it;
- reduce the flux normal to the loop by repositioning or reorienting the loop or the interfering source;
- reduce the interfering source, for instance by using a toroidal transformer.

- 通过只在一点接地打开环路
- 通过将侵害线靠近地平面或机箱布线或直接短路来减少环路面积(上面公式中的 A 项)
- 通过重新调整环路或干扰源的位置或方向来减少归一化到环路的磁通量
- 减少干扰源，比如使用环形变压器