2 A Short Introduction to Electrical Parameters

v1.4 – June 2021

Prerequisite knowledge required: Newtonian Physics

2.1 Introduction

There are a few fundamental concepts in electronics which it's very important to have a clear idea about, otherwise most of what's coming up in the rest of your degree programme won't make a lot of sense. These include the ideas of electrical charge, current, voltage and potential, the concept of a field, and of flux lines.

When trying to understand something new, it's often useful to relate it to something you're already familiar with. By far the most common way of understanding these electronic concepts is by using something known as the hydraulic analogy[1]. The idea is to think of electricity as if it were water flowing round a series of pipes[2].

(Note that most of the content of this note is also included in the short note about Newtonian Physics, but here I'll start with the electronics, rather than the plumbing.)

2.2 Charge

In the plumbing analogy, charge is analogous to the water itself. It's what's inside the pipes, and what flows around the circuit. Note it must flow around, never just to or from: the pipes are never left empty, and you can't put more water into a pipe than the volume of the pipe can hold: the pipes are always full and the water always flows around a circuit of pipes. (This is why the concept of an *electronic circuit* is a very important one: in this analogy the water is always flowing around a circuit of pipes, there is no connection to the air at any point.)

In electronics, charge is measured in coulombs[3] (C). One coulomb is the charge on $1.6*10^{19}$ electrons[4].

2.3 Current

It's no coincidence that the word "current" is used when talking about water as well. It's the same idea here as the current in the ocean: it's the amount of fluid (in this case the charge) moving along

---

[1] See http://en.wikipedia.org/wiki/Hydraulic_analogy

[2] It's important to point out that this is not an exact analogy, and it has several problems when stretched too far (particularly at higher frequencies), but it's a reasonable place to start, and works quite well for basic circuit theory. For those interested in the problems with this analogy, the Wikipedia article is a good place to start.

[3] Named after Charles-Augustin de Coulomb, an 18th century French physicist who did a lot of pioneering work on electricity, and has his name inscribed on the Eiffel tower.

[4] Actually not quite true, since electrons have negative charge. More accurately, one coulomb is minus one times the charge on $1.6*10^{19}$ electrons. This causes a lot of confusion, but for the purposes of basic circuit theory the problem can usually be ignored by dealing with "conventional current". A positive conventional current (composed of a net positive charge moving around a circuit) is actually composed of a lot of negatively charged electrons going the other way.

the pipe. It can be measured in coulombs per second or ampères (usually shortened to amps[5]). This definition provides the first useful equation of electronics:

$$\begin{aligned} \text{charge} &= \text{current} \times \text{time} \\ Q &= I \times t \end{aligned} \tag{2.1}$$

The charge passing a certain point in a circuit during a certain time is the product of the current and the time. Here I've used I to represent current, Q to represent charge[6], and t for time.

2.4 Voltage

You can think of voltage as being like the pressure of water in a pipe. If put under pressure the water will try and leave, and as soon as it can find a way out, the water will squirt out to somewhere where there is less pressure. Charge does the same thing with voltage: charge tries to move from a point in a circuit at a higher voltage to a point at a lower voltage, and this results in current flowing.

Voltage is measured in volts. A difference between the voltages of two points in the circuit of one volt means that it takes one joule of energy to move one coloumb of charge between them. This definition gives us the second useful equation of electronics:

$$\begin{aligned} \text{work or energy} &= \text{voltage difference} \times \text{charge} \\ W &= V \times Q \end{aligned} \tag{2.2}$$

Note that if left to itself, current always flows from high voltages to low voltages (indeed, if there is a way for charge to move from a higher voltage to a lower voltage, it will do so) and this releases energy from the circuit. If you want to get charge to move from a lower voltage to a higher voltage (for example in a battery or other voltage source), then you have to do work; and that means getting energy from somewhere outside the circuit (just like having a pump).

There's another interesting point here, and that's about the concept of zero voltage. You might think that a zero voltage would be analogous to zero pressure: but in fact zero pressure only exists in a vacuum (like outer space), and while voltages can be negative, you can't put water under a negative pressure.

What actually happens is that the "zero" level of voltage is arbitrary: it's not equivalent to zero pressure in the water analogy. For any given circuit, you can choose one point where you define the voltage to be zero. The important thing is the difference in voltage between two points (known as the *potential difference*).

2.5 Resistance

Resistance is what limits the current. Suppose you have a battery (in the hydraulic analogy, a pump) which maintains the voltage difference (the difference in pressure between the input and output) at three volts (or three Pascals in the hydraulic analogy, where it's a pressure difference).

---

[5] Named after André-Marie Ampère, another French physicist who also has his name on the Eiffel tower.

[6] Note that I'm not using 'C' for either Charge or Current since 'C' is commonly used for Capacitance, which is an entirely different thing.

If there wasn't a circuit, but just a pump connected to two bits of pipe with their ends sealed, then all you'd have is this:

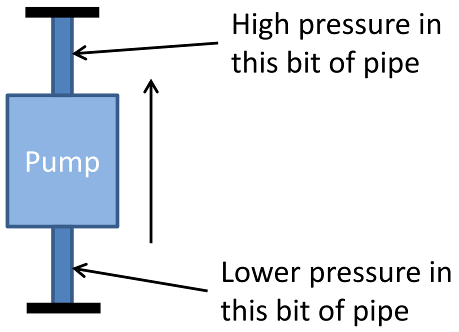

Figure 2.1 Pump with pipe ends sealed (no current)

No current would flow; there is just a pipe with a pump which keeps the pressure at one end higher than the pressure at the other end.

However, connect the high-pressure end to the low-pressure end with a narrow pipe, and current will begin to flow:

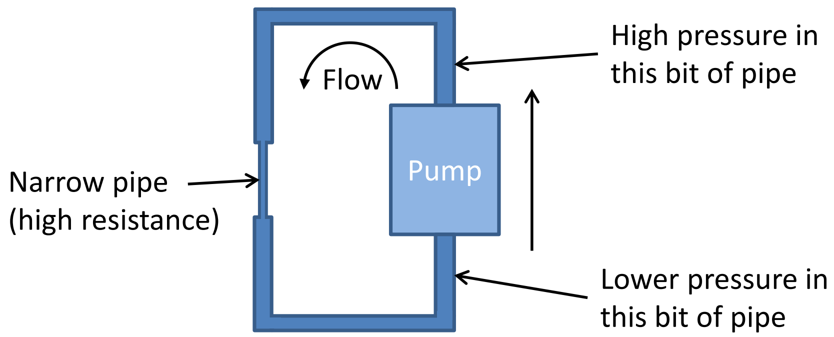

Figure 2.2 Pump with flow around a closed loop (circuit)

The speed at which the fluid will move around the system is determined by how narrow the pipe is. A very narrow pipe will limit the rate at which current can flow; this is called having a high resistance. On the other hand, a wide pipe allows much more water to flow, and this is analogous to a small resistance. Resistance is measured in ohms[7].

The greater the resistance, the less will be the current that flows. This can be expressed in the third useful equation of electronics, which relates the resistance to the current and the voltage difference:

$$\begin{aligned} \text{Voltage} &= \text{Current} \times \text{Resistance} \\ V &= IR \end{aligned} \tag{2.3}$$

The voltage across a resistor (the difference in pressure between one end of the pipe and the other) is the product of the resistance and the current. I've used V here to represent voltage difference

[7] Named after Georg Ohm, who doesn't have his name on the Eiffel Tower, mostly due to not being French. (He was born in what is now Germany).

and R to represent resistance; again these are the conventional choices. This result is often called "Ohm's Law" and was one of the first important results to be derived about circuit theory[8].

2.6 Capacitance

This is a tricky concept and is often misunderstood[9]. Think of a capacitor as a barrel with pipes coming out of each end, and a rubber membrane inside. If the pressure on one side of the membrane increases, the rubber membrane will distort, and force water out of the other end of the pipe. Similarly, if the pressure on one side of the pipe decreases, water will flow out of the capacitor, the membrane will distort, sucking water in from the other end.

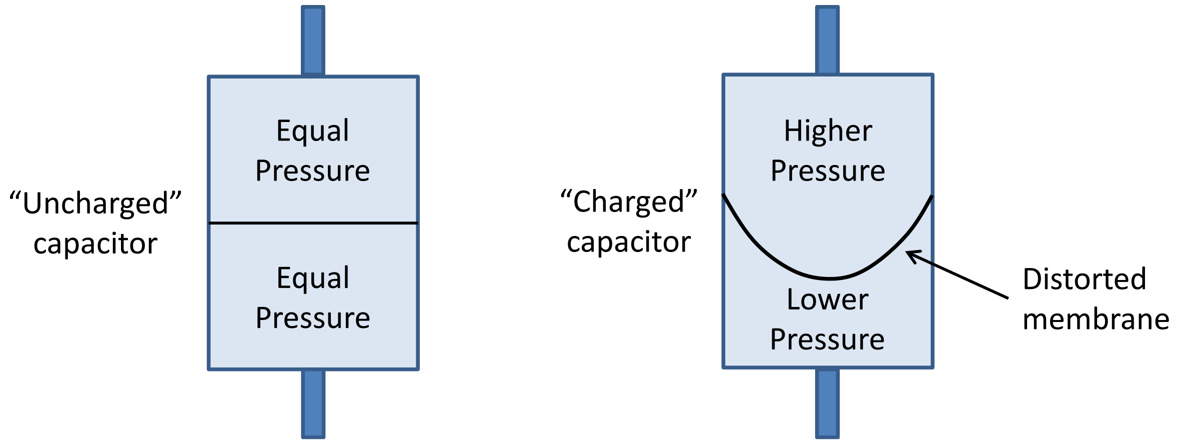

Figure 2.3 "Charged" and "Uncharged" capacitors

Note that the total amount of water (charge) in the capacitor never changes. All that happens is that the rubber membrane distorts towards the end of the capacitor at a lower pressure, forcing water out of that end, while sucking in water from the other (higher pressure) end. The term "charged capacitor" just refers to the imbalance in pressure between the ends of the capacitor, not the total charge in the capacitor as a whole.

Capacitors are linear devices too (at least ideal capacitors are), so the voltage difference across a capacitor (the pressure difference between the two ends) is proportional to the amount of additional charge in the higher-voltage end. We can write another useful equation:

$$\begin{gathered}\text{Excess charge} = \text{Capacitance} \times \text{Voltage Difference} \\ Q = CV\end{gathered} \tag{2.4}$$

---

[8] Strictly speaking it's not Ohm's law: Ohm's law just says that the current flowing through a conductor is proportional to the voltage difference across it. The important thing is that it specifies that the relationship is a linear one: double the voltage difference and you double the current. In other words, the ratio of voltage difference to current (the resistance) is constant, it doesn't change with the current flowing through the resistor). We'll be seeing why this happens a bit later.

[9] You may come across people who say that "capacitors store charge". I think this is rather misleading. Capacitors don't really store charge; they store voltage, and they store energy, but the total amount of charge in a capacitor is constant.

where Q is the amount of additional charge in the high-voltage end, C is a constant known as the capacitance of the capacitor (measured in farads), and V is the potential difference between the two ends.

2.7 Inductance

Warning: this one is going to stretch the plumbing analogy to breaking point, however it's very important in electronic circuits. While capacitors try and maintain the voltage difference across them (you can't suddenly change the voltage difference across a capacitor), inductors try and maintain the current flowing through them (you can't suddenly change the current through an inductor[10]).

Imagine that inside a pipe, occupying the entire cross-sectional area of the pipe, is a propeller. It's mounted so that the propeller fills the whole of the pipe, and any water going past it will force it to rotate:

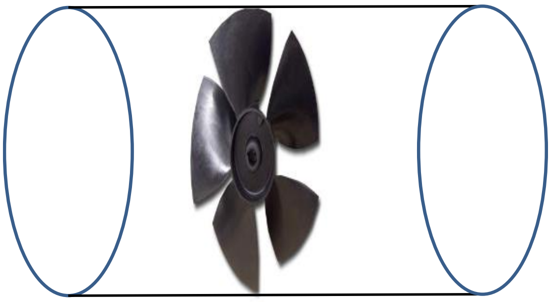

Figure 2.4 A propeller in a pipe

(You have to try and imagine a device which only allows water to flow when it is rotating, and the faster it rotates, the more water can flow.)

Now, when there is a pressure difference across the propeller, water will start to flow, and this will start the propeller rotating. The propeller has mass, so it takes some energy from the current, and this energy is converted into kinetic energy in the propeller.

If the pressure on both sides of the propeller is suddenly made equal, but the propeller will still be rotating due to its inertia. It will effectively turn into a pump, forcing some water to keep moving. This moving water will increase the pressure on the output side of the propeller, relative to the input side, effectively creating a new pressure difference.

Back in the world of electronics, this corresponds to a voltage difference, and can be quantified in terms of the size of the inductor (think of a big inductor as a very heavy propeller: it takes a lot of energy and time to get it rotating, but once rotating it stores a lot of energy, and can keep the current moving for a long time after any pumps in the circuit are switched off).

---

[10] If you try to suddenly change the current by opening a switch in series with the inductor, the inductor will do its best to keep the current flowing, and that means producing a very large voltage across the switch: large enough to cause arcing and sparks to fly. This can cause damage to the switches; it's a real problem in high-current switching.

The voltage across an inductor is given by:

$$e = L\frac{dI}{dt} \tag{2.5}$$

where e is the voltage across the inductor, L is the size of the inductance (measured in henrys) and dI/dt is the rate of change of the current. You'll note that with a constant current (so the propeller is rotating at a constant rate) there is no potential difference across the inductor, however if the propeller is either speeding up or slowing down (as it would when the current is changing), there will be a potential difference across it.

This makes sense from the point of view of energy as well. If the propeller is speeding up, then energy must be coming from the flow of water to provide the kinetic energy for the rotor, according to the principle of conservation of energy. And we've seen that energy is given by voltage difference times current, so there would have to be a voltage difference across the component when energy is being transferred to, or from, the flowing current.

2.7.1 Mutual inductance and transformers

Now imagine two propellers in two different pipes, connected together with a bicycle chain. Any attempt to rotate one forces the other one to rotate as well: this is known as *mutual inductance*.

(At this point you might be wondering how the chain can get out of the pipe without all the water flowing out as well. You just have to imagine that it can. I think I did mention that the analogy would be stretched to breaking point here.)

It's worth noting that there can be some gearing as well: the two propellers don't have to rotate at the same speed. One could, for example, always be rotating at twice the speed of the other one. This can happen in circuits with coupled inductances as well.

We now have a way of transferring energy from one circuit to another, without any charge flowing between the two circuits. This is the basis of the operation of a transformer. For more details, see the note on electromagnetism.

2.8 Summary: the most important things to know

- Charge acts like water in the hydraulic analogy: there is a fixed amount of it in a circuit and it moves around the circuit. It's measured in coulombs.
- Voltage acts like pressure in the hydraulic analogue. It's the voltage difference between two points which is important, not any absolute value of voltage. It's measured in volts. It takes one joule of energy to move one coulomb through one volt.
- Current acts like the rate of flow in the hydraulic analogy. It's measured in amps[11]; one amp is one coulomb per second.
- The resistance of a component is the ratio of the potential difference across it to the current flowing through it. For some components (known as resistors) this ratio is constant. Resistance is measured in ohms.
- Capacitors act like barrels with elastic membranes across the middle preventing any charge moving from one side to the other. The capacitance of a capacitor is the ratio of the charge

11

added to one side to the voltage difference across the component; capacitance is measured in farad.

- Inductors act like heavy rotors in the hydraulic analogy. The inductance of an inductor is the ratio of the voltage difference across the inductor to the rate of change of the current flowing through it. Inductance is measured in henries.