Passives | Volume 25

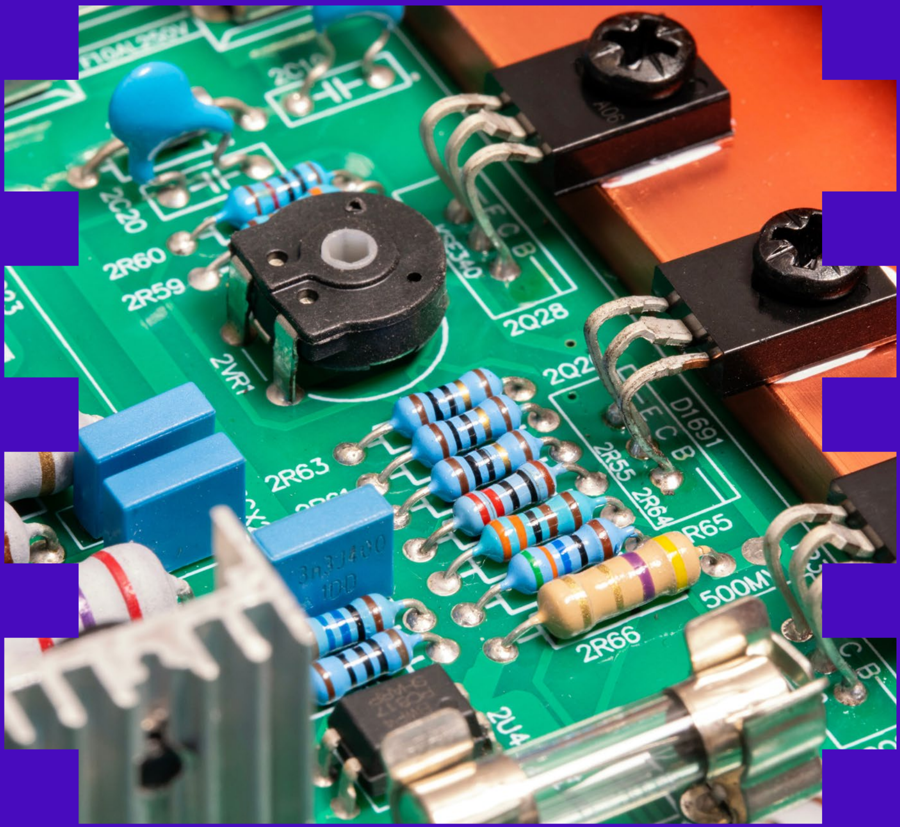
We get technical

Understand crystal oscillator parameters to optimize component selection

Fundamentals: Understand the characteristics of capacitor types to use them appropriately and safely

Use specialized inductors for high-current, fast-transient DC/DC converters

Temperature coefficient of resistance for current sensing



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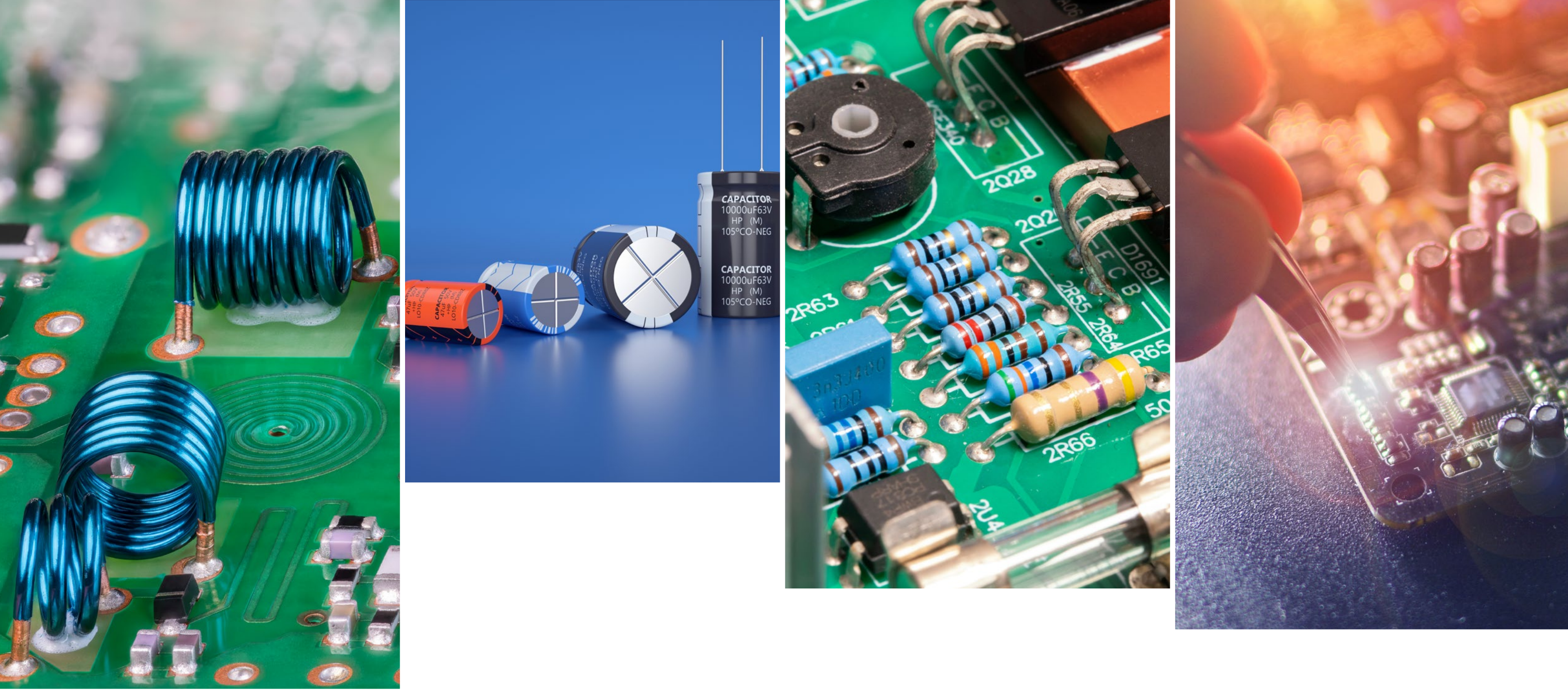

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Editor's note

Welcome to the DigiKey eMagazine Volume 25 – Passives.

This edition will delve into the intricacies and innovations shaping the world of passive components and electronic design.

In this issue, we've compiled a selection of insightful articles that address both foundational principles and advanced application techniques. From understanding inrush current management and temperature sensing with Vishay Ametherm components, to optimizing performance with Wurth Elektronik RF inductors, our features are designed to support engineers in making informed component choices.

We take a closer look at crystal oscillator parameters to help you fine-tune your designs for stability and precision, and offer a deep dive into the characteristics of various capacitor types to ensure safe and effective usage. If you're working with high-current, fast-transient DC/DC converters, our guide to selecting specialized inductors is a must-read.

Additional articles explore critical topics such as temperature coefficient of resistance for accurate current sensing, the nuances of film capacitor selection for power applications, and the benefits of using thin-film resistors in demanding automotive and industrial environments.

Complementing our written features is a newly added video section, where we explore practical and often overlooked phenomena—such as the "Flowers of Sulfur" effect, and how ambient temperature impacts aluminum electrolytic capacitors. Plus, our tutorials on inductors and film capacitors bring clarity to the core concepts every designer should master.

Whether you're a seasoned engineer or an enthusiast seeking to deepen your understanding, this issue offers valuable insights to guide your work and inspire innovation.

A closer look at inrush current protection with thermistor-based solutions

The DNA of tech.®

An MRI machine powers on in preparation for its next scan. In that first moment, the system draws a significant surge of electrical current, known as inrush current. Though it lasts only milliseconds, the spike can far exceed the machine's normal operating current and place stress on sensitive components.

This type of current spike is a concern across many types of electronics. Inrush current limiters (ICLs) help reduce startup surges while allowing systems to operate efficiently once normal current levels are reached.

In this article, we will explore the fundamentals of inrush current, and how Vishay Ametherm's SL Series ICLs provide an effective solution for protecting electrical systems during power-up.

Understanding inrush current

Inrush current is the maximum instantaneous current drawn by a device when it is first powered on. This spike occurs in AC systems that include transformers, rectifiers, and filter capacitors. Because the equivalent series resistance (ESR) of a filter capacitor is very low, the initial current can surge to several times the device's steady-state operating level. Even though the surge may last less than half a 60 Hz cycle, it can still stress diodes, motors, and other sensitive components. The maximum allowable inrush current is often determined by the most vulnerable component in a circuit, such as a fuse, circuit breaker, or bridge rectifier.

Modern electronics are particularly susceptible to inrush current due to their lower overall system impedance and high power density. As devices become more compact and efficient, the combination of low resistance and high-capacitance loads can make these initial spikes more pronounced.

The role of inrush current limiters

Inrush current limiters manage startup surges by temporarily introducing resistance into the circuit. Most ICLs are built on negative temperature coefficient (NTC) thermistor technology, where resistance drops logarithmically as the device heats.

At the moment power is applied, a thermistor offers high resistance, limiting the initial surge of current and protecting downstream components. As current continues to flow through the thermistor, it self-heats. Within milliseconds, its resistance drops significantly, allowing current to pass with minimal loss and render the ICL transparent during steady-state operation.

One important consideration in ICL design is the cool-down period. Once the ICL has self-heated and the system is powered down, the thermistor must return to its original high-resistance state before it can effectively suppress another inrush event. This recovery period typically lasts around one minute depending on the device, ambient temperature, and mounting method.

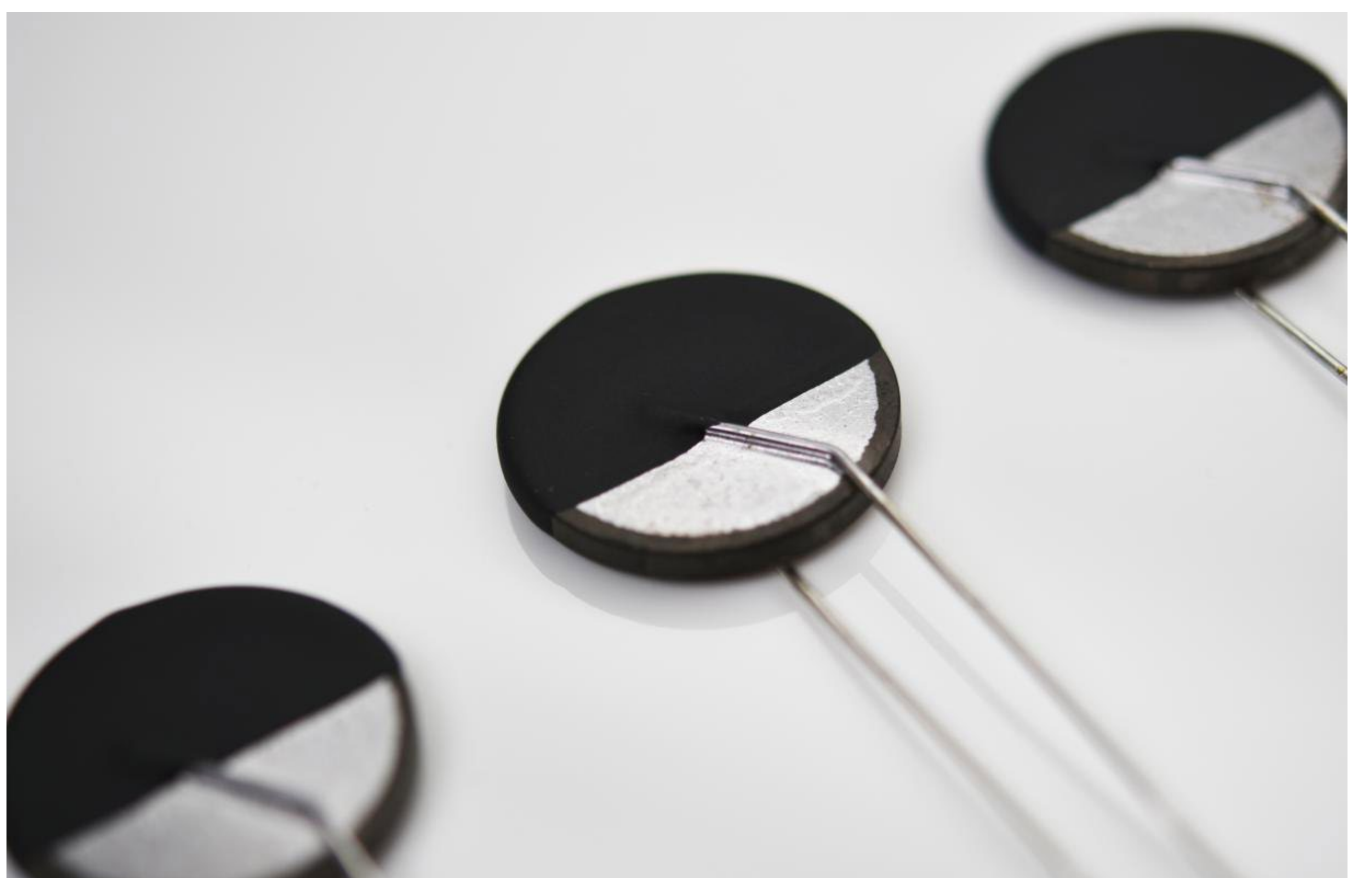
ICLs are typically placed in series with the line voltage of a diode bridge, motor, or other sensitive components. Common applications include power supplies, transformers, audio amplifiers, motor drives, and medical imaging equipment such as MRI, CAT scan, and X-ray machines. By limiting inrush current in these systems, ICLs help extend component life and reduce the potential for premature failure.

Why choose ICLs over active circuits?

Several approaches exist for suppressing inrush current, but thermistor-based limiters are the most widely used. Industry research shows that NTC thermistors account for more than 90% of inrush suppression components used in power supplies.

One reason is cost. In a power supply, a pair of thermistor-based inrush current limiters are relatively inexpensive compared to an active solution, which could require a TRIAC, a resistor, and a driver circuit.

Beyond cost due to an increased component count, active designs require more board space, introducing additional complexity and more potential points of failure. Active circuits generally rely on switching components such as TRIACs or relays, controlled by logic that determines when full current should be applied. While this can provide benefits in certain scenarios, it also increases design time. Thermistor-based ICLs can typically be integrated much faster, with fewer layout and component considerations. From a manufacturing perspective, simpler designs can help reduce assembly steps and lower the risk of defects.



ICLs also behave differently under fault conditions compared to active circuits. As they heat up, their resistance decreases, allowing current to continue flowing. Alternatively, a failed component in an active circuit may require replacement before the system can return to operation.

Active suppression may be preferred in higher-wattage systems or applications with frequent power cycling, since thermistor-based devices require time to cool before they can effectively limit another surge. However, ICLs provide a straightforward solution for most low- to mid-power systems.

Ametherm's SL Series

Vishay Ametherm's SL Series inrush current limiters employ NTC thermistors to handle high startup surges while maintaining a small footprint. The series is UL and CSA recognized and fully RoHS compliant, meeting established safety, performance, and environmental standards.

Ametherm's SL Series ICLs are among the most compact in their class, making them a practical option for systems with limited board space. This suits applications such as switching power supplies, motor drives, and appliance control boards. Use cases span residential, commercial, industrial, healthcare, and renewable energy systems. For example, the SL Series helps limit current surges in electric vehicle chargers when a unit is first connected to the grid. Other applications include HVAC blower motors, audio amplifiers, and inverters.

Temperature sensing with NTC thermistors

The same NTC thermistor technology used in Ametherm's inrush current limiters also forms the basis of its temperature sensing components. These thermistors are available in a range of sizes, shapes, and materials, with many models recognized by UL and rated for high dielectric strength.

Ametherm's temperature sensors are used in electric vehicles, HVAC systems, medical devices, industrial equipment, and automotive electronics. In battery management systems, for instance, they monitor cell temperature to support state-of-charge estimates and help prevent thermal stress.

Conclusion

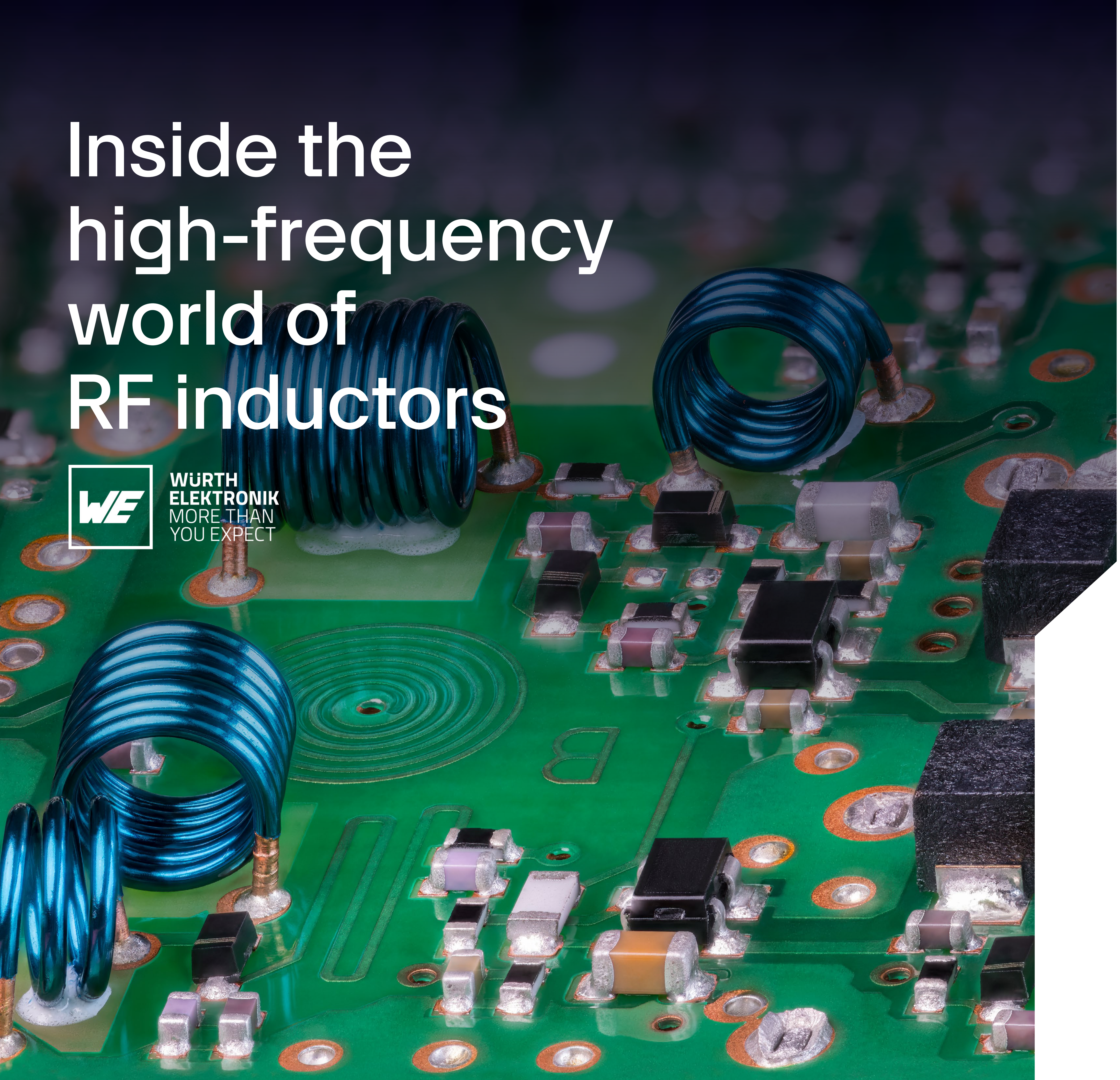
Inrush current may last only a fraction of a second, but it can affect how electrical systems behave at startup and influence the longevity of sensitive components. NTC thermistors provide a practical means to limit these surges and are widely used across a range of applications.

Vishay Ametherm's SL Series inrush current limiters apply this approach through a compact, UL-recognized design. Whether protecting an MRI machine from current spikes at power-up or regulating inrush in industrial devices, these ICLs help engineers build systems that support reliable operation from the moment power is applied.

To learn more, visit SL Series Inrush Current Limiters.

Inside the high-frequency world of RF inductors

WÜRTH ELEKTRONIK
MORE THAN YOU EXPECT



Designing reliable RF circuits has always been a balancing act. Unlike low-frequency or power electronics where current and voltage behave predictably, radio-frequency (RF) systems are uniquely sensitive. Tiny bits of capacitance or resistance—known as parasitics—come into play once signals start racing through a circuit at gigahertz frequencies. The result is signal degradation, unwanted electromagnetic interference (EMI), or circuit behavior that changes once the design is pushed to full operation. And as wireless systems become smaller and more complex, designers have less room to absorb these imperfections.

Inductors form the backbone of many RF building blocks, such as tuning circuits, impedance-matching networks, filters, and high-frequency chokes. They determine how smoothly a signal flows, how cleanly it's filtered, and how stable a circuit remains over time.

Würth Elektronik offers a comprehensive portfolio of RF inductors characterized across broad frequency ranges. By tailoring construction technologies and materials to different application demands, they give engineers options to manage the trade-offs inherent to RF design.

Understanding the properties of RF inductors

At first glance, RF inductors obey the same rules as any inductor: they resist sudden changes in current by storing energy in a magnetic field. However, at high frequencies, that picture starts to break down.

Because every coil of wire has some parasitic capacitance, an inductor naturally resonates at a certain frequency. Below the self-resonant frequency (SRF), the inductor behaves normally. Once it hits SRF though, it flips personalities, i.e., it stops acting like an inductor and starts behaving like a capacitor. Engineers often think of SRF as the inductor's speed limit.

Equally important is the quality factor, or Q, which describes how efficiently the inductor does its job. A higher Q means lower losses and cleaner signals, like a sharply resonant bell versus a dull, quickly muted drum.

Another key parameter is DC resistance. This is the resistance of the wire, or the internal friction that wastes power as heat. Think of it like water flowing through a hose—the smoother the inside, the less friction, the more freely the water (or current) moves.

ESR, or equivalent series resistance, is like a bit of extra drag that shows up when current keeps switching direction. Lower

ESR means fewer signal losses and cleaner performance in high-frequency circuits.

Thermal stability and tolerance also weigh heavily. An inductor that drifts with temperature or varies too much from its nominal value can detune an entire circuit.

Finally, rated current defines how much load an inductor can handle before heating alters its resistance and inductance. Especially in bias networks or RF chokes, overlooking this parameter can destabilize circuits.

Trade-offs in RF inductor design

Choosing RF inductors is far from straightforward; improving one characteristic can sometimes mean compromising another. Thinner wire increases resistance, which lowers Q—but thicker wire may increase size or cost. Tighter spacing increases parasitic capacitance, pulling SRF downward. Every choice—how the inductor is built, where it sits on the board, and what materials it uses—affects how it performs once it is placed in a circuit.

One of the first design choices comes down to construction. Wire-wound inductors use coiled wire around a core and generally offer high Q factors and a wide range of inductance values. Multilayer and thin-film inductors, by contrast, are built directly on ceramic substrates using printed or layered conductors. These compact designs are ideal for space-limited circuits, though they typically trade off some Q and current handling for smaller size.

Even the printed circuit board (PCB) contributes to the equation. The copper pads and traces, known as the land pattern, affect the stray capacitance and inductance around the component. At gigahertz frequencies, that layout can slightly shift the inductor's SRF or change how energy moves through the circuit.

Then there's the matter of core material, which determines how magnetic energy is stored. Ferrite cores offer the highest inductance in the smallest volume, due to their magnetic permeability. However, at very high frequencies they begin to lose efficiency—like a heavy mountain bike that carries more but moves slower uphill.

Air-core designs, which use no magnetic material, deliver the highest Q factor and lowest losses but can only achieve low inductance values. Going back to biking analogies, they're like racing bikes—lightweight and fast, but less suited for carrying heavy loads.

Ceramic cores sit between the two, providing mechanical stability and low losses across a wide frequency range—like a balanced hybrid bike that's stable and efficient.

The art of RF inductor design lies in managing these interactions so that every component plays in tune with the rest of the system.

Inside Würth's RF inductor portfolio

Because no single inductor design suits every RF circuit, Würth Elektronik's RF inductor portfolio covers a range of construction types and material technologies, each developed for specific frequency and current requirements. Together, these series give engineers options to select components that fit both electrical and mechanical constraints.

Wire-Wound ceramic – WE-KI and WE-KI HC

The WE-KI family is designed for circuits that need a combination of high Q, low DC resistance, and broad frequency range. With SRFs reaching roughly 12.5 GHz, these inductors perform well in filters, oscillators, and impedance-matching networks. The WE-KI HC version uses thicker wire to carry higher current and achieve slightly better Q performance in the same footprint.

Wire-Wound Ferrite – WE-RFI and WE-RFH

The WE-RFI and WE-RFH series offer higher inductance values in smaller packages. They are often used in bias networks, DC-DC converters, and lower-frequency filters that require higher current handling. At higher frequencies, however, their ferrite materials introduce additional losses, which limit their usable range to roughly 500 MHz. The WE-RFH variant is designed with thicker wire to support higher rated currents.

Air-Core – WE-CAIR and WE-ACHC

Air-core designs such as the WE-CAIR series yield very high Q factors and minimal DC resistance. These characteristics help them maintain low loss in high-frequency applications such as resonant circuits, antenna matching, and RF amplifiers. The WE-AC HC variant, built with flat wire, supports currents up to about 40 A for higher-power RF designs.

Multilayer ceramic – WE-MK

The multilayer WE-MK series targets compact systems such as mobile and IoT devices. Their stacked-layer construction allows very small package sizes and high SRFs above 17 GHz, while maintaining stable inductance over temperature. These inductors are typically chosen for impedance matching or high-frequency noise suppression in space-limited layouts.

Thin-film – WE-TCI

The WE-TCI series uses a thin-film photolithographic process to achieve precise geometries and tight inductance tolerances, down to 1 – 2%. They maintain high SRF values and are suited for small, high-frequency circuits such as RF filters or matching networks.

Tools and design support

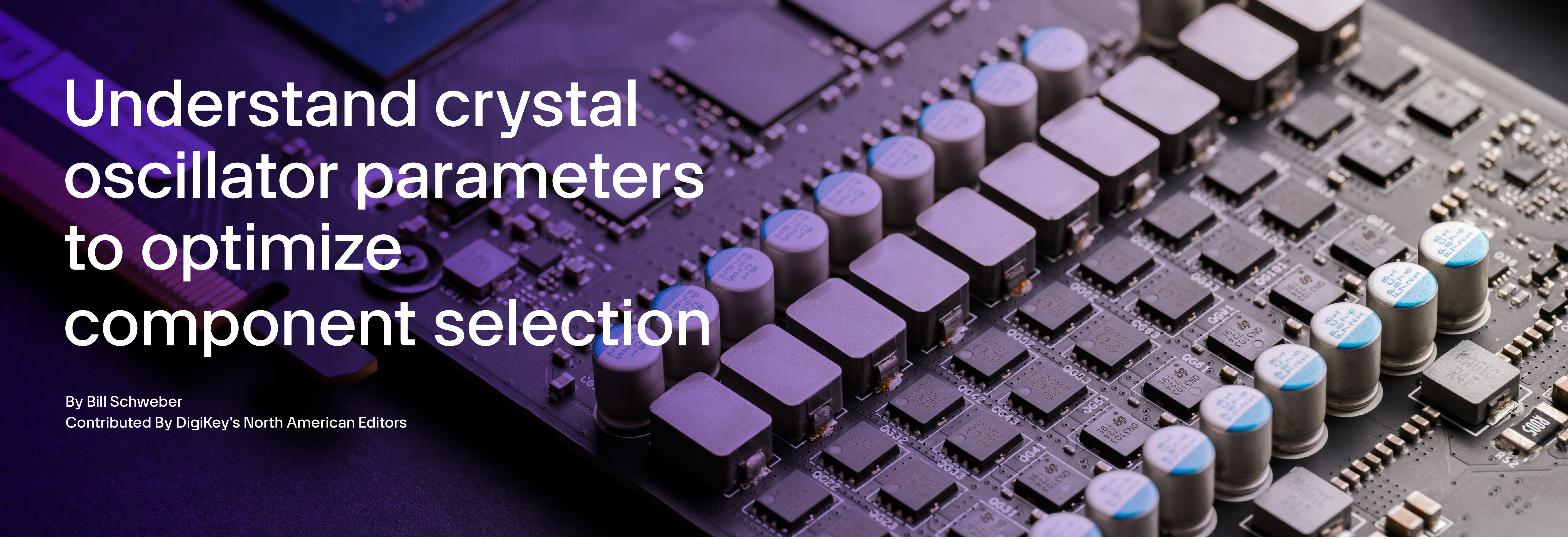
Selecting the right inductor for an RF circuit depends not only on the component but also on how accurately it's modeled during design. Würth Elektronik provides several resources to help engineers predict circuit behavior under realistic conditions.

Each RF inductor series includes measured S-parameters, allowing engineers to analyze impedance and circuit performance across frequency. For more detailed modeling, Würth offers Modelithics models, which account for substrate effects such as PCB material and thickness. These models make it possible to simulate real-world parasitic behavior with greater accuracy.

For broader comparison, the company's REDEXPERT online tool provides a searchable interface to evaluate parameters such as Q factor, DC resistance, and SRF under different operating conditions. The platform also allows engineers to compare series side by side to identify the part that best fits a given frequency range or current level.

Beyond these digital tools, Würth maintains detailed datasheets and supports custom requests for nonstandard or tight-tolerance designs. Collectively, these resources help engineers integrate components while reducing design iterations and shortening development time. In doing so, Würth Elektronik supports engineers not just as a supplier, but as a design partner in achieving reliable RF performance.

To learn more, visit Würth Electronik RF Inductors



Understand crystal oscillator parameters to optimize component selection

By Bill Schweber
Contributed By DigiKey's North American Editors

Quartz-based crystal oscillators are the core component responsible for frequency/timing accuracy and performance in nearly all electronic circuits. As such, they are required to be accurate and precise over time. Of course, the "perfect" oscillator only exists in theory, so the problem for designers is the right oscillator to meet the design objectives. This is not an easy task.

Once the performance requirements have been determined for the application, designers need to find the solution with the right balance of performance, cost, stability, size, power, physical structure and drive capabilities for the associated circuitry. To do so, they need to understand oscillator operating principles, key characteristics, and how they have evolved.

This article will provide an overview of crystal oscillator basics before looking at various perspectives related to high-performance crystal oscillator modules. Then, using representative devices from ECS Inc., it will briefly review the basics of these oscillators before identifying the top and second-tier parameters, along with some realistic values for these parameters. It will also show how different units are matched to the need of some typical applications.

How crystal oscillators work

Crystal oscillators provide the clock heartbeat for processors, bit timing for data links, sampling time for data conversions, and the master frequency in tuners and synthesizers. In simplified terms, the quartz element of the crystal oscillator acts as an extremely high-Q resonant element within the feedback network of an oscillator circuit (Figure 1). Due to the importance of crystals and their oscillators, the fundamental physics of the quartz material as well as its electrical and mechanical performance, along with the various oscillator circuits, have been researched and analyzed extensively.

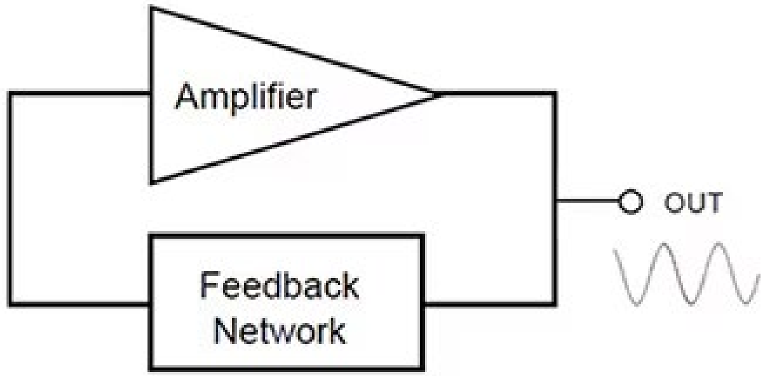


Figure 1: Employing the piezoelectric effect, a crystal functions as a high-Q, stable, and precise resonant element in the feedback loop of an oscillator circuit. (Image source: ECS Inc. International, modified)

For many years, users would specify the crystal's frequency and other key characteristics, then provide their own separate oscillator circuit using vacuum tubes (in the early days), then transistors, and finally ICs. This circuit was usually a combination of careful design analysis as well as some "art" and experience-based judgement, as there were many interrelated subtleties. The designer would attempt to balance these factors to match the oscillator performance to the quartz crystal "cut" and characteristics, as well as the application priorities.

Nowadays, such do-it-yourself (DIY) crystal oscillator design efforts are relatively rare because it takes time and effort to get the initial design right. Then there's the accurate measurement of the performance of an oscillator. This is complex and requires precision instrumentation and a careful setup. Instead, for many applications, designers can purchase a tiny, fully enclosed module which includes both the quartz element as well as the oscillator circuit and its output driver. This obviously reduces the design effort and time, while the user gets a fully characterized unit and a datasheet with guaranteed specifications.

A note about terminology: For historical and other reasons, engineers often use the word "crystal" when then are really talking about the entire crystal oscillator circuit. This is normally not a problem as the intended meaning is understood from the context. However, it can sometimes lead to confusion, as it is still possible to purchase a crystal as a standalone component and then provide separate oscillator circuitry. This article uses the word "oscillator" to refer to the crystal plus its oscillator circuitry as a self-contained module rather than just the oscillator circuit alone.

Characterizing crystal oscillators

As with any component, the crystal oscillator's performance is initially defined by a set of top-tier parameters. In their general order of importance are:

Operating frequency: This can range from tens of kilohertz (kHz) to hundreds of megahertz (MHz). Oscillators for frequencies above the basic reach of an oscillator, such as into the gigahertz (GHz) range, usually use a phase-lock loop (PLL) as a frequency multiplier to upconvert the fundamental frequency.

Frequency stability: This is the second key performance factor for oscillators. It defines the deviation of output frequency from its original value due to external conditions, and so the smaller this number, the better.

There are many external conditions which affect stability, and many vendors call them out individually so the designer can assess the actual impact in the applications. Among these factors are temperature-related variation with respect to nominal frequency at 25°C; other factors include long-term stability due to aging as well as effects of soldering, supply voltage variations, and output load changes. For high-performance units, it is usually characterized in parts per million (ppm) or parts per billion (ppb), with respect to the nominal output frequency.

Phase noise and jitter: These are two perspectives on the same general class of performance. Phase noise characterizes clock noise in the frequency domain, while jitter does so in the time domain (Figure 2).

Depending on the application, the designer will be focused on errors primarily as defined in one domain or the other. Phase noise is usually defined

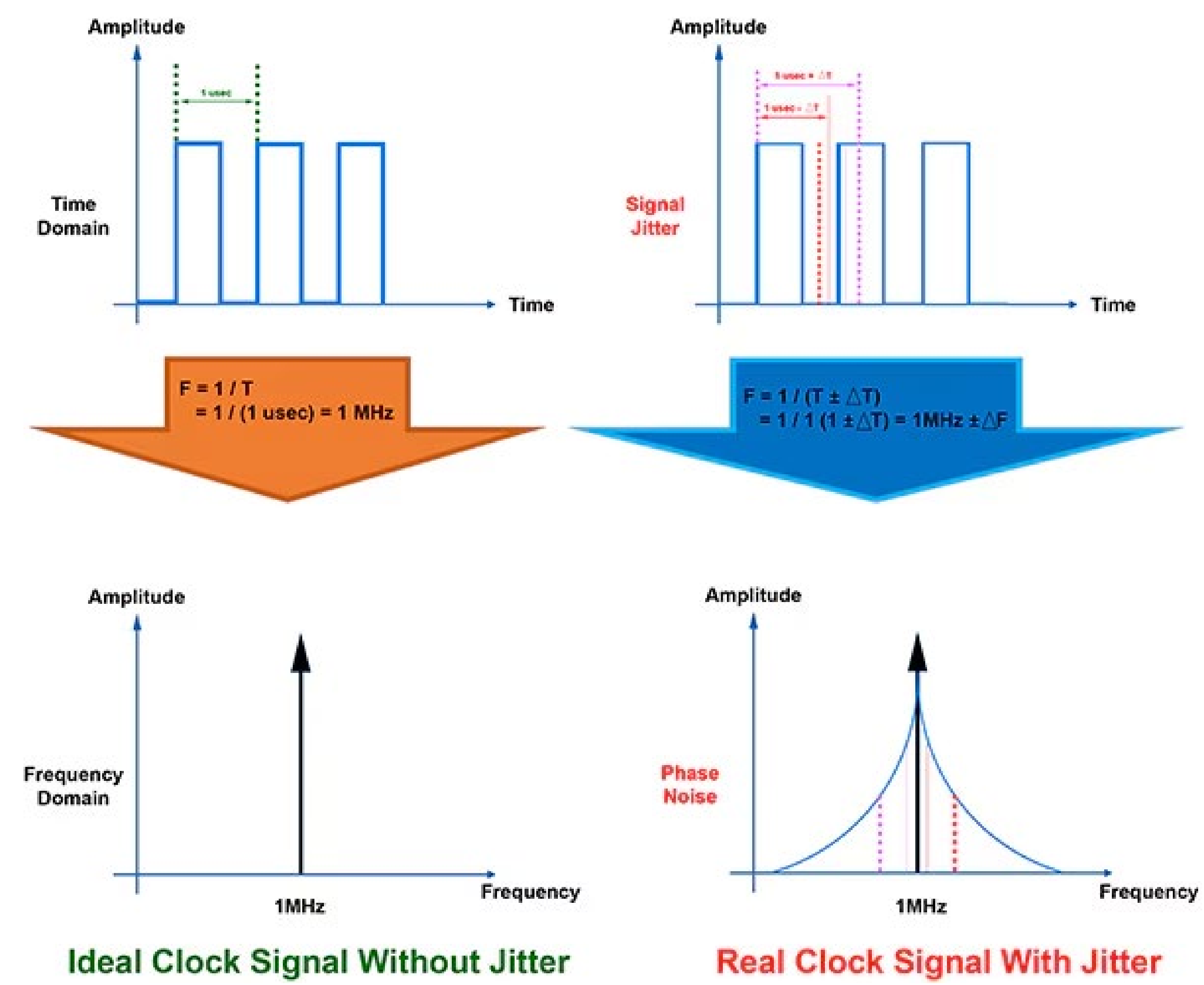


Figure 2: Jitter in the time domain and phase noise in the frequency domain are two equally valid interpretations of the same imperfections. The preferred view is a function of the application. (Image source: ECS Inc. International)

as the ratio of the noise in a 1 Hertz (Hz) bandwidth at a specified frequency offset, $_{fm}$, to the oscillator signal amplitude at frequency f_o. Phase noise degrades accuracy, resolution, and the signal-to-noise ratio (SNR) in frequency synthesizers (Figure 3), while jitter causes timing errors and thus, contributes to increased bit error rate (BER) in data links.

Timing jitter causes sampling-time errors in analog/digital conversions and thus, also affects the SNR and subsequent fast Fourier transform (FFT) frequency analysis.

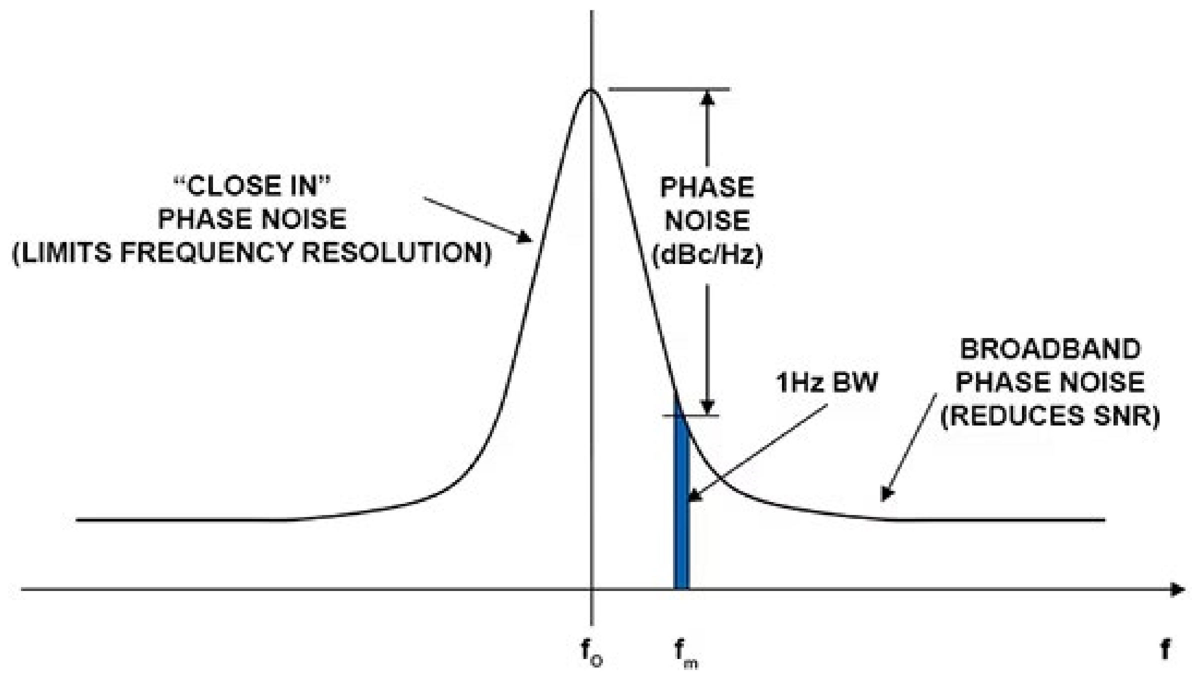


Figure 3: Phase noise spreads the power spectrum of the oscillator and has a detrimental effect on resolution and SNR. (Image source: ECS Inc. International)

Devices in the MultiVolt family of standard oscillators (MV) from ECS Inc. are available with stabilities as low as ±20 ppm, while their tight stability oscillators (SMV) offer stabilities down to ±5 ppm. For even tighter stability, the MultiVolt TCXOs offer ±2.5 ppm performance with HCMOS outputs and ±0.5 ppm for clipped sine wave outputs (both TCXOs and clipped sine waves are explained further below).

Regardless of domain, phase noise/jitter is an important factor for high-performance designs and must be taken into account in the error budget while keeping the needs of the application in mind. Note that there are many types of jitter, including absolute jitter, cycle-to-cycle jitter, integrated phase jitter, long-term jitter, and period jitter; for phase noise there are different integration ranges and types as well, including white noise and various noise "colors".

Understanding the specifics of both jitter and phase noise at the oscillator and the impact in the application can often be a challenge. It is difficult to convert a specification from one domain to the other; instead, users should look to the datasheet. It's also important to understand the legitimate, yet different vendor definitions quantifying performance when accounting for these errors in the overall error budget.

Output signal type and drive: These must be matched to the connected load (Figure 4). The two output drive topologies are single-ended and differential.

Single-ended oscillators are easier to implement but have more sensitivity to noise and are typically a better fit only up to several hundred megahertz.

Among the single-ended output types are:

- TTL (transistor-to-transistor logic): 0.4 to 2.4 volts (rarely used now)
- CMOS (complementary metal oxide semiconductor): 0.5 to 4.5 volts
- HCMOS (high-speed CMOS): 0.5 to 4.5 volts
- LVCMOS (low-voltage CMOS): 0.5 to 4.5 volts

Differential outputs are more difficult to design but provide better performance in high-frequency applications, as any noise common to the differential traces cancels out. This helps maintain oscillator performance as seen by the load circuit. Differential signal types are:

- PECL (positive emitter coupled logic): 3.3 to 4.0 volts
- LVPECL (low-voltage PECL); 1.7 to 2.4 volts
- CML (current-mode logic): 0.4 to 1.2 volts and 2.6 to 3.3 volts
- LVDS (low-voltage differential signaling): 1.0 to 1.4 volts
- HCSL (high-speed current-steering logic): 0.0 to 0.75 volts

The choice of signal type is determined by the application priorities and associated circuitry.

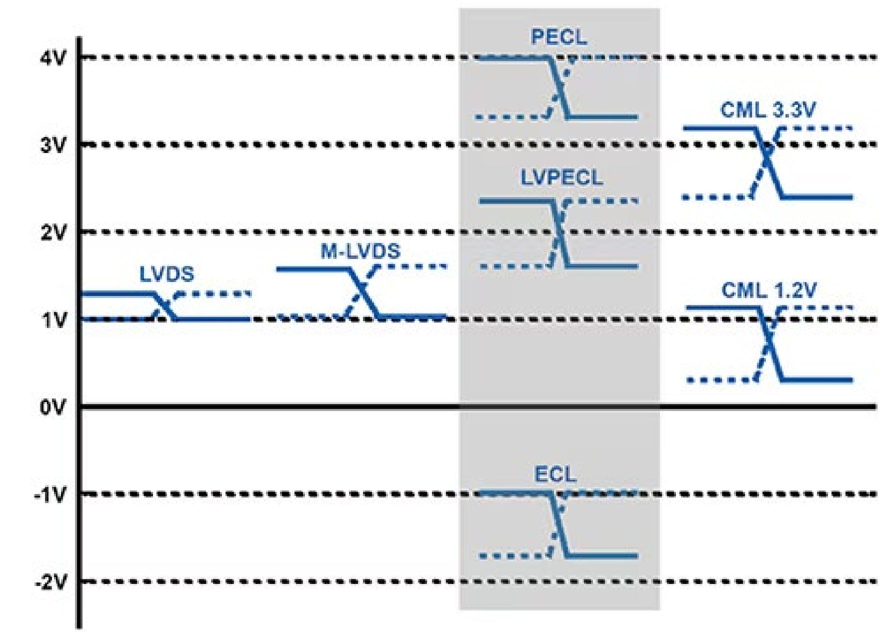


Figure 4: Different output formats are available and must be compatible with the oscillator load configuration. (Image source: ECS Inc. International)

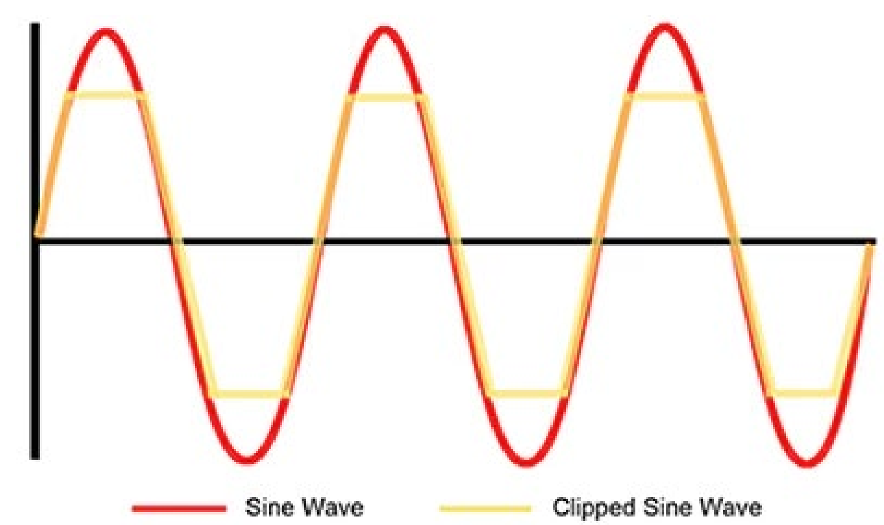


Figure 5: The clipped sine wave approximates a square wave while minimizing any additional jitter or phase noise. (Image source: ECS Inc. International)

The oscillator output waveform can be a classic single-frequency sine wave or a clipped sine wave (Figure 5). The analog wave is the "cleanest" and least subject to jitter/phase noise, versus using a comparator circuit to transform it into a square wave, as doing so adds jitter/phase noise and thus, degrades it. The clipped sine wave creates a square wave-like output that is compatible with digital loads without sacrificing any of the performance.

Supply voltage and current: These have both decreased to meet the needs of today's lower voltage and often battery-powered systems. Most MultiVolt series oscillators can operate with supply voltages of 1.8 volts, 2.5 volts, 3.0 volts, and 3.3 volts.

Package size: Just as with operating voltage and current, oscillator packages have also gotten smaller. The industry has some standardized sizes for single-ended devices (which only need four connections), while differential oscillators have six contacts and use the larger packages, with dimensions given here in millimeters (mm):

1612: 1.6 mm × 1.2 mm

2016: 2.0 mm × 1.6 mm

2520: 2.5 mm × 2.0 mm

3225: 3.2 mm × 2.5 mm

5032: 5.0 mm × 3.2 mm

7050: 7.0 mm × 5.0 mm

It's largely about temperature

The largest external factor affecting and shifting oscillator performance is temperature. Even if the oscillator operating power is low and thus, self-heating is almost negligible, the ambient temperature affects operating frequency as those changes affect mechanical dimensions and stresses of the quartz crystal. It's important to check the performance of the selected oscillator at the extremes of the expected ranges. These ranges are commonly described as:

- Commercial, Automotive Grade 4: 0 to +70°C
- Extended Commercial: −20 to +70°C
- Industrial, Automotive Grade 3: −40 to +85°C
- Extended Industrial, Automotive Grade 2: −40 to +105°C
- Automotive Grade 1: −40 to +125°C
- Military: −55 to +125°C
- Automotive Grade 0: −40 to +150°C

For some designs, it's not just performance over temperature that is a consideration but also the need to meet other reliability specifications. The ECS-2016MVQ, for example, is a miniature surface-mount MultiVolt HCMOS-output oscillator for 1.7 to 3.6 volts operation (Figure 6). The 2016 (2.0 mm × 1.6 mm, per above) ceramic package measures 0.85 mm high, targets harsher industrial applications, and is AEC-Q200 Qualified (Automotive) for Grade 1 temperature requirements. It is available for frequencies ranging from 1.5 to 54 MHz in four grades of frequency stability, from ±20 ppm to ±100 ppm over -40°C to +85°C; phase jitter is very low at just 1 picosecond (ps), measured from 12 kHz to 5 MHz.

For applications where drift over the operating range is unacceptably high, two advanced oscillator implementations are available: the temperature-compensated crystal oscillator (TCXO) and the oven-controlled crystal oscillator (OCXO). (Note that XTAL is the designation for crystal on many schematics, and "X" is used as an abbreviation for that in the acronym.) A TCXO uses an active circuit to compensate for the change in output frequency due to temperature variation. In contrast, in the OCXO, the crystal oscillator is placed in a thermally insulated oven that is heated and maintained at a constant temperature above maximum ambient temperature (a heating-only oven cannot cool to below ambient).

TCXOs require additional circuitry compared to a basic oscillator but far less power than the OCXO with its oven, which typically requires several watts. In addition, the TCXO is only slightly larger than an uncompensated unit and is much smaller than an OCXO. A TCXO will typically show an improvement in drift between 10 and 40 times that of an uncompensated unit, while an OXCO may show drift performance which is two orders of magnitude improvement in comparison, but with a significant penalty in size and power.

The ECS-TXO-32CSMV is a clipped-sine-wave surface-mount TCXO with MultiVolt capability (1.7 to 3.465 volts supply) for frequencies between 10 and 52 MHz (Figure 7). The 3.2 × 2.5 × 1.2 mm high ceramic package is well-suited to portable and wireless applications where stability is critical. The key specifications show its extremely high stability versus temperature, supply change, load change, and aging along with its modest current requirement of under 2 mA (Table 1).

Figure 6: The ECS-2016MVQ is available for frequencies from 1.5 to 54 MHz and in four grades of stability from ±20 ppm to ±100 ppm.(Image source: ECS Inc. International)

Figure 7: The ECS-TXO-32CSMV is a clipped sine-wave output crystal oscillator that incorporates internal compensation circuitry to greatly improve stability performance. (Image source: ECS Inc. International)

Parameters	Conditions	ECS-TXO-32CSMV MIN	TYP	MAX	Units
Frequency Range		10.000		52.000	MHz
Frequency Tolerance	@ +25°C ±2°C			±2.0	PPM
Frequency Stability	Vs. Temp (-40 ~ +85°C) BN Opt			±1.0	PPM
	Vs. Supply Change (±5%)			±0.2	PPM
	Vs. Load Change (±10%)			±0.2	PPM
	Vs. Aging 1st Year			±1.0	PPM
Input Voltage	VDD	+1.7		+3.465	VDC
Current Consumption	10 ~ 26 MHz			2.0	mA
	26.1 ~ 52 MHz			2.5	mA
Output Level	Clipped Sine Wave	0.8			V p-p
Output Load		10KΩ//10 pF			
Start-up Time				2	mS
Phase Noise	@ 10 KHz Offset		-145		dBc/Hz
Operating Temperature	* N Option	-40		+85	°C
Storage Temperature		-40		+90	°C

Table 1: The specifications of the temperature-compensated ECS-TXO-32CSMV TXCO show how its internal compensation improves stability performance despite a set of external disturbances. (Image source: ECS Inc. International)

Low-power operation: often a priority

Despite the trends towards ever-higher frequency processor clocks and data rates, there is still a large need for lower frequency crystal oscillators for timing in extreme low-power applications. For example, the ECS-327MVATX is a miniature surface-mount oscillator operating at a fixed frequency of 32.768 kHz with MultiVolt capability (1.6 to 3.6 volts). With its current requirement of just 200 microamps (µA) and single-ended CMOS output, it's a good fit for real-time clock (RTC), low-power/portable, industrial, and Internet of Things (IoT) applications. It is offered in 2016 through 7050 package sizes, with frequency stability ranging from a tight ±20 ppm to a somewhat-looser ±100 ppm over the temperature range -40°C to +85°C, depending on model.

To minimize average power consumption, many oscillators also offer an enable/disable function. For example, the ECS-5032MV is a 125 MHz surface-mount oscillator with MultiVolt operating capability from 1.6 to 3.6 volts and CMOS output, offered in a 5032 ceramic package (Figure 8).

Figure 8: The ECS-5032MV is a 125 MHz surface-mount oscillator with an enable/disable function that can help save power. (Image source: ECS Inc. International)

One of its four contacts allows the oscillator to be put into standby mode, reducing required current from the 35 mA active value to only 10 microamperes (µA) standby current. Start-up time is 5 milliseconds (ms) after re-enabling the unit.

Matching specifications to the application

Deciding on a suitable crystal oscillator for an application is, as expected, a balance of specifications, priorities, cost, and their relative weighting.

It's more than the obvious consideration of selecting a unit with the required nominal frequency, frequency stability, jitter/phase noise, and other attributes as a standalone oscillator. Users must also ensure that the output drive of the oscillator is compatible with the associated load and system so that the pairing will not degrade performance. While there are many such considerations, there are some general guidelines:

- An LVDS output requires only a single resistor at the receiver, whereas LVPECL requires termination at both transmitter and receiver.
- LVDS, LVPECL and HCSL have faster transitions than CMOS but will require more power and are best suited for high-frequency designs.
- For lowest power consumption above 150 MHz, CMOS or LVDS are the best choices.
- LVPECL, LVDS, and then CMOS offer the best jitter performance at lower frequencies.

Conclusion

The quartz crystal oscillator is at the heart of many circuits and systems. Ensuring that the performance of this function matches the application requirements requires careful balancing among key parameters, beginning with nominal frequency accuracy, stability versus temperature, and other factors such as jitter and phase noise. It also requires matching the oscillator's output drive format to the characteristics of the load circuitry. Crystal oscillators in the ECS MultiVolt families offer superior performance with combinations of specifications in complete, easy-to-use modules.

Fundamentals: Understand the characteristics of capacitor types to use them appropriately and safely

By Art Pini
Contributed By DigiKey's North American Editors

Capacitors are energy storage devices that are essential to both analog and digital electronic circuits. They are used in timing, for waveform creation and shaping, blocking direct current, and coupling of alternating current signals, filtering and smoothing, and of course, energy storage. Due to the wide range of uses, an abundance of capacitor types has emerged using a variety of plate materials, insulating dielectrics, and physical forms. Each of these capacitor types are intended for a specific range of applications. The wide variety of options means it can take time to sort through them all to find the optimum choice for a design in terms of performance characteristics, reliability, lifespan, stability, and cost.

A knowledge of the characteristics of each capacitor type is required in order to properly match the capacitor to the intended circuit application. This knowledge must cover the electrical, physical, and economic characteristics of capacitors.

This article will describe the various types of capacitors, their characteristics, and the key criteria for their selection. Examples from Murata Electronics, KEMET, Cornell Dubilier Electronics, Panasonic Electronics Corporation, and AVX Corporation will be used to illustrate key differences and attributes.

What is a capacitor?

The capacitor is an electronic device that stores energy in an internal electric field. It is a basic passive electronic component along with resistors and inductors. All capacitors consist of the same basic structure, two conducting plates separated by an insulator, called the dielectric, that can be polarized with the application of an electric field (Figure 1). Capacitance is proportional to the plate area, A, and inversely proportional to the distance between the plates, d.

The first capacitor was the Leyden jar, developed in 1745. It comprised a glass jar lined with metal foil on the inner and outer surfaces and was originally used to stored static electric charges. Benjamin Franklin used one to prove that lightning was electricity, which became one of the earliest recorded applications.

The capacitance of the basic parallel plate capacitor can be calculated using Equation 1:

Equation 1

$$C = \varepsilon * \frac{A}{d}$$

Where:

C is the capacitance in Farads

A is the plate area in square meters

d is the distance between the plates in meters

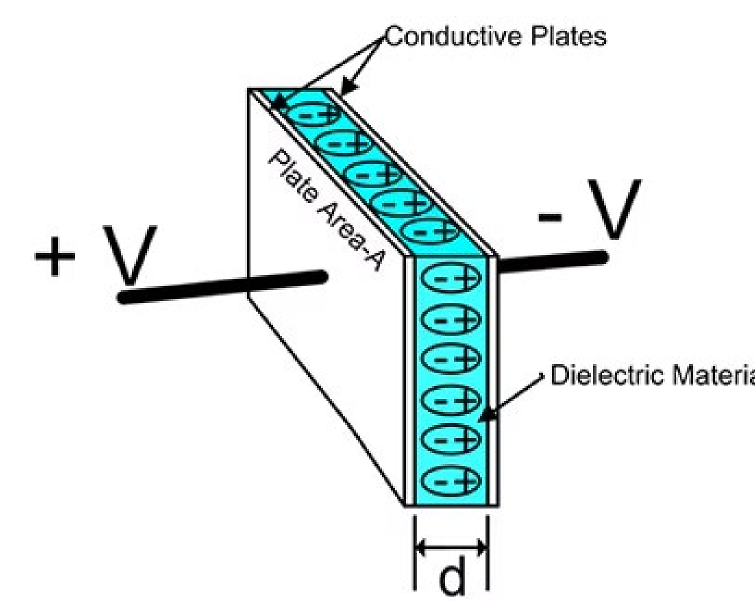


Figure 1: The basic capacitor consists of two conducting plates separated by a non-conducting dielectric which stores energy as polarized regions in the electric field between the two plates. (Image source: DigiKey)

ε is the permittivity of the dielectric material

ε is equal to the relative permittivity of the dielectric, ε_r, multiplied by the permittivity of a vacuum, ε_0. The relative permittivity, ε_r, is often referred to as the dielectric constant, k.

Based on Equation 1, capacitance is directly proportional to the dielectric constant and plate area, and inversely proportional to the distance between the plates. To increase capacitance, the area of the plates can be increased and the distance between the plates can be decreased. Since the relative permittivity of a vacuum is 1, and all dielectrics have a relative permittivity greater than 1, inserting a dielectric will also increase the capacitance of a capacitor. Capacitors are generally referred to by the type of dielectric material used (Table 1).

Some notes on the column entries:

- The relative permittivity or dielectric constant of a capacitor affects the maximum value of capacitance achievable for a given plate area and dielectric thickness.
- The dielectric strength is a rating of the dielectric's resistance to voltage breakdown as a function of its thickness.
- The minimum achievable dielectric thickness affects the maximum capacitance that can be realized, as well as the capacitor's breakdown voltage.

Capacitor Type	Dielectric	Relative permittivity	Dielectric strength (V/µm)	Minimum dielectric thickness (µm)	Typical range of values (µF)	Dissipation factor X 10^{-4}	Notes
Ceramic Class 1	Paraelectric (titanium dioxide)	12-90	<100	1	10^{-6} to 1	10 @1 MHz	Typical parts NPO, P100, N33
Ceramic Class 2	Ferroelectric (barium titanate)	200-14,000	<35	0.5	10^{-6} to 1	251 @1 MHz	Typical parts X7R, X5R, T5V
Film	Polypropylene (PP)	2.2	650/450	1.9 to 3.1	10^{-4} to 102	2-25 @100 kHz	
Film	Polyethylene terephthalate (PET)	3.3	470/220	0.7 to 0.9	10^{-4} to 10	170-300 @100 kHz	Aka: polyester or mylar
Film	Polyphenylene sulfide (PPS)	3.0	470/220	1.2	10^{-3} to 10	12-60 @100 kHz	
Film	Polyethylene naphthalate (PEN)	3.0	500/300	0.9 to 1.4	10^{-3} to 1	120-300 @100 kHz	
Film	Polytetrafluoroethylene (PTFE)	2.0	450/250	5.5	10^{-3} to 1	100 @100 kHz	Aka: teflon
Paper	Waxed paper	3.5-6.0	60	5 to 10	10^{-3} to 1	628 @1 MHz	
Aluminum electrolytic	Aluminum oxide	9.6	710	<0.01 (6.3 volt) <0.8 (450 volt)	1 to 47,000	100 @120 Hz	Polarized
Tantalum electrolytic	Tantalum pentoxide	26	625	<0.01 (6.3 volt) <0.08 (450 volt)	1 to 100	600 @120 Hz	Polarized
Niobium electrolytic	Niobium pentoxide	42	455	<0.01 (6.3 volt) <0.1 (40 volt)	10 to 1000	600 @120 Hz	Polarized
Glass	Glass	3.7-10	450	- - -	10^{-6} to 3 10^{-3}	10 @1 kHz	
Mica	Mica	5-8	118	4 to 50	10^{-6} to 3 10^{-3}	4 @1 MHz	

Table 1: Characteristics of common capacitor types, sorted by dielectric material. (Table source: DigiKey)

Capacitor construction

Capacitors are available in a variety of physical mounting configurations, including axial, radial, and surface mount (Figure 2).

The axial construction is based on alternate layers of metal foil and dielectric, or a dielectric metalized on both sides rolled into a cylindrical shape. Connections to the conducting plates can be via an inserted tab or a circular conducting end cap.

The radial type usually consists of alternating metal and dielectric layers. Metal layers are bridged at the ends. Radial and axial configurations are intended for through-hole mounting.

Surface mount capacitors also rely on alternate conducting and dielectric layers. The metal layers at each end are bridged by a solder cap for surface mounting.

Capacitor circuit model

The circuit model for a capacitor includes all three passive circuit elements (Figure 3).

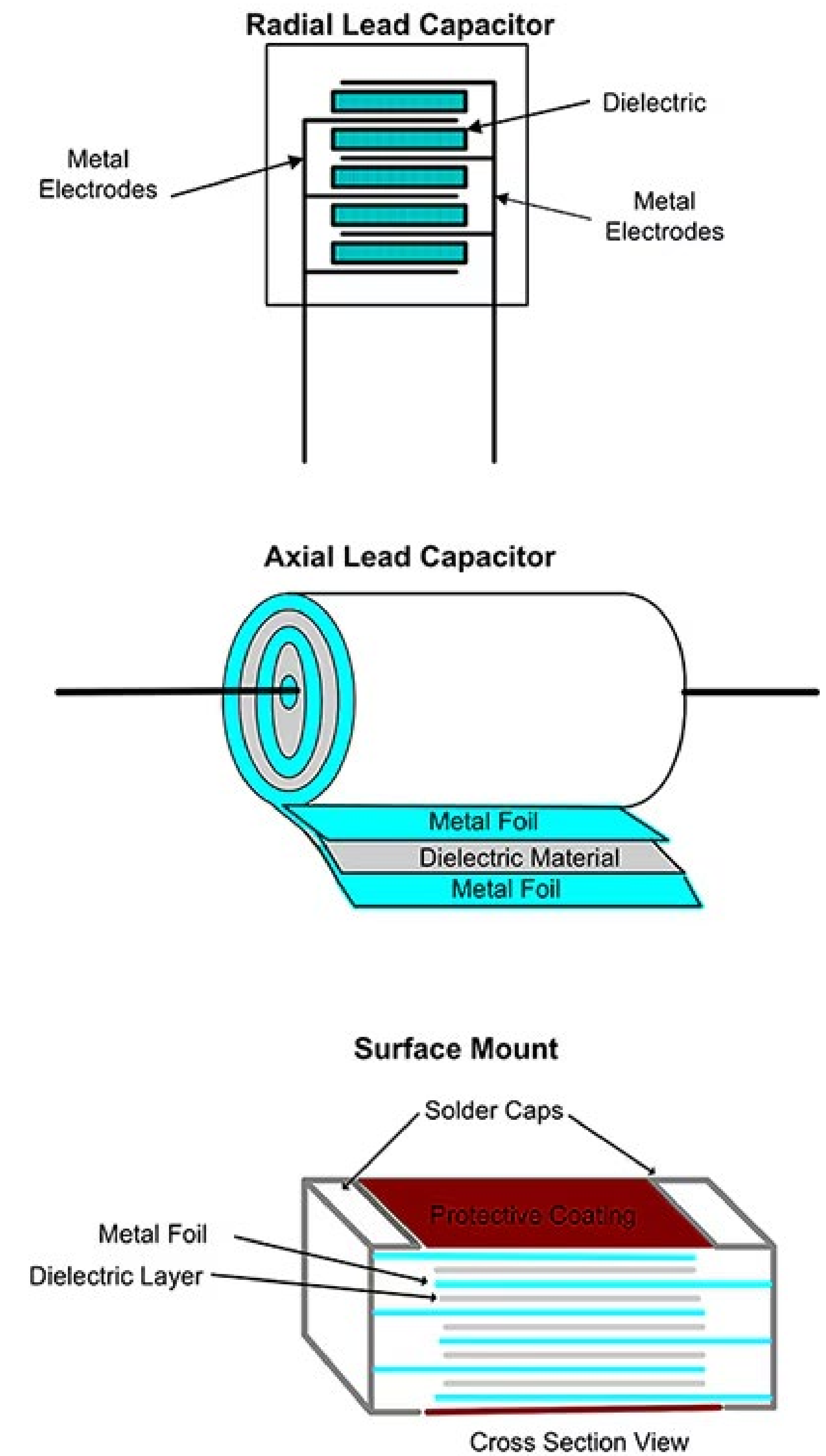


Figure 2: Capacitor mounting, or configuration types include axial, radial, and surface mount. Surface mount is very widely used at this time. (Image source: DigiKey)

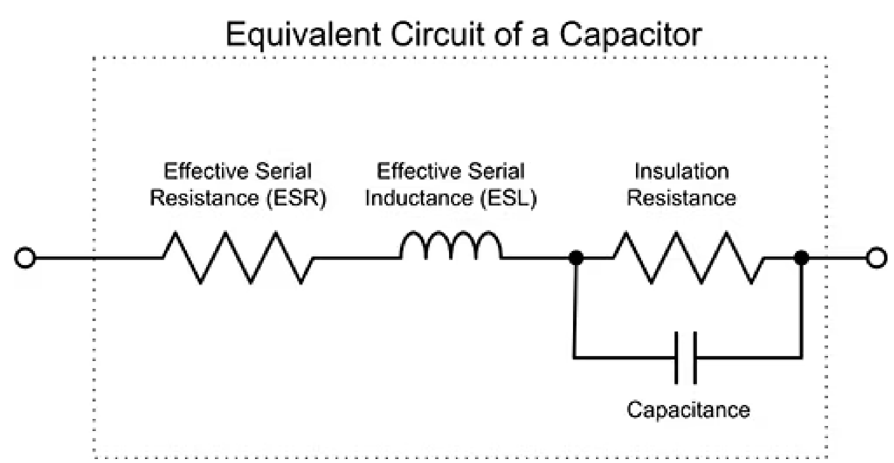


Figure 3: The circuit model for a capacitor consists of the capacitive, inductive, and resistive elements. (Image source: DigiKey)

The circuit model of a capacitor consists of a series resistive element representing the ohmic resistance of the conducting elements along with the dielectric resistance. This is called the equivalent, or effective, series resistance (ESR).

The dielectric effects occur when AC signals are applied to the capacitor. AC voltages cause the polarization of the dielectric to change on every cycle, causing internal heating. The dielectric heating is a function of the material and is measured as the dissipation factor of the dielectric. The dissipation factor (DF) is a function of the capacitor's capacitance and ESR, and can be calculated using Equation 2:

Equation 2

$$DF = \frac{ESR}{|X_C|}$$

Where:

X_C is the capacitive reactance in ohms (Ω)

ESR is the equivalent series resistance (in Ω)

The dissipation factor is frequency dependent due to the capacitive reactance term and is dimensionless, often expressed as a percentage. A lower dissipation factor results in less heating and therefore lower loss.

There is a series inductive element, called the effective or equivalent series inductance (ESL). This represents lead and conductive path inductance. The series inductance and capacitance give rise to a series resonance. Below the series resonant frequency, the device exhibits primarily capacitive behavior, above it, the device is more inductive. This series inductance can be problematic in many high-frequency applications. Suppliers minimize inductance by using the layered construction shown in the radial and surface mount component configurations.

The parallel resistance represents the insulation resistance of the dielectric. The values of the various model components are dependent upon the capacitor configuration and the materials selected for its construction.

Ceramic capacitors

These capacitors use a ceramic dielectric. There are two classes of ceramic capacitors, Class 1 and Class 2. Class 1 is based on para-electric ceramics like titanium dioxide. Ceramic capacitors in this class have a high level of stability, good temperature coefficient of capacitance, and low loss. Due to their inherent accuracy, they are used in oscillators, filters, and other RF applications.

Class 2 ceramic capacitors use a ceramic dielectric based on ferro-electric materials like barium titanate. Due to the high dielectric constant of these materials, the Class 2 ceramic capacitors offer a higher capacitance per unit volume but have lower accuracy and stability than Class 1 capacitors. They are used for bypass and coupling applications where the absolute value of capacitance is not critical.

Murata Electronics' GCM1885C2A101JA16 is an example of a ceramic capacitor (Figure 4). The Class 1 100 picoFarad (pF) capacitor has 5% tolerance, is rated at 100 volts, and comes in a surface mount configuration. This capacitor is intended for automotive use with a temperature rating of -55° to +125° C.

Figure 4: The GCM1885C2A101JA16 is a Class 1, 100 pF ceramic surface mount capacitor with 5% tolerance and a rating of 100 volts. (Image source: Murata Electronics)

Film capacitors

Film capacitors use a thin plastic film as a dielectric. Conducting plates can be implemented either as foil layers or as two thin layers of metallization, one on each side of the plastic film. The plastic used for the dielectric determines the characteristics of the capacitors. Film capacitors come in many forms:

Polypropylene (PP): These have particularly good tolerance and stability with low ESR and ESL and high voltage breakdown ratings. Due to temperature limits of the dielectric they are available only as leaded devices. The PP capacitors find applications in circuits where high power or high voltage are encountered like switch mode power supplies, ballast circuits, high frequency discharge circuits, and in audio systems where their low ESR and ESL are prized for signal integrity purposes.

Polyethylene terephthalate (PET): Also called polyester or mylar capacitors, these capacitors are the most volumetrically efficient of the film capacitors due to their higher dielectric constant. They are generally applied as radial lead devices. They are used for general purpose capacitive applications.

Polyphenylene sulfide (PPS): These capacitors are manufactured only as metallized film devices. They have particularly good temperature stability and so are applied in circuits that require good frequency stability.

An example PPS film capacitor is the ECH-U1H101JX5 from Panasonic Electronics Corporation. The 100 pF device has a tolerance of 5%, is rated at 50 volts, and comes in a surface mount configuration. It has an operating temperature range of -55° to 125°C and is intended for general electronics applications.

Polyethylene naphthalate (PEN): Like the PPS capacitors, these are only available in a metalized film design. They have high temperature tolerance and are available in surface mount configuration. Applications focus on those requiring high temperature and high voltage performance.

Polytetrafluoroethylene (PTFE) or Teflon capacitors are noted for their high temperature and high voltage tolerance. They are manufactured in both metalized and foil construction. PTFE capacitors mostly find applications requiring exposure to high temperature.

Electrolytic capacitors

Electrolytic capacitors are notable for their high capacitance values and high volumetric efficiency. This is achieved by using a liquid electrolyte as one of its plates. An aluminum electrolytic capacitor comprises four separate layers: an aluminum foil cathode; an electrolyte-soaked paper separator; an aluminum anode which has been chemically treated to form a very thin aluminum oxide layer; and finally, another paper separator. This assemblage is then rolled and placed in a sealed metallic can.

Electrolytic capacitors are polarized, direct current (DC) devices, meaning that the applied voltage must be applied to the specified positive and negative terminals. Failure to correctly connect the electrolytic capacitor can result in explosive failure, though the enclosures have pressure relief diaphragms to manage the reaction and minimize the potential for damage.

The principal advantages of the electrolytic capacitor are high capacitance values, small size, and relatively low cost. The capacitance values have a wide tolerance range and relatively high leakage currents. The most common applications for electrolytic capacitors are as filter capacitors in both linear and switching power supplies (Figure 5).

Referring to Figure 5 and moving from left to right, the ESK106M063AC3FA from Kemet is a 10 µF, 20%, 63 volt, radially leaded, aluminum electrolytic capacitor. It can be operated at temperatures up to 85°C and has an operating life of 2,000 hours. It is intended for general purpose electrolytic applications including filtering, decoupling, and bypass operations.

An alternative to the aluminum electrolytic capacitor is the aluminum polymer capacitor which replaces the liquid electrolyte with a solid polymer electrolyte. The polymer aluminum capacitor has lower ESR than the aluminum electrolytic and a longer operating life. Like all electrolytic capacitors, they are polarized and find application in power supplies as filter and decoupling capacitors.

The Kemet A758BG106M1EDAE070 is a 10 µF, 25 volt, radially lead, aluminum-polymer capacitor with longer life and greater stability across a wide range of temperatures. It is intended for industrial and commercial application such as mobile phone chargers and medical electronics.

Tantalum capacitors are another form of electrolytic capacitor. In this case, a layer of tantalum oxide is chemically formed on tantalum foil. Their volumetric efficiency is better than an aluminum electrolytic but the maximum voltage levels are generally lower. Tantalum capacitors feature lower ESR and higher temperature tolerance than aluminum electrolytics, meaning that they can better withstand the soldering process.

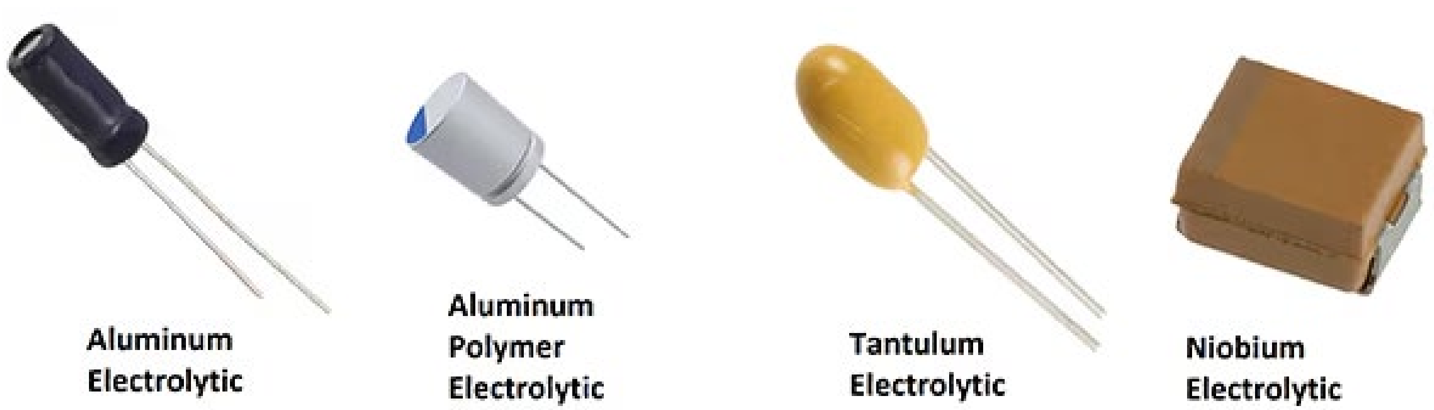


Figure 5: Examples of electrolytic capacitors; all have a capacitance of 10 microfarads (µF). (Image source: Kemet and AVX Corp.)

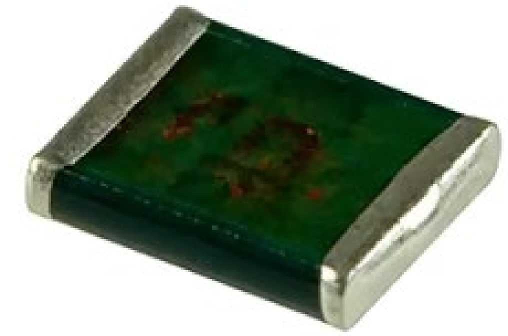


Figure 6: The Cornell Dubilier Electronics MC12FD101J-F is a surface mount mica capacitor intended for RF applications. (Image source: Cornell Dubilier Electronics)

The Kemet T350E106K016AT is a 10 µF, 10%, 16 volt, radial lead tantalum capacitor. It offers the advantages of small size, low leakage, and low dissipation factor for filtering, bypass, AC coupling, and timing applications.

The final electrolytic capacitor type is the niobium oxide electrolytic. Developed during a tantalum shortage, the niobium electrolytic capacitor replaces tantalum with niobium and niobium pentoxide as the electrolyte. Due to its higher dielectric constant, it offers smaller package size per unit capacitance.

An example niobium oxide electrolytic is the NOJB106M010RWJ from AVX Corp. This is a 10 µF, 20%, 10 volt capacitor in a surface mount configuration. Like the tantalum electrolytic, it is used for filtering, bypass, and AC coupling applications.

Mica capacitors

Mica capacitors (mostly silver mica) are characterized by tight capacitance tolerance (±1%), low temperature coefficient of capacitance (typically 50 ppm/°C), exceptionally low dissipation factor, and a low capacitance variation with applied voltage. The tight tolerance and high stability make them suited to RF circuits. The mica dielectric is silvered on both sides to provide the conducting surfaces. Mica is a stable mineral that does not interact with most common electronic contaminants.

The Cornell Dubilier Electronics' MC12FD101J-F is a 100 pF, 5%, 500 volt, mica capacitor in a surface mount configuration (Figure 6). It is used in RF applications like MRI, mobile radios, power amplifiers, and oscillators. They are temperature rated to operate over the range of from -55° to 125°C.

Conclusion

Capacitors are an essential component in electronics design. Over the years a wide range of device types have been developed with various characteristics that make some capacitor technologies particularly suited to specific applications. For designers, acquiring a good working knowledge of the various types, configurations, and specifications is a worthwhile endeavor to ensure the optimal choice is made for a given application.

Video spotlight

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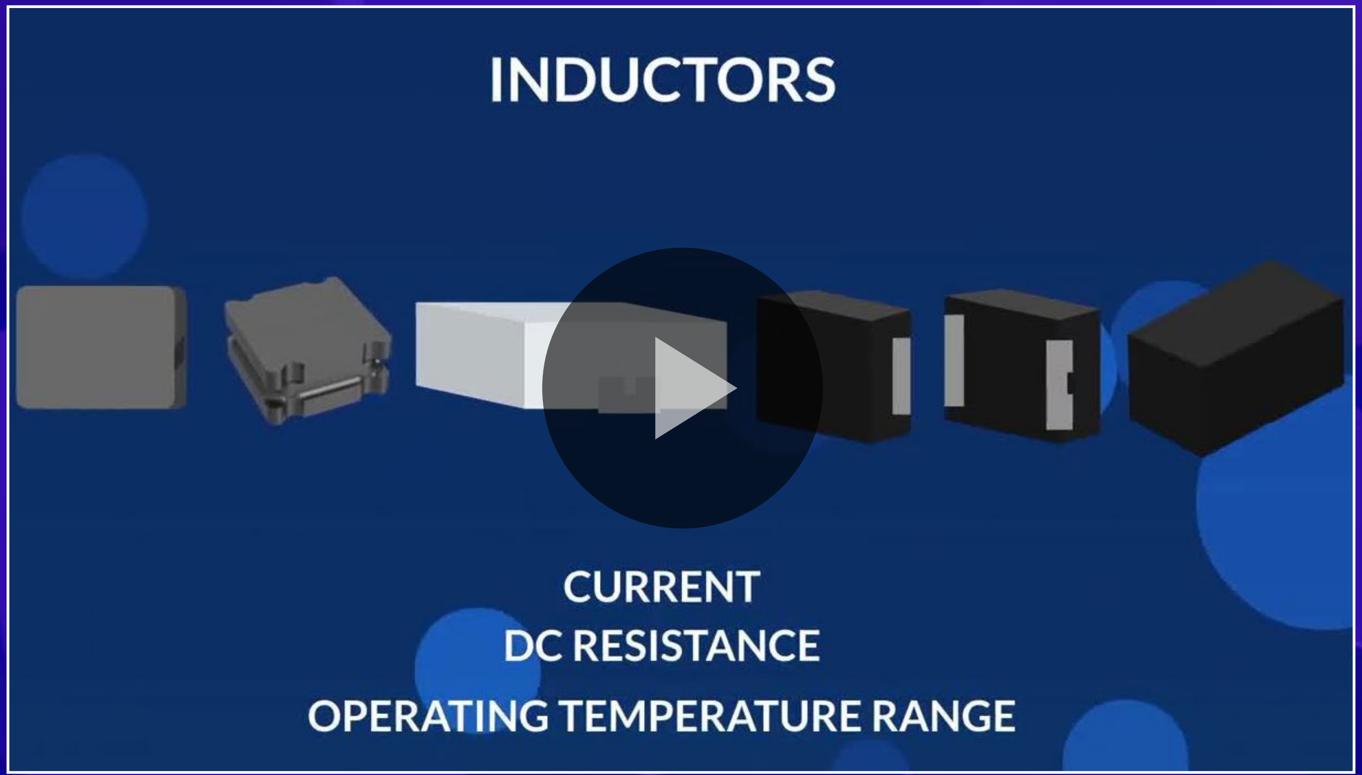

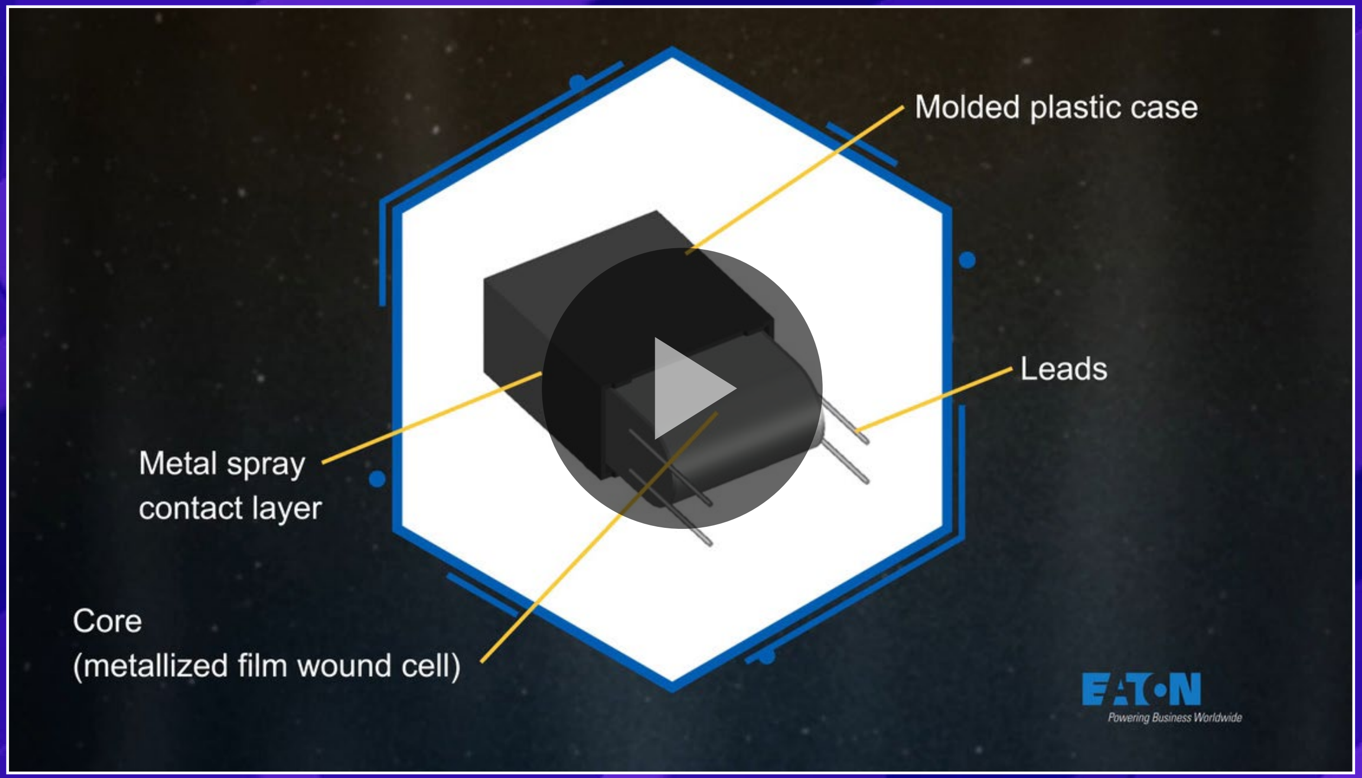

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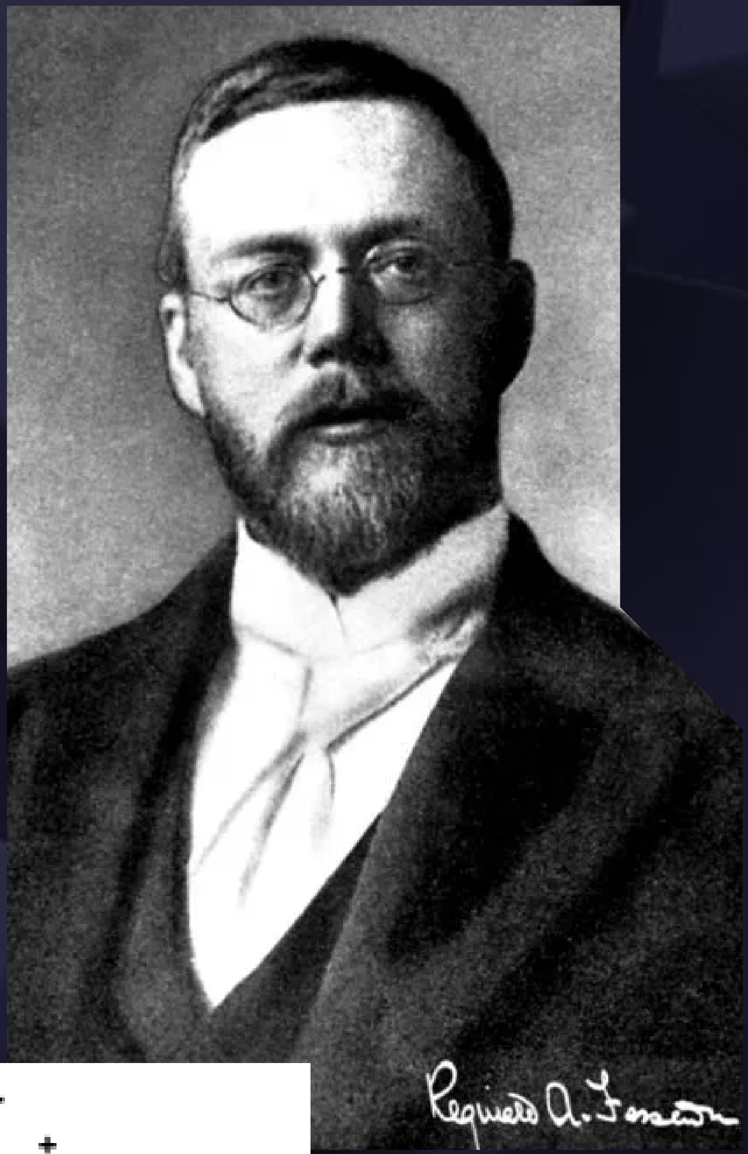
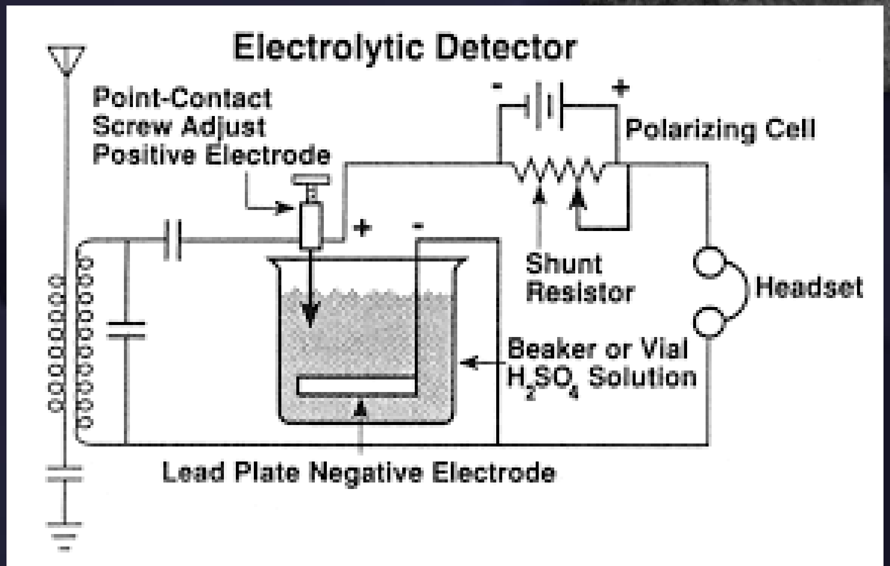




Builder of tomorrow: Reginald Fessenden's legacy in radio and beyond

By David Ray
Cyber City Circuits

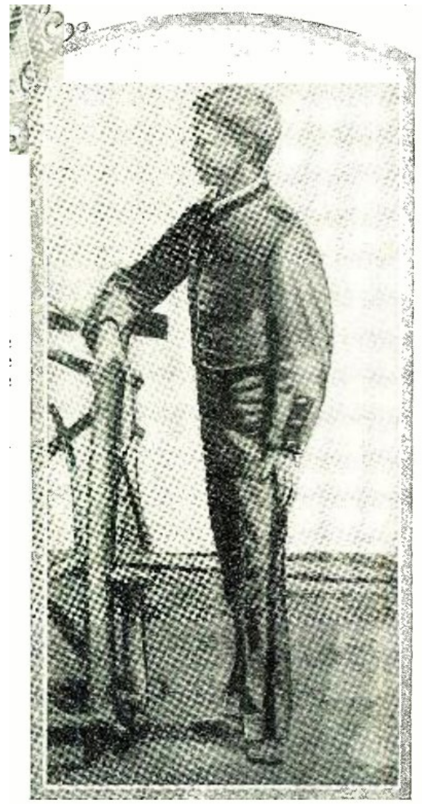
At the dawn of the twentieth century, amid a whirlwind of invention and rivalry, Reginald Fessenden emerged as a visionary who dared to make the airwaves sing. Born in a quiet Canadian village in 1866, this man transformed the crackle of Morse code into the world's first voice radio broadcast, sending music and words across the Atlantic in 1906. From doing research for Edison's labs to doing research on the battlefields of World War I, Fessenden's relentless pursuit of innovation—spanning radio, sonar, and beyond—reshaped communication and exploration.

Writer's Note: Reginald Fessenden's career was extensive and complex, involving various business dealings, bankruptcies, patent infringements, and government interference. While not every aspect will be covered here, these topics are detailed in the biography his widow published eight years after his death. This biography includes letters he wrote to business partners and many of his own writings about his inventions. Most information for this article comes from that biography. There are other sources that sometimes present conflicting accounts, and in such cases, the writer relies on the facts as documented by the Fessenden family. Although this article is quite lengthy, it omits much for the sake of the reader. Readers interested in more details can refer to "FESSENDEN: Builder of Tomorrows."

Reginald Fessenden's parents, Elisha Joseph Fessenden and Clementina Trenholme Fessenden.

The lad is of finer clay

Reginald A. Fessenden was born in East Bolton, Quebec, Canada, on October 6, 1866. His father, Elisha Joseph Fessenden, was an Anglican priest, and his mother, Clementina Trenholme, was a proud Canadian imperialist and lobbyist who championed the Canadian holiday 'Empire Day' to promote Canada's British heritage. Both of his parents dedicated themselves to public service. Growing up inside the church and living in the church's rectory as a child, Reginald was described as obedient and industrious. In a biography, it is stated that his obedience was such that not once in his childhood was a punishment administered or needed, saying *"The lad is of finer clay."*



Fessenden in his military school uniform.

"Nothing was meaningless or without import to him."

Primary school

He was a very strong reader and got most of his early education between being self-taught and learning from his mother, his first teacher. His family moved to Niagara Falls in 1874, where Fessenden was able to get a scholarship to the De Veaux Military College at age nine. There, he was an exemplary honor roll student, and in 1877, at the age of eleven, he was sent to Trinity College in Port Hope, Ontario.

In letters he wrote to his mother in his first year, he ranked at the top of his class in divinity, grammar, physics, geography, and dictations.

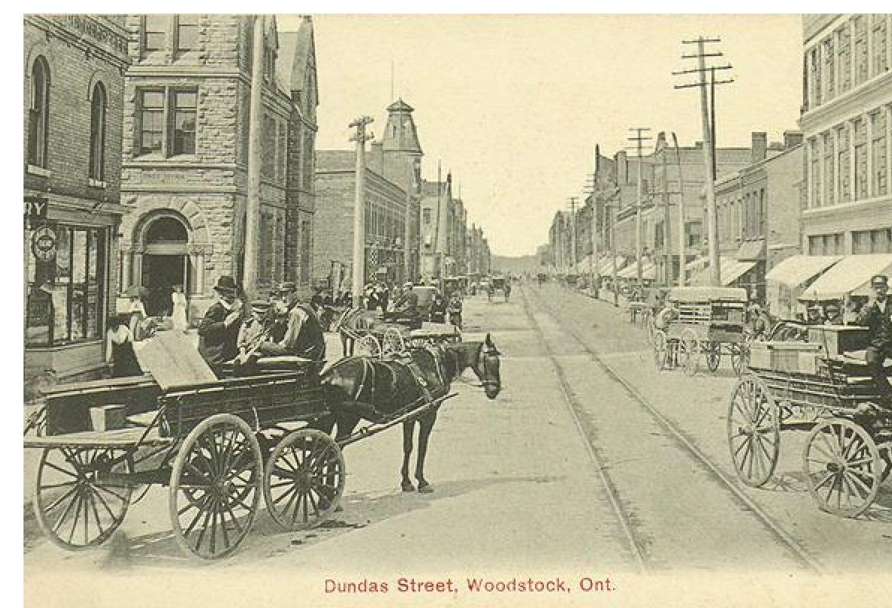
Fessenden grew up in the East Bolton Anglican Church, living in the rectory with his father who was the Anglican priest.

Trinity College School as it looked when Fessenden attended.

He was second in Latin and reading out of a class of 27. He claimed that "if I go on like this I will get out of college when I am fifteen years old." In letters home from Trinity College, it seems like his classmates were not fond of him. He was always head of his class and half a dozen years younger than they were. He was the poorest of students, given the nickname 'Pheasant' or 'Soldier Boy'. He spent the next couple years trying to double his classes to graduate as soon as he could. He wrote to his mother, "I hope to walk out without a whisker on my chin. I think as God has made me beat boys of 18 in my studies, he means me to be of use in the way of learning."

Bishops' College

He ended up graduating from Trinity College School at the age of fourteen. Unfortunately, the minimum age was sixteen for the University he wanted to attend, so he found a job at a bank in Woodstock, Ontario, which had just opened. After a short time working as a young banker, his father was able to secure a scholarship for Reginald to pursue a master's degree in mathematics at Bishop's College. He spent much of his little leisure time reading magazines like Scientific American. Here, he would study natural philosophy, Greek, French, and advanced math while also teaching mathematics to undergraduates, many of whom were older than him.



The bank young Fessenden worked at was on Dundas St.

Professor Fessenden's graduating class at Bishops College, Lenoxville, Quebec. Here Professor Fessenden while still quite young taught mathematics, Greek and French to classes some of whose members were older than himself. Professor Fessenden is the second from the right in the row at the back, standing.

The Whitney Institute in Bermuda.

The Whitney Institute in Bermuda

At the end of the 1881 school year, he had met all the graduation requirements but was offered a job if he left school. The job was as the head principal at a new school, The Whitney Institute, in Bermuda. At 15, he was the senior academic at the school. Not only that, but most of the time, he was the entire teaching staff. One of the school's clergy was an American missionary who had spent much of his life in Turkey. Fessenden became good friends with him and learned Aramaic. He would spend time on his own studies while managing four different classes across the school grades. He says it was very difficult but very satisfying because it gave him the freedom to use his own teaching methods. Looking back, he describes his methods of "teaching people how to find out things for themselves" as a mission because they brought responsibility to the youth and helped develop the region's future.

He spent Saturdays on adventures. Boating, cave diving, and other land adventures, and by all accounts, he loved his time there. It was here that he met his wife, Helen, the niece of one of the school's trustees, but they wouldn't reconnect and marry until several years later. He worked there for two years when his father wrote him a letter saying that he had applied for his son to receive a scholarship at Keble College in England.

Then he realized that he would have no career growth if he stayed at The Whitney Institute, but if he went to college in England, the rest of his professional life would be in teaching. However, by now, he wasn't as fond of teaching as he used to be. He never stopped reading magazines and books about the sciences, feeling drawn towards some sort of career in the sciences. With a few letters of recommendation, he left Bermuda and went to New York.

Image of Reginald and Helen as they were when they first met in 1881. Reginald is fifteen years old, while Helen is twelve.

A definite ratio of failure to success

Once he arrived in New York, he attempted to get a regular job writing for one of the numerous radio and electrical magazines. This didn't seem to go too well. Fessenden is described as getting comfort from his ideas of mathematical certainty, that *"there is a definite ratio of failure to success and that the sooner the quota of failures is exhausted, the sooner the plums of success are reached."* He did this for a couple of years, between New York and Canada.

Eventually, he went to try his luck with Thomas Edison. He traveled to Edison's Lamp Works in Harrison, New Jersey. He handed his card to the front desk to be passed on to Edison. He wanted to use mathematical skills at Edison's, but the front desk came back with a written message from Edison saying, *"Am very busy. What do you know about electricity?"* Fessenden recounts the story as 'I am a pretty fair mathematician, but the idea that mathematics was of real value in electrical work didn't cross my mind' and in a rush to give a reply, he wrote, "Do not know anything about electricity, but can learn pretty quick." Then Edison responded, *"Have enough men now who do not know anything about electricity."* Defeated, he returned to New York.

He spent more time writing after this, eventually becoming an assistant editor of a Social Science Journal, where he established many strong industry contacts. Each week, he would make his way back over to Edison's Machine Works to see if there were any job openings. Two years after leaving Bermuda, in 1886, he secured a position as an assistant tester for conduits and electrical lines, as Edison was laying electrical and telephone lines through Manhattan.

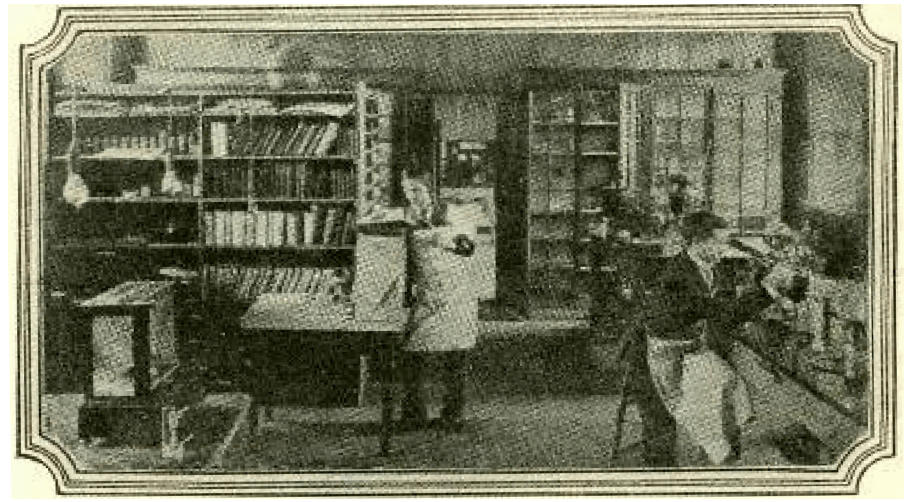
A portrait of Edison as Fessenden knew him in the late 1880s.

Working with Edison

He says that this job was more difficult than it sounds, but he would use a galvanometer to test the ends of pipes. He spent his lunch breaks learning as much as he could about electrical theory and analytical mechanics. He worked hard to make his section the best and fastest in the entire project, earning his chief tester a promotion and quickly taking over the role. Eventually, he was chosen to lead a project installing telephone lines, where he was in charge of three thousand men.

In a biography, he says, "The only exciting part of the work was getting up defective mains without permits. Once the street was closed there was a heavy fine for opening without a permit, which was hard to get, took much time and generally a money payment. It was a matter of high strategy to open a street, replace a dozen lengths of main, and get the street into innocent-looking shape again between police patrols."

This work earned him a promotion by 1887 as one of Edison's research assistants, where he thought he was going to experiment with dynamos in the Llewellyn Park Laboratory. "With Edison dawned the Golden Age of Invention. The Laboratory was its shrine, and Edison its



Edison kept a collection in his chemical library of samples for every mineral known, along with every organic and inorganic substance available in the world.

Edison's private library kept bound copies of all of his personal laboratory notebooks.

High Priest." This gave Fessenden access to things he could never dream of before. Edison kept a sample of every known mineral, many of them very rare. He had a collection of all known organic and inorganic substances. Edison had 'special agents' all around the world who could get him anything, including a sample of every known species of bamboo.

Of all these things, the library drew most of his attention. It was a nearly complete technical library with copies of every technical journal and proceedings for different conferences and societies. Several times, when he writes about working for Edison, he mentions his nostalgia for this library.

Do you know anything about chemistry?

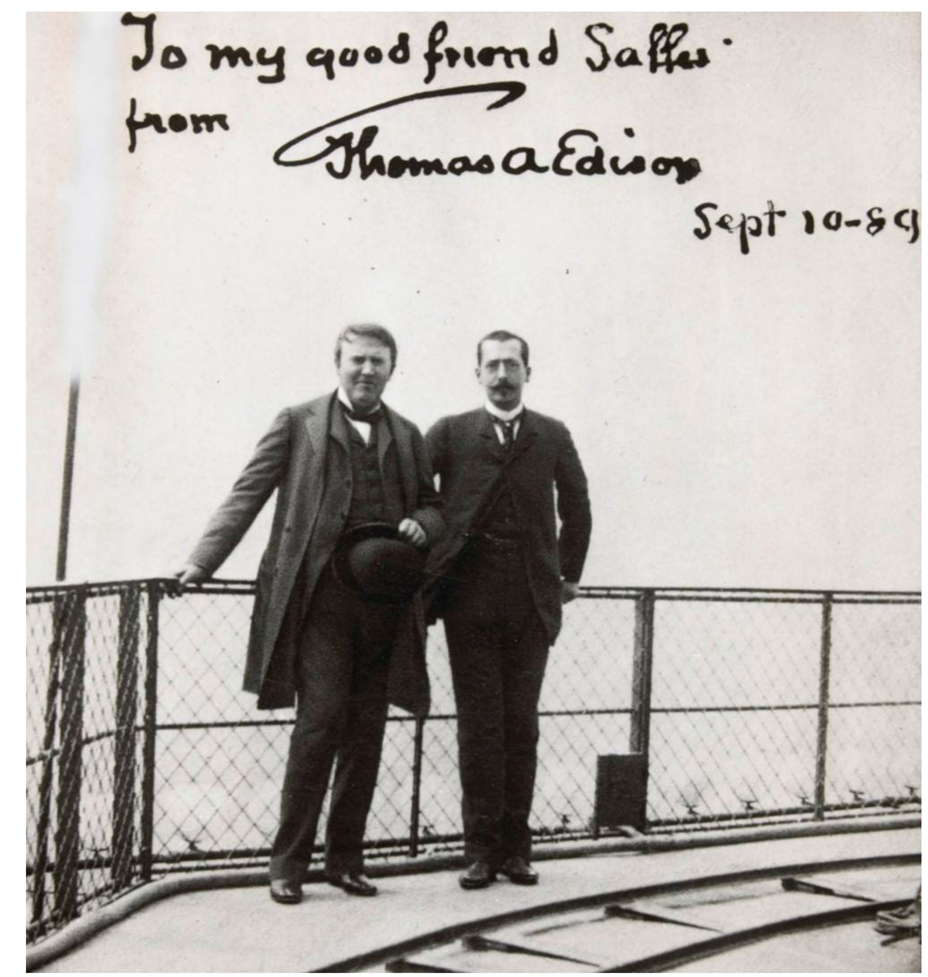
Working as a research assistant on dynamos turned out to be a pretty big disappointment. The work had not actually started. The building wasn't even wired up. His first job was to wire the building, which he did begrudgingly. Afterwards, the manager of the team wanted to release him back to the Machine Works, but Fessenden wasn't going to have that. He felt jaded and betrayed by his hard work. He wanted a square deal and he felt shorted. So, the next day he went to Thomas Edison's house and explained the situation to him.

Edison asked him, *"Do you know anything about chemistry?"*

Fessenden responded, *"No."*

Then Edison announced, *"Then I want you to be a chemist. I have had a lot of chemists. I had one whose name was all through Watt's Dictionary, but none of them yielded results. I want you to take it up."* The Machine Works was having problems with the electric lights starting fires, and he needed an wire insulation that was fireproof.

His first task was to literally take every chemical from the shelves in the building's inventory, mix it with linseed oil, and keep a record in a notebook of how it burned on a Bunsen burner. When giving one of his first successful reports to Edison, with his manager present, Edison was very impressed. The manager, interested in high-speed telegraphy, decided to give Fessenden the role of manager and reassigned himself to the telegraphy project with Edison's approval. Soon after he also replaced the head of the entire chemistry laboratory.



Thomas Edison with Gustave Eiffel at the grand opening of the Eiffel Tower in 1889.

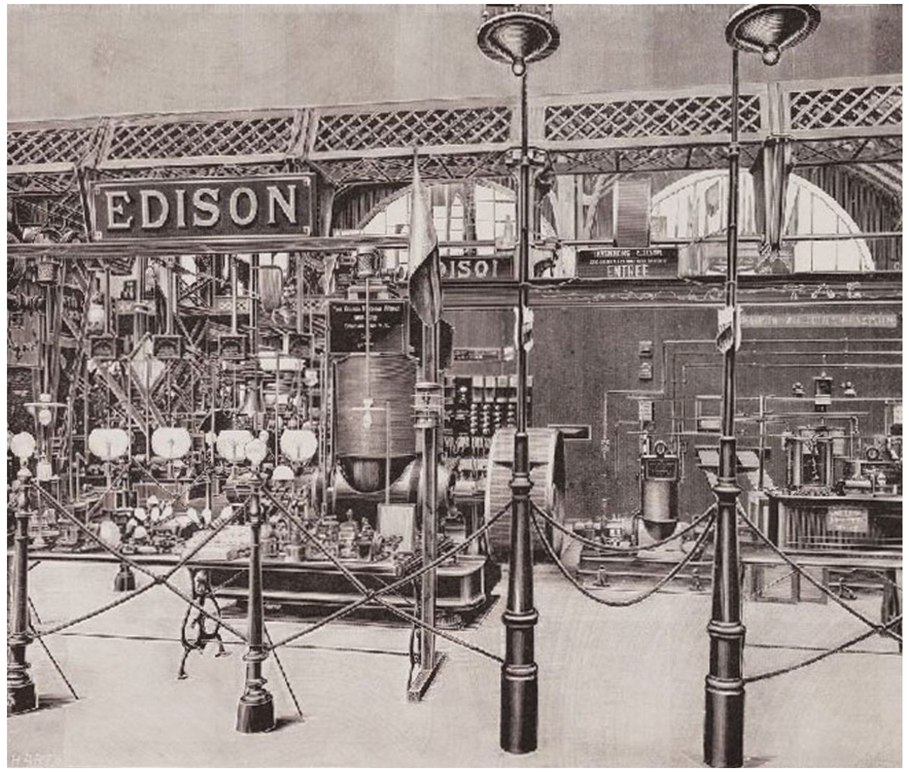
The 1889 Paris Exposition World's Fair

In 1889, Edison had a very large series of displays at the Paris World's Fair. They were mostly housed in the 'Palace of Electricity,' where he had to share space with his nemesis, George Westinghouse. Westinghouse was armed with inventions from inventors like Tesla and Stanley, but most importantly he had real practical AC power that worked.

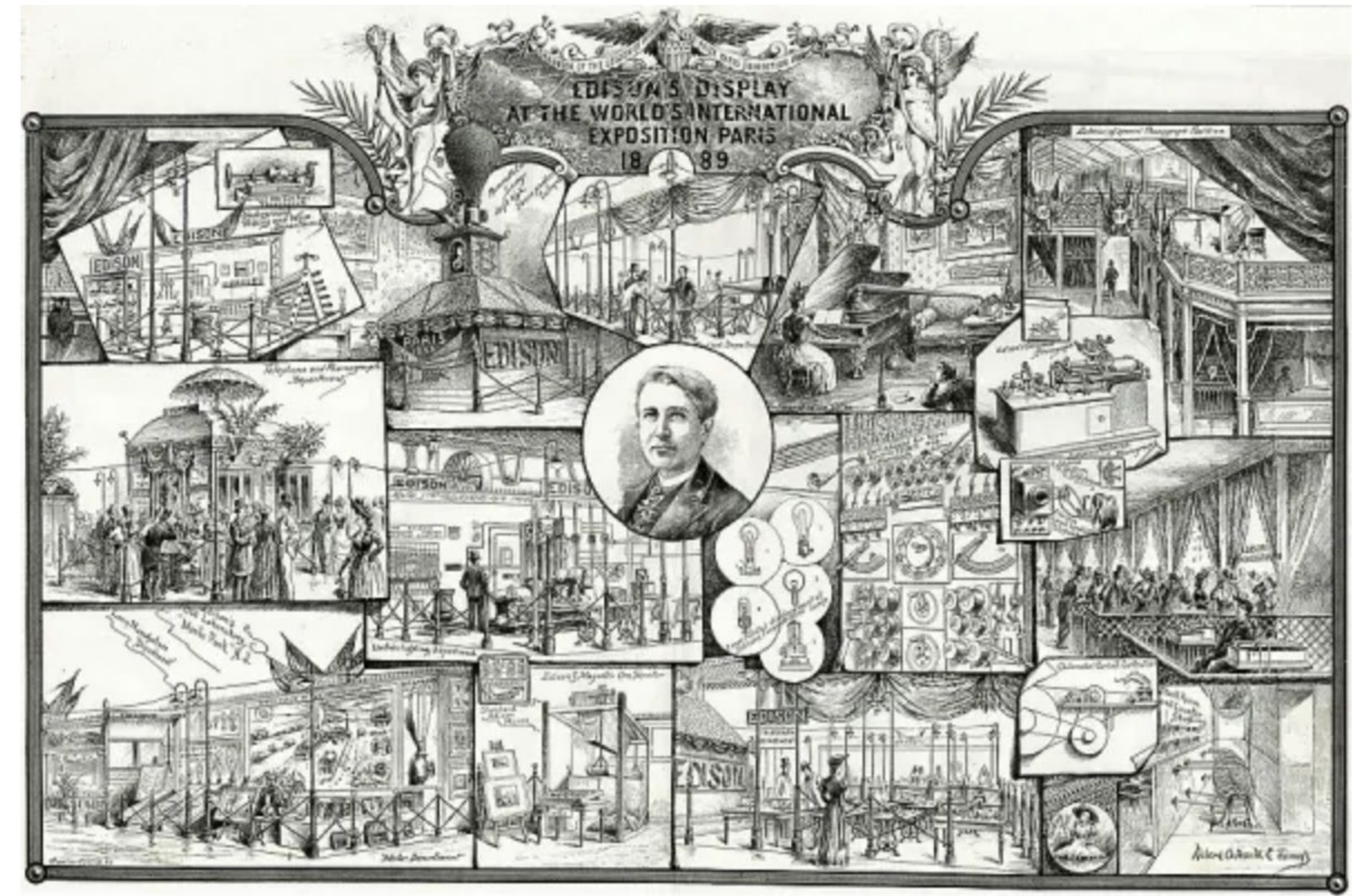
This was devastating for Edison's DC power systems. No matter how much he pushed his DC power, it would never perform as good as Westinghouse's new AC power and now the world knew it. Much of Edison's worth was because of residuals he gets off of installing his lighting systems. When people moved over to Westinghouse's utility, he was going to lose all of that revenue. Investors pulled out. J.P. Morgan, the lead investor, forced Edison's companies to reorganize and merge into the Edison General Electric brand, become simply General Electric, and removed Edison from his own companies.

Fessenden continued working for Edison, publishing a number of patents involving the incandescent lamp until 1890, when he was laid off as part of the reorganization.

One of Edison's many displays at the Paris World's Fair.



This did not dim his opinion of Edison, later writing, "The question has often been put to me '**Is Edison really a good inventor?** Are not his inventions really due to his assistants?' Having worked with him for a number of years and having made a rather special study of the science of invention and of inventors, my own conclusion is that all of the inventions which go by his name were made by him personally, and that there is only one figure in history which stands in the same rank with him as an inventor, **Archimedes**."



The 1889 Paris World's Fair was disastrous for Edison and his investors.

Post Edison career

After being laid off, he took the time for independent study. He relished the idea of solving problems without having problems to solve and eventually found himself studying the elasticity of rubber. Being the head of Edison's chemistry laboratory brought him job offers from notable companies, including Pratt & Lambert and Carnegie, but he turned them all down because he simply wanted to work with Edison. He felt that he could wait and return to work on the Dynamo project, but this never happened. Edison's companies never recovered from the decline following the 1889 World's Fair.

He was meant to marry Helen in September of 1890, but he didn't have a well-paying job, and it didn't look like he should wait for Edison any longer, so he took an opening at the United States Company, a branch of the Westinghouse Company. Here he did get to work on dynamos, where he made many great improvements.

"An inventor must never be intimidated by what appear to be facts when he knows they are not."

– Reginald Fessenden

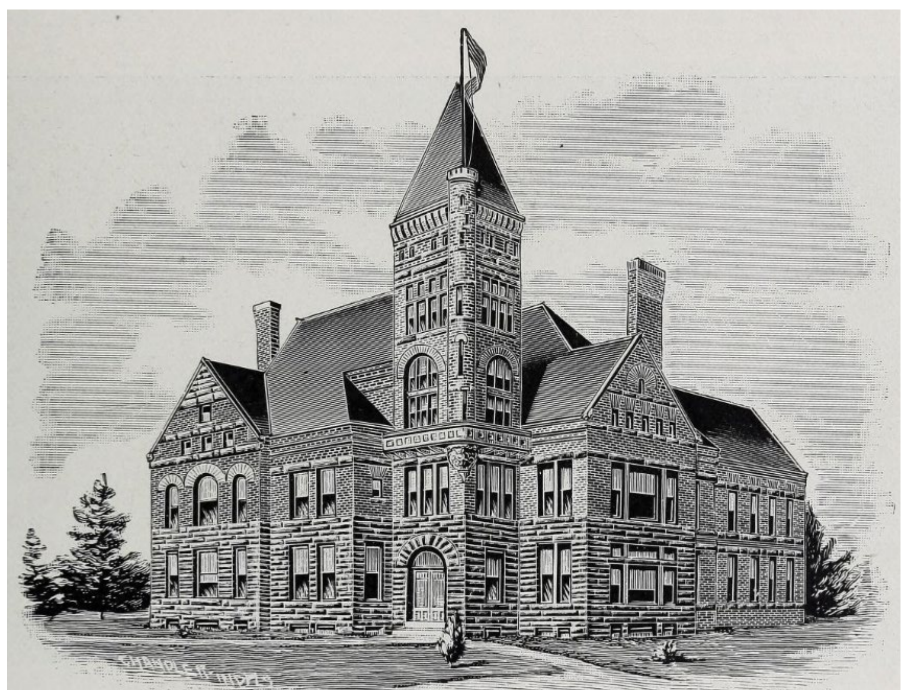
William Stanley Jr. rented out part of the building that housed the lab where he worked. By the time they met, William Stanley Jr. had already established himself as one of the great early innovators of the electrical age. Westinghouse hired Stanley in 1884, and in 1885–86, he created the first truly practical alternating-current transformer system, demonstrating in March 1886 that AC power could light an entire town. This experiment laid the groundwork for Westinghouse's new electric company, and by 1886, Westinghouse Electric & Manufacturing was deploying AC systems nationwide. Stanley left Westinghouse in 1888 after disputes, sold his patents, and by 1890, he founded the Stanley Electric Manufacturing Company, focusing on transformers and power meters.

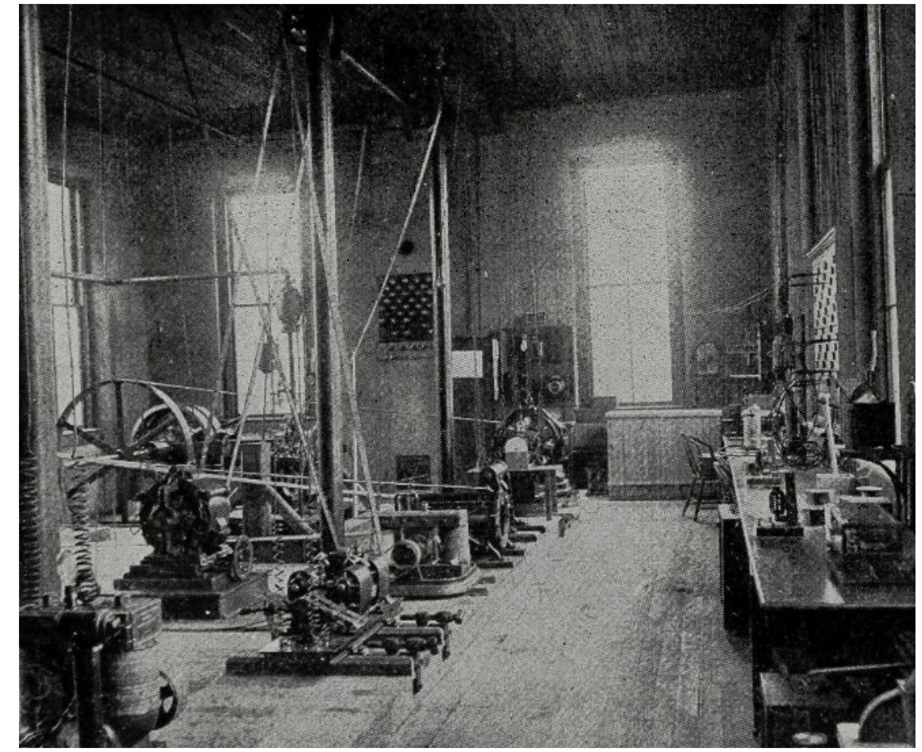
The following year, Fessenden started working for the Stanley Company, but it wasn't long-lived as lawsuits with Westinghouse over his power meter design forced Stanley to downsize the company, breaking many guarantees he had made to Fessenden.

A renewed career in education

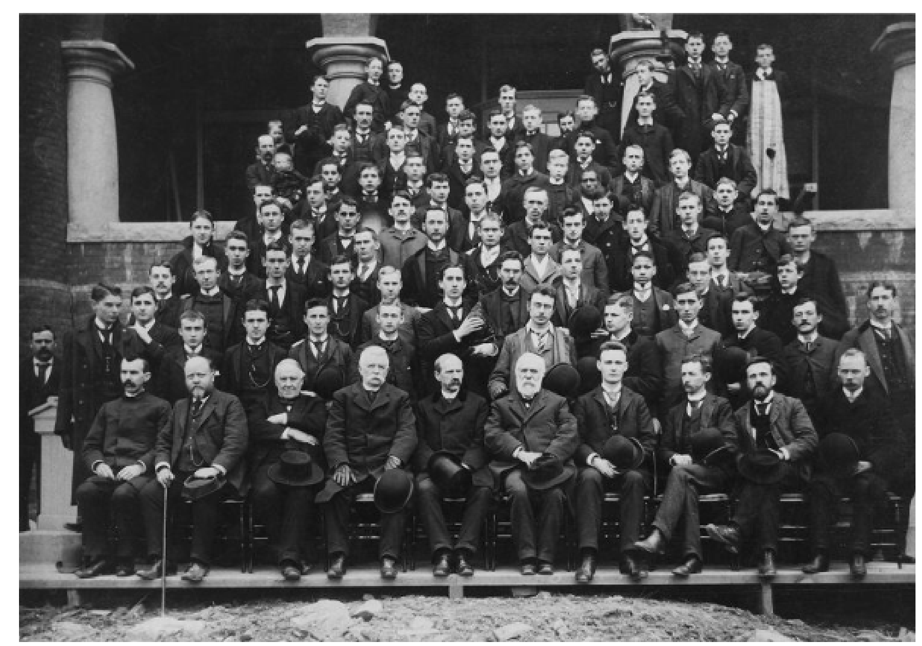
Newly married and without a job. This was a problem, but he was offered to be the chair of the electrical engineering department at Perdue University in Indiana in 1892, which he did for one school year, but soon opportunity came knocking once again and he was offered the position of the chair for the Electrical Engineering department at Western University in Pittsburgh followed by a letter from Westinghouse, urging him to move to Pittsburgh with a check for $1000.

Retro Electro Fun Fact: One of the main reasons Westinghouse won "The Current Wars" is because of inventors like William Stanley Jr. Stanley was crucial in making the modern electric grid possible. You can read his story in the Retro Electro article "Forgotten Genius: William Stanley Jr's Legacy in Electrical Engineering." (Link: https://www.digikey.com/en/emedia/emagazine/2025/power?page=12)





The Perdue University Electrical Laboratory as it was when Fessenden was the chair of the department.



Western University Graduating Class of 1894. Fessenden can be seen in the front row, second from the right.

He accepted this job, moved to Pittsburgh, and established a world-class electrical laboratory. Here, he experimented with X-rays, consulted for Carnegie Steel, several lamp companies, and other things. He spent a couple of years working on 'Hertzian Waves' (radio) and developed a new way for more reliable wireless telegraphy. He would spend seven years at Western University.

The Weather Bureau

At the turn of the century, Fessenden had already accumulated many patents. Improvements to galvanometer design, fire-proof insulation, better transformer core lamination, and patents related to wireless signaling concepts made him attractive to the weather bureau. In September 1900, Galveston, Texas, was attacked by a hurricane, killing more than 6,000 people and becoming the deadliest natural disaster in US history.

The chief of the Weather Bureau, Willis Moore, envisioned a network of wireless transmitters capable of sending storm warnings before disasters occurred, and Fessenden had a history of creating precise detection instruments for the telegraph.

The 1900 Galveston Hurricane is on record as the deadliest natural disaster in US history, with some estimates of over 8,000 people dying in the storm.

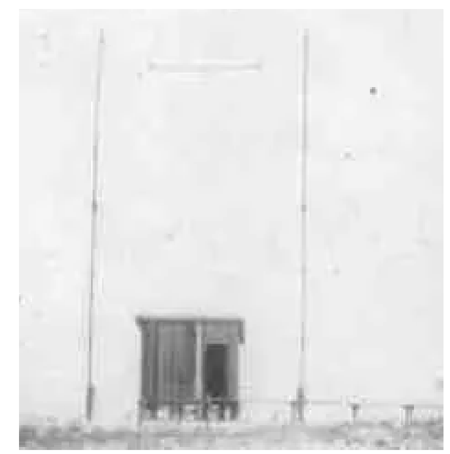
Willis Moore, Chief of the US Weather Bureau

He couldn't pay Fessenden for the patents, since it was a government institution, but they could put it on a salary and be allowed to use the patents for the time. The government just spent $25,000 to expand the Bureau's buildings in Washington, DC, allowing for plenty of room for a new laboratory. He would have machinists, instrument makers, blacksmiths, and other sorts of artisans at his disposal for anything he needed.

He accepted the job and was assigned to Cobb Island, Maryland where he studied how radio waves move. Here, he realized that he could modulate a lower-frequency waveform onto a higher-frequency waveform, thereby increasing distance and reliability. This is known as the heterodyne principle. The system was developed for advanced storm alerts, but he also used it for his own experiments. Using this and other pieces of his detector system, he was able to pass an intelligible voice wirelessly, saying simply *'HELLO TEST'* to his assistant Frank Very. This is the first time somebody transmitted a voice wirelessly.

Motivated by the successful results from the Cobb Island experiments, they commissioned three more wireless stations to be built, with Fessenden in charge. This was about the time that things started going wrong for the relationship Fessenden had with Moore. Moore was under the expectation that any new patentable materials developed while Fessenden was working for the Bureau would become the intellectual property of the Bureau and himself. Apparently, this was never part of the deal that Fessenden made, but Moore just assumed it was. In letters back and forth between the two men, Fessenden tries to remain polite, but steadfast that his work remains his own, stating *"the work is the result of my own originality, and I cannot alienate my rights as an inventor."*

Retro Electro Fun Fact: Ironically, the very patents Moore had wanted, especially Fessenden's detector work, later became central in fights against Marconi and in litigation over radio patent priority. The letters that were sent back and forth while he was at the Weather Bureau, regarding who would own the patents, were used as clear evidence of who developed it first.



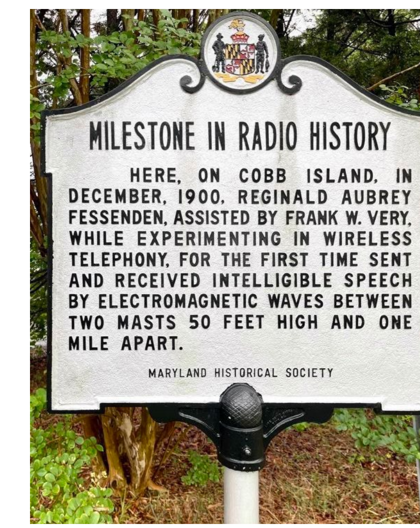
A photograph of the transmitting station Fessenden was working in during his time on Cobb Island.

In 1902, Moore sent letters to all Bureau staff that they MUST assign to the government any patentable devices created while working for them and it came down to either assigning the patents to Moore and the government or resign. It could be said without hesitation that he resigned, but he granted the Bureau a non-exclusive license to use all the patents he had developed, freely. Then, once again, he found himself unemployed.

National Electric Signal Company (NESCO)

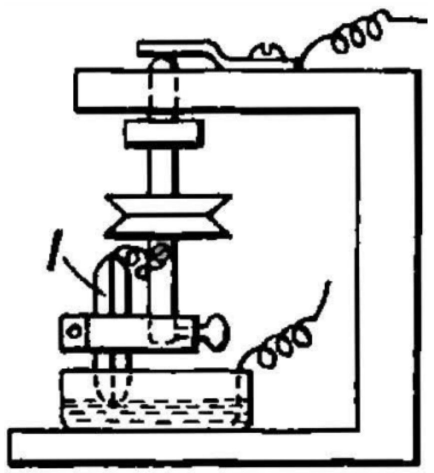
After leaving the Weather Bureau in 1902, Fessenden quickly secured private financing to continue his wireless research. Two wealthy Pittsburgh steel magnates, Thomas H. Given and Hay Walker Jr., offered the backing he needed to found the National Electric Signaling Company (NESCO). Their ambition was to take Fessenden's promising wireless telephony system and develop it commercially, both for government contracts and for private industry. With funding in hand, Fessenden established laboratories and began constructing powerful transmitting stations that would demonstrate the superiority of his continuous-wave system over the crude spark-gap equipment used by Marconi.

In 1903, he filed a patent for one of his key inventions, the Electrolytic Detector (*sometimes called the Liquid Barreter*).



Historical marker on Cobb Island commemorating Fessenden and Very's voice experiments.

This invention addressed the limitations of Marconi's coherer detectors. Marconi's coherer was like a switch that only turned on in the presence of radio waves. It was used in stations all around the world and, at one point, was likely one of the most valuable patents of its day, but it was very slow and was useless for detecting small variations in AM signals.



The Electrolytic Detector

Fessenden's electrolytic detector replaced Marconi's coherer with a fine platinum wire dipped into a cup of acid solution. A small DC bias created a tiny insulating gas bubble around the wire, and when a radio signal arrived, the oscillations disturbed the bubble, allowing current to pass intermittently. The result was a sensitive one-way valve, or rectifier, that could demodulate continuous waves into audible signals in headphones.

Soon, it was the flagship product of NESCO and was replacing Marconi's coherer in regular use both in the US and Europe. This, of course, triggered a barrage of lawsuits from Marconi.

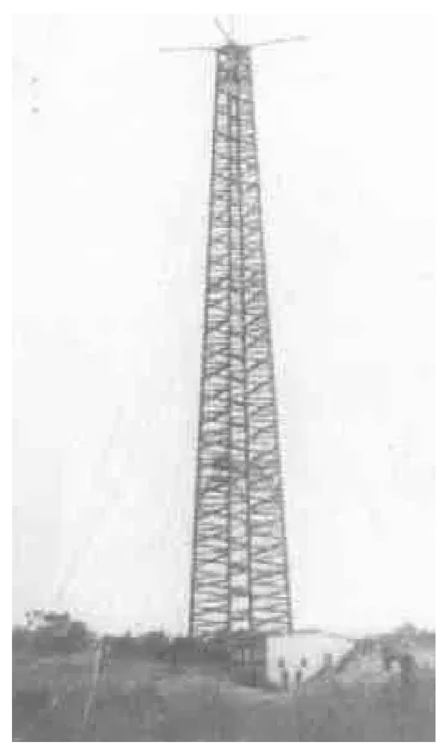
Experiments leading to the 1906 broadcast

The company's flagship site was at Brant Rock, Massachusetts, where a massive 420-foot tower was erected in 1905. The hollow mast became a local landmark, though many townspeople were suspicious of the strange "wizard's tower" looming over their seaside village. From Brant Rock, Fessenden conducted ship-to-shore tests and experimented with long-distance signaling.

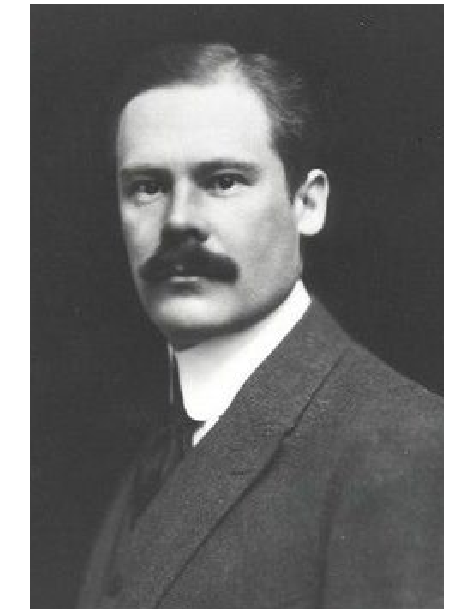
With his primary station in Brant Rock, Massachusetts, operational, Fessenden turned the bulk of his attention from telegraphy to telephony. He wanted to continue the experiments he had made years earlier on Cobb Island, transmitting voice over radio. The electrolytic detector was sensitive enough to provide the quality reception needed. He was still missing an important piece.

> "A fine platinum wire immersed in an electrolyte solution acts as a rectifier for a small oscillating charge. When the oscillation gives the tip a positive charge, electrolysis of the electrolyte produces bubbles that cling to the wire, preventing current from flowing. When the oscillation makes the tip negative, current flows across the electrolyte."
>
> **– Reginald Fessenden describing how his Electrolytic Detector works.**

NESCO's 'Wizard Tower' was one of the tallest radio towers in the world at the time and could be seen from miles away.



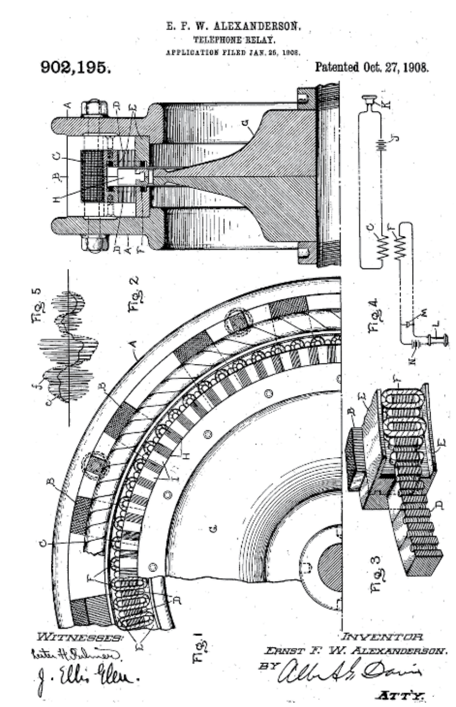
Fessenden in his radio laboratory at Brant Rock in 1906.



Ernst Alexanderson

Before this, waves were primarily made with crude spark gaps, but if he was going to use his heterodyne principle of modulating one signal onto a higher frequency, then he would need a reliable, constant, source of continuous radio waves. He didn't have any kind of precision oscillator he could use to create this signal, so he partnered with General Electric to design a signal generator that could produce a clean, continuous wave at tens of thousands of cycles per second.

He worked with a General Electric engineer named Ernst Alexanderson and in 1906 he delivered the first Alexanderson Alternator to NESCO. The Alexanderson alternator worked much like a conventional electrical alternator but spun much faster and used many magnetic poles to produce continuous waves of RF. A rotor with slots passed between stator windings, and as it turned at high speed, it induced a steady sinusoidal current. Unlike spark-gap transmitters, which produced noisy bursts, the alternator delivered a smooth, stable signal ideal for Fessenden's needs. Its size was immense, often several tons of precision machinery, but it was the only practical source of continuous radio waves powerful enough for these experiments. Alexanderson received a patent for this invention in 1911.

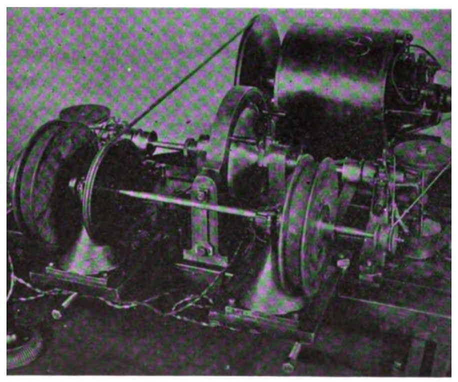


Drawings from Alexanderson's patent, demonstrating that there were alternating magnets lined along a spinning wheel.

Retro Electro Fun Fact: The licensing rights for General Electric's Alexanderson Alternator was in play when the US Navy commandeered the American Marconi Company's transmitting stations, leading to the creation of RCA. Learn more of that story in the Retro Electro article "The Rise of Designators: From DeForest to Western Electric." (Link: https://www.digikey.com/en/emedia/emagazine/2024/sensors?page=17.)

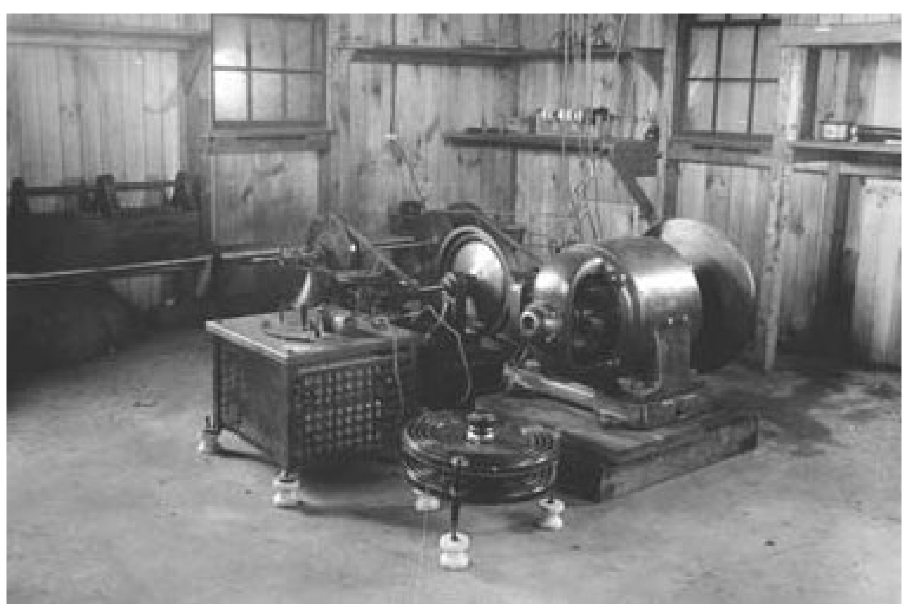
Alexanderson would continue his career with General Electric, moving to RCA, where he worked on the team that developed electronic television in the late 1920s.

While Marconi claims to have received a transatlantic telegraph in 1900, the reception was poor and really of no use, but in 1906, NESCO engineers carried out the first two-way transatlantic wireless telegraphy to Scotland, and later to a second station in Ireland, achieving two-way telegraph communication over nearly 3,000 miles. Although these transatlantic links were short-lived, they demonstrated that Fessenden's approach could rival and even surpass Marconi's in both clarity and range. This made the British Marconi Company very suspicious of the equipment Fessenden and NESCO were using, alleging that he had stolen their patents. The fact is that Marconi's techniques made true two-way transatlantic communication impossible.



A close image of the Alexanderson Alternator

Fessenden and his team also began a series of experiments by attaching a carbon microphone directly to the transmitter circuit. This allowed the modulation of the radio wave's strength in proportion to sound vibrations, a technique known today as amplitude modulation (AM). Early tests demonstrated that speech and music could be sent and recovered, though the signal quality varied.



A wide image of the Alexanderson Alternator

By November 1906, he succeeded in transmitting clear voice and music over several miles to ships equipped with the electrolytic detector. These were the final rehearsals for a more ambitious public demonstration.

The 1906 Christmas Eve broadcast

On the evening of December 24, 1906, Fessenden carried out what has since been described as the first broadcast of voice and music in radio history. Using the Brant Rock alternator as the transmitter, he sent out Christmas greetings into the ether.

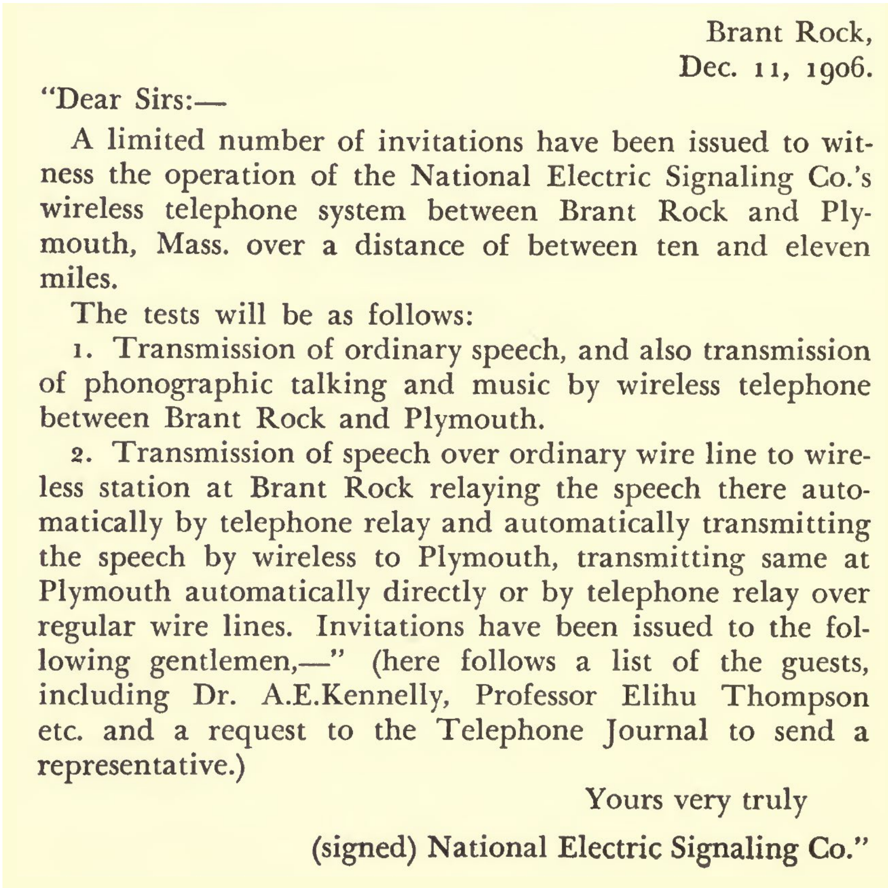
It turns out, to his dismay, that many people so heavily infringed upon his design for the electrolytic detector that the experimental broadcasts ended up being more successful than he thought possible. *The irony was not lost on him: the very infringement of his patent that deprived him of royalties also guaranteed that there were enough receivers in operation to make his vocal broadcasts historic events.* By February the following year, Newspapers all over the Atlantic were publishing reports of hearing the broadcast nearby, with reports as far away as Ireland.

Reginald Fessenden and his team of NESCO engineers at Brant Rock in 1906.

"We got word of reception of the Christmas Eve program as far down as Norfolk, Va., and on the New Year's Eve program we got word from some places down in the West Indies.

As a matter of fact, at the time of the broadcast, practically everyone was infringing the liquid barrater (electrolytic detector). When the broadcast was made, practically every ship along the coast was equipped to receive it."

– Reginald Fessenden describing the Christmas and New Year's broadcast.



Brant Rock,
Dec. 11, 1906.

"Dear Sirs:—

A limited number of invitations have been issued to witness the operation of the National Electric Signaling Co.'s wireless telephone system between Brant Rock and Plymouth, Mass. over a distance of between ten and eleven miles.

The tests will be as follows:

1. Transmission of ordinary speech, and also transmission of phonographic talking and music by wireless telephone between Brant Rock and Plymouth.

2. Transmission of speech over ordinary wire line to wireless station at Brant Rock relaying the speech there automatically by telephone relay and automatically transmitting the speech by wireless to Plymouth, transmitting same at Plymouth automatically directly or by telephone relay over regular wire lines. Invitations have been issued to the following gentlemen,—" (here follows a list of the guests, including Dr. A.E.Kennelly, Professor Elihu Thompson etc. and a request to the Telephone Journal to send a representative.)

Yours very truly

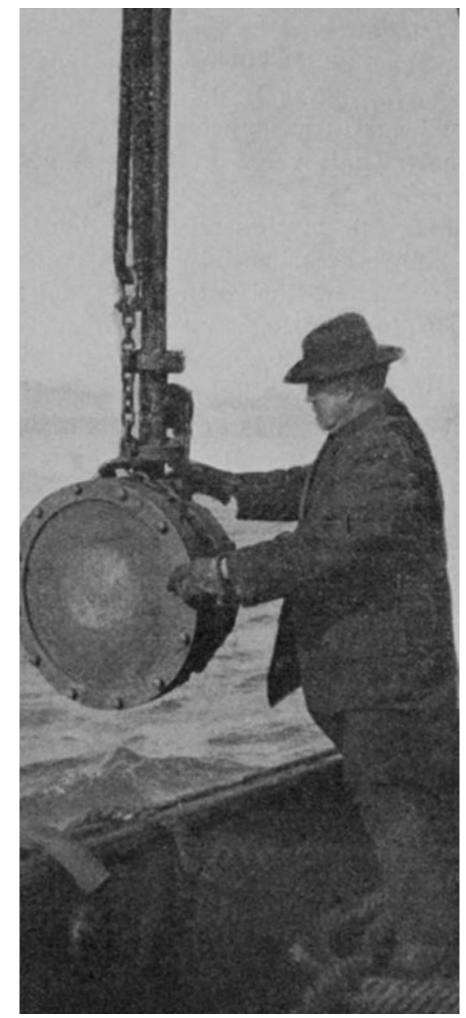
(signed) National Electric Signaling Co."

The letter Fessenden sent to several people to witness his history-making broadcast.

Plaque at the Brant Rock antenna site commemorating the broadcast.

Retro Electo Fun Fact: This is the actual recording of the first radio broadcast on Christmas Eve 1906, with Reginald Fessenden playing the violin himself. This broadcast was unexpectedly heard by hundreds of stations all over the North Atlantic. (Link: https://archive.org/details/first-radio-broadcast-christmas-eve-1906)

Yet despite these technical triumphs, NESCO was plagued by legal disputes from the Weather Bureau, Westinghouse, Marconi and others, personality clashes, and the enormous expense of maintaining giant transmitting stations. By 1911, Fessenden had quarreled bitterly with his investors, and lawsuits flew in both directions, eventually forcing Fessenden out of his company and in 1912, the Brant Rock tower was dismantled, and the company went into receivership and liquidated, leaving Fessenden once again without financial support, though not without having made history.



Reginald Fessenden on a battleship, developing what would later be known as SONAR.

The next twenty-five years

After the fallout of NESCO, Fessenden "retired" from the radio industry. Inspired by the disaster of the Titanic, he sought to help make sure that it didn't happen again. Designing the first alert signals for Icebergs. His work was indispensable during the First World War, as he developed underwater communication systems for Submarines, and what became SONAR and echo-range finding of undersea objects. He also developed a new type of engine for the Navy's Battleships called the Fessenden Combustion Engine and the first Turbo-Electric Drive, dramatically increasing the ship's speed and maneuverability.

In 1917, he received a patent for Reflection Seismology, titled "Methods and Apparatus for Locating Ore Bodies," which was used to locate oil and mineral deposits using radio waves, crucial to the growing petroleum industry of the 1920s.

Fessenden spent some time in his retirement hunting for ancient civilizations, like Atlantis. Here is a map he drew, showing where he thought Atlantis would have been, before the Deluge.

Later, he invented tracer bullets, a wireless paging system, and a new type of tea maker, ending with over 500 patents to his name.

In 1925, Fessenden began writing a regular, autobiographical, and profound serial article for Radio News. He wrote eleven long-form articles titled “The Inventions of Reginald A. Fessenden” before being too ill to continue, making the November 1925 issue the last article in the series, never actually completing the series. In this series, he addresses questions about the nature of invention and offers guidance to aspiring inventors.

Reginald Aubrey Fessenden’s gravesite in the St. Mark’s church cemetery, Smith’s Parish, Bermuda.

In 1928, he was finally able to settle his lawsuits with NESCO, as they had been acquired by RCA, accepting a cash settlement. Retiring back to the Bahamas with his family. In his retirement, he started research in ancient civilizations. A regular Indiana Jones, stalking the mountains of Eastern Europe, trying to find evidence of pre-deluge civilizations, like Atlantis. He wrote a book about this research, “The Deluged Civilization of the Caucasus Isthmus”, but it was not published in his lifetime, later posthumously published by his son.

Fessenden died on July 22, 1932, at his home in Bermuda, closing a remarkable career ranging from radio, chemistry, SONAR, and beyond.

Suggested Reading

The Actual Recordings of the First Radio Broadcast – Christmas Eve 1906

“Fessenden: Builder of Tomorrows” by Helen M Fessenden (1940)

“Fessenden – The Forgotten, Indispensable Man in Radio History” by RoaringTwentiesRadio

“The Inventions of Reginald A Fessenden” by Reginald Fessenden in Radio News Magazine (Issues 1925-01 through 1925-11)

“Reginald Fessenden & the Physics of the First Radio Broadcast” by Kathy Loves Physics

“On The Platinum Point Electrolytic Detector for Electrical Waves” by L. W. Austin

Early Radio Wave Detectors

“The Deluged Civilization of the Caucasus Isthmus” by Reginald Fessenden

“Experiments and Results in Wireless Telephony” by John Grant for The American Telephone Journal

1866 Oct 6
Born in East Bolton, Quebec, Canada; parents: Rev. Elisha Joseph Fessenden and Clementina Trenholme.

1881
Accepts post as head principal of the Whitney Institute (Bermuda).

1883-1885
Tries magazine/journal work between New York and Canada.

1886
After repeated attempts, secures a job with Edison’s Lamp/Machine Works

1887
Promoted to Edison research assistant, soon becoming the head of the Chemistry Laboratory, developing fire-proof insulation and other materials.

1889
Paris Exposition (World’s Fair) highlights strengths of Westinghouse/Tesla AC systems; Edison’s DC business falters; investors force reorganization.

1890
Marries Helen May Trott.

1892
Appointed Chair of Electrical Engineering at Purdue University.

1893
Moves to Pittsburgh to become Chair of Electrical Engineering at Western University of Pennsylvania and begins radio experiments.

1900
Galveston hurricane catastrophe underscores need for better storm warnings.

Joins U.S. Weather Bureau to create a coastal wireless network.

1900 December
Transmits the first intelligible wireless speech using his detector system and heterodyne ideas.

1902
Resigns from Weather Bureau rather than assign inventions; grants government a non-exclusive license to his patents.

Founds the National Electric Signaling Company (NESCO)

1903
Files patent for the Electrolytic Detector (Liquid Barretter)

1906 November
Conducts clear voice/music transmissions over several miles to ships equipped with electrolytic detectors.

1906 Dec 24 Christmas Eve Broadcast
Fessenden leads a program of Christmas Greetings over the first voice broadcast.

1912-1914
Turns to marine safety after the Titanic disaster

1914
Develops and tests the Fessenden oscillator (two-way underwater signaling and echo detection).

1914-1918 (WWI)
Contributes underwater communications for submarines; works on naval systems, including propulsion concepts (Fessenden combustion engine; turbo-electric drive).

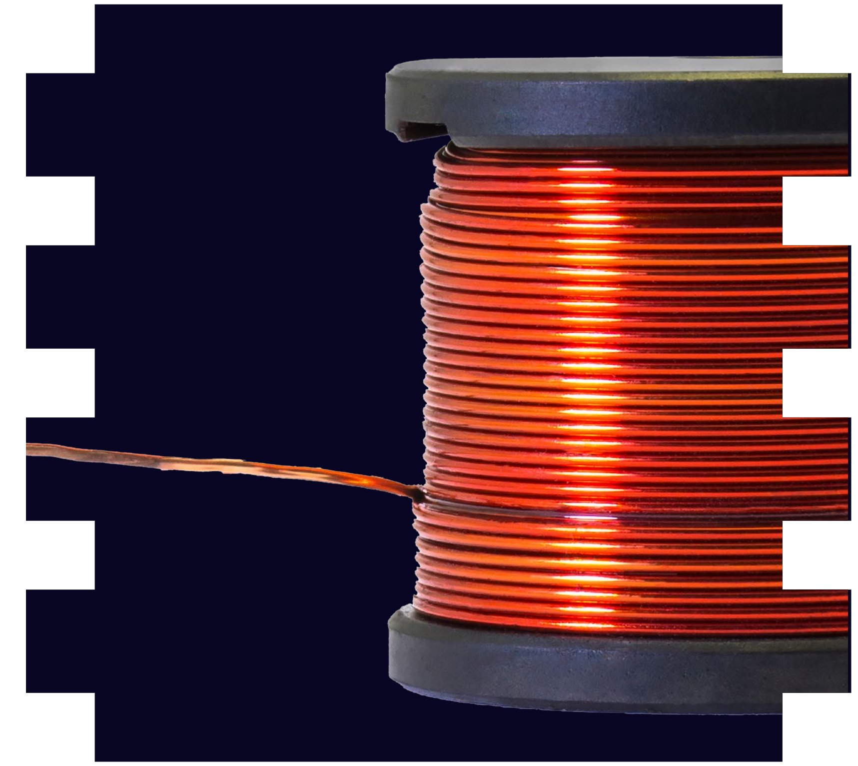
1928
Settles long-running NESCO/RCA suits for cash and retires to the Bahamas with family.

1932 Jul 22
Dies in Bermuda; buried at St. Mark’s church cemetery, Smith’s Parish.

Use specialized inductors for high-current, fast-transient DC/DC converters

By TechWire

Datacenters and server racks require kilowatts of power and hundreds of amperes of current. Providing this amount of DC power is a design challenge, even at low voltages. The problem is exacerbated by the need for microsecond transient response times to prevent more than a few millivolts of voltage-rail droop, which could cause intermittent circuit behavior.



To enhance response to transient demands, designers have transitioned to a multiphase DC/DC converter topology where multiple single-phase buck converters are used in parallel. However, this approach has inherent limitations due to the unavoidable parasitic inductance and resistance of the output capacitors, both of which slow the converter's transient response.

To overcome this weakness, an advanced multiphase topology known as the trans-inductor voltage regulator (TLVR) has been developed. Key to a successful TLVR implementation are two low-value, high-current inductors, one for each TLVR power phase, and a single compensation inductor on the primary side of the TLVR inductors.

This article examines the challenges associated with high-current DC/DC converters and explores the application of multiphase DC/DC topologies to address these challenges. It then describes the critical role of compensation inductors and how the performance requirements of these circuit elements can be met using example components from Abracon.

From single-phase to multiphase topologies

There are two related challenges in delivering regulated power to systems such as datacenters and server racks. First, they require hundreds of amperes of current. This static maximum current demand can be satisfied with a suitable switching converter design using high-value bulk capacitors to smooth out the switching ripple.

The second challenge is the dynamic one due to load transients, as loads quickly increase from a no-load or low-load idle state, necessary to reduce power use and minimize thermal issues, to their fully active state. The converter must respond within microseconds, yet without overshooting or undershooting the nominal rail voltage.

While bridging these contradictions is challenging, power supply and converter designers have devised ways to do so.

Begin with the single-phase converter

The standard step-down (buck) switching-topology DC/DC converter uses a single-phase approach (Figure 1, left). It takes an input DC rail, chops it into a high-frequency, square-like AC wave, and then downconverts this using a transformer or other arrangement. The resultant nearly pure DC is filtered via bulk capacitors to minimize ripple and provide a current boost if the load suddenly demands more current. To regulate the output to the desired voltage as the load varies, the converter uses feedback to adjust the chopped signal's pulse width and duty cycle (Figure 1, right), ensuring its average value matches the target value.

However, this single-phase design has deficiencies in its transient response. The unavoidable parasitics of the capacitor's effective series resistance (ESR) and effective series inductance (ESL) slow down its response time as it attempts to supply the required current when the load transitions from sleep mode to maximum demand.

Further, the additional current that is directed to the capacitor as the delivered voltage starts to sag must go through the converter's inductor. While a larger-value inductor is preferable for certain aspects of converter performance, it also results in a slower rate of current change. Therefore, it will take the inductor longer to reach the current value needed to recharge the capacitor and meet the load requirement. Thus, inductor sizing is one of the many tradeoffs in converter design.

Then go multiphase

An ingenious topology that overcomes the limitations of the single-phase converter is the multiphase converter, which uses multiple single-phase buck converters operating in parallel.

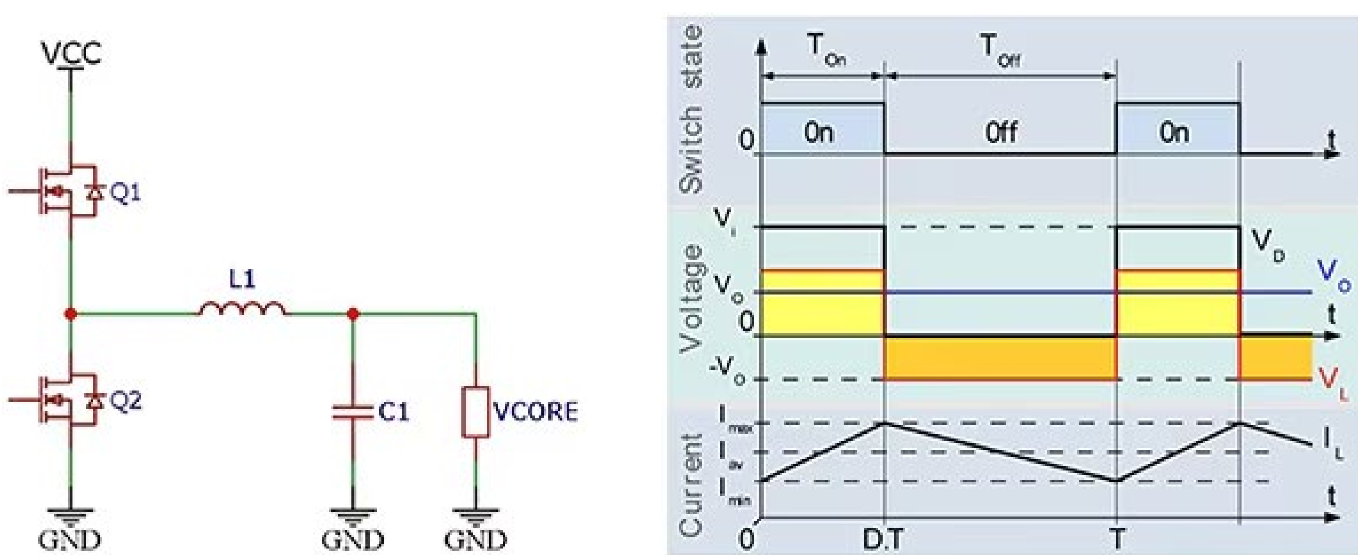


Figure 1: For regulation, the single-phase converter (left) modulates the on/off duty cycle of the switched pulse width (right) to maintain a stable DC output despite variations in load current. (Image source: Abracon)

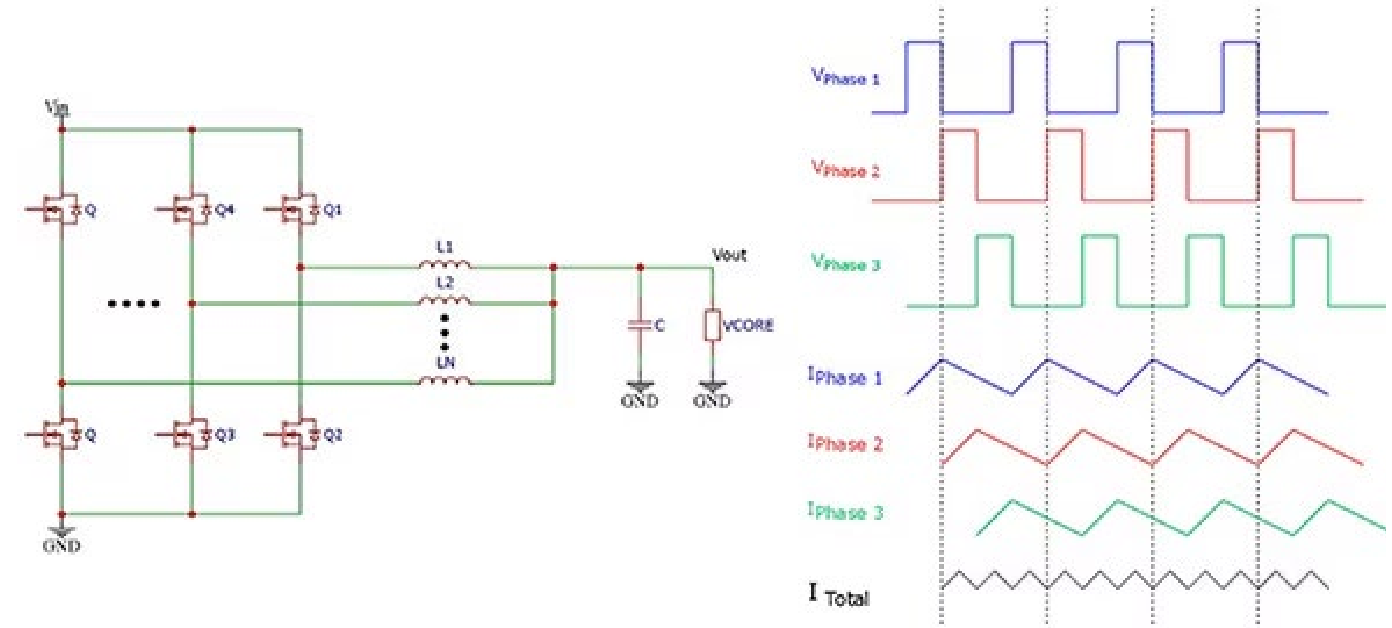


Figure 2: By employing multiple phases in a parallel arrangement (left) and summing their individual outputs, the transient response of the multiphase converter is much faster with lower droop (right) than it is for the single-phase topology. (Image source: Abracon)

This provides designers with the flexibility to simultaneously use several smaller inductors to drive the load, rather than relying on a single large inductor.

The current to the load is the sum of the currents from all the phases (Figure 2, left). Since the inductance in each phase is lower than in a single-phase design, the current rises more quickly. This yields a faster response and lower voltage droop during load transients (Figure 2, right).

Typical design practice is to limit a single phase to between 30 and 40 amperes (A), although it can be higher. A multiphase design typically consists of between two and eight phases, although more phases are possible. The choice between fewer, more powerful phases versus a higher number of less powerful ones involves many trade-offs among various aspects of electrical performance, physical size, bill of materials (BOM), and cost.

Improve multiphase with TLVR

The multiphase circuit output requires time to adjust the phases as they are sequentially triggered. In a clever circuit enhancement, the converter's reaction time can be reduced by controlling how each phase is triggered in response to load transients. This is done using the TLVR approach.

This multiphase DC/DC converter topology provides a faster transient response by adding a series connection of secondary windings via inductors that couple all phases together. This, in turn, allows a simultaneous induction of current across the phases in response to an increase in load (Figure 3).

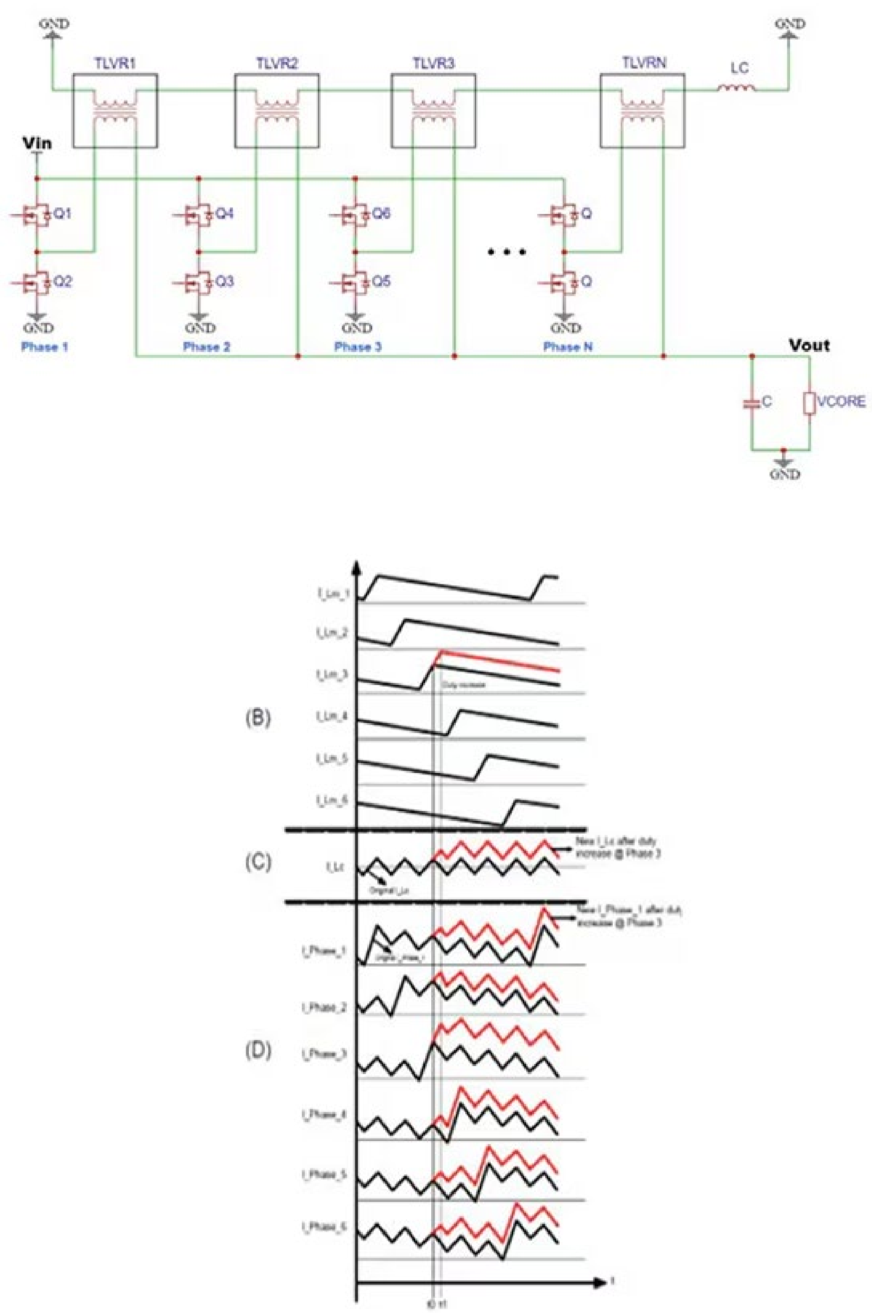


Figure 3: The TLVR topology adds interphase inductors (top) to couple the phases and enable them to have earlier "knowledge" of current demand (bottom). (Image source: Abracon)

Essential to the TLVR topology are the TLVR inductors and the compensation inductor. The former are specialized transformers where the primary and secondary windings comprise two copper clips to minimize DC losses (Figure 4). Both clips are contained within a magnetic core made of ferrite or iron-based material, thus magnetically coupling the primary and secondary sides. The key difference between the TLVR design and the basic multiphase configuration is the use of the primary winding of each TLVR inductor as an output inductor for every phase.

In addition, the secondaries of all phases are interconnected in series to a single compensation inductor (LC) (Figure 3, top right). Each primary winding voltage is reflected on the corresponding secondary winding. Since all secondaries are connected in series, the compensation inductor sees the sum of all these waveforms.

In operation, when more current is drawn from the converter, the voltage at the output begins to drop due to the parasitic ESR and ESL of the capacitor. The feedback control loop senses this drop and responds by increasing the drive level of whichever phase

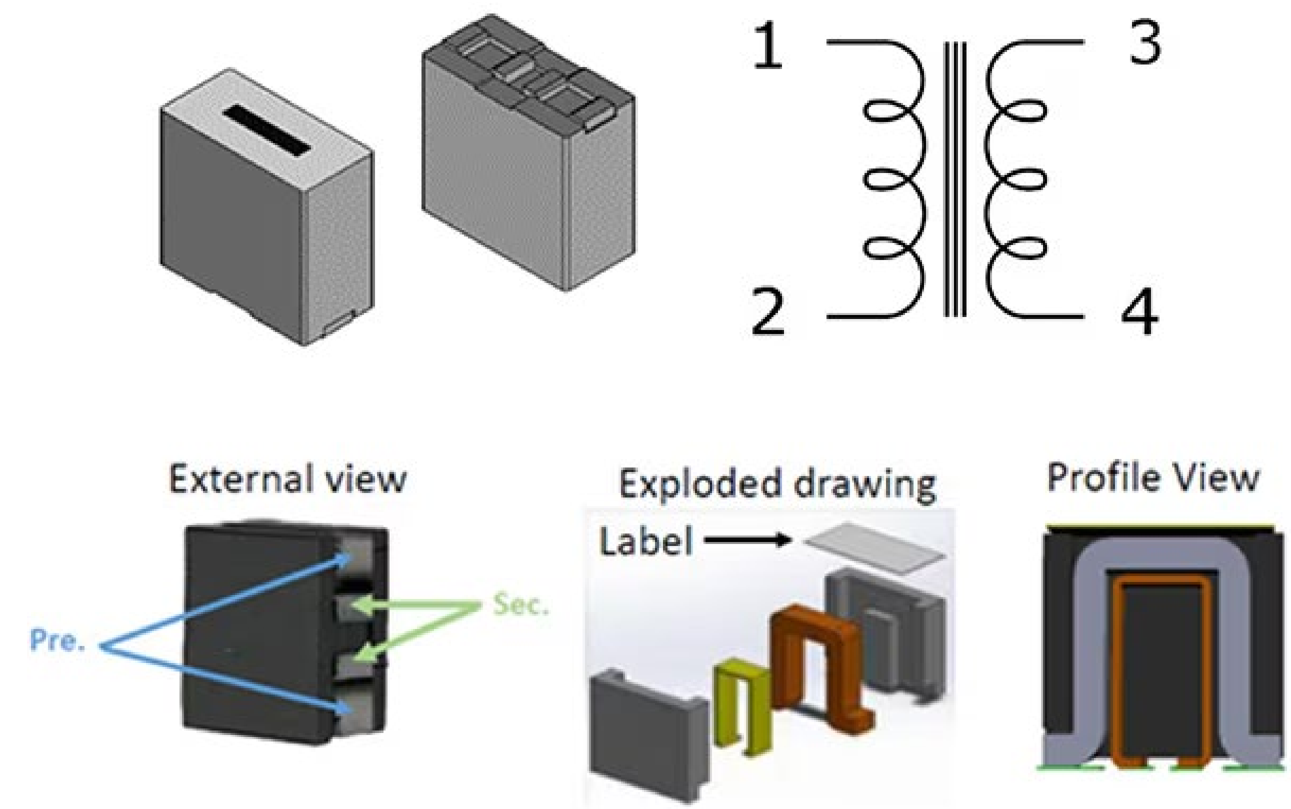


Figure 4: The TLVR inductor is a specialized transformer that links each phase's output to the next phase. (Image source: Abracon)

is active at that time, sourcing more current through that phase to limit the voltage drop and meet the new load demand.

This is why TLVRs provide superior performance compared to traditional multiphase converters. When a given phase demands more current, this new current waveform is reflected across all primary windings since the secondary is coupled with all other phases. The result is a nearly instantaneous increase in current across all phases, due to the response of one phase to the feedback system, which induces a current through the other phases.

The "trans-inductor" in the TLVR name is due to this cross-phase inductor-linked approach. The collective response of all phases to changes in load bypasses the time interval that the controller needs to trigger each of the other phases, leading to a faster transient response.

TLVR inductors typically have a 1:1 turn ratio, with both inductance values the same. The inductance value is primarily a function of the duty cycle and the acceptable amount of ripple current.

Inductor design is key to TLVR performance

Passive components, such as resistors, capacitors, and inductors, are often looked upon as simple devices. While they are conceptually straightforward, the reality is complicated with many subtleties. The inductor is perhaps the most deceptive, as, in principle, it is "merely" a piece of bent or wound wire or conductor.

As noted, a TLVR inductor (Lm_n) is needed in TLVR topologies for each power phase (Figure 5, bottom), allowing the system-level current supply to exceed hundreds of amperes.

In contrast, on the primary side of the TLVR topology, only a single compensation inductor (Lc_1) (Figure 5, top) is required to regulate the supply. It achieves this by smoothing and adjusting the phase relative to the voltage, thereby increasing the phase margin and ensuring stable operation.

AVR series assembly inductors

The compensation inductor used in TLVR designs must have low DC resistance, handle high currents, be specified over a wide temperature range, and be physically small. Abracon's AVR series of assembly inductors (Figure 6) meets these requirements with its ferrite-based construction, inductance range of 22 nanohenries (nH) to 680 nH, operating temperature range of -40°C to +125°C, DC resistance (DCR) as low as 0.100 milliohms (mΩ), and saturation currents up to 160 A.

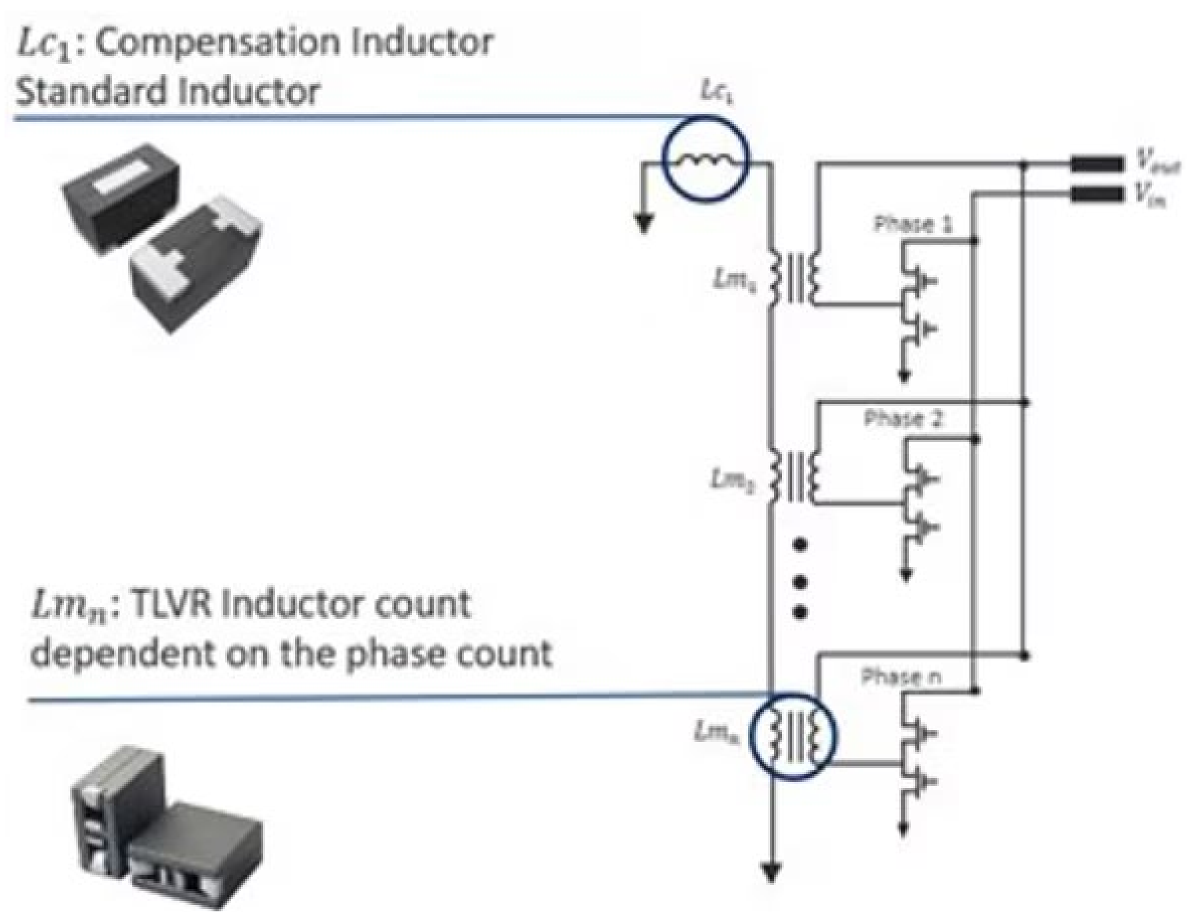


Figure 5: A complete TLVR multiphase converter requires one TLVR inductor per phase for interphase linking, plus a single compensation inductor to support stable operation. (Image source: Abracon)

The compensation inductor packaging also contributes to the success of a compact converter design. While molded inductors were previously standard for compact converter applications, these assembly inductors offer improved performance at a lower cost.

For example, the AVR-1F070605S90NLT is a shielded 90 ±15% nH inductor (0.1 MHz/1.0 V) measuring approximately 6 mm × 7 mm. Its DCR is 0.17 ±30% mΩ, and its typical saturation current is 50 A at +25°C, dropping only slightly to 45 A at +100°C.

For higher-current applications, the AVR-1Z090610SR12KT is an unshielded 120 ±10% nH inductor (800 kHz and 0.8 V). This 9.5 mm × 10 mm component features a typical DCR of 0.10 mΩ (maximum of 0.12 mΩ) along with a saturation current of 90 A at +25°C and 75 A at +100°C.

Conclusion

Transitioning from a single-phase DC/DC converter to a multiphase approach and then to a TLVR topology yields superior performance in applications where load currents are high and fast, requiring a crisp transient response and high output accuracy. Enhancing a multiphase design with the addition of a TLVR inductor for each phase, as well as with a single compensation inductor, enables this approach to meet design objectives. For the necessary compensation inductor, Abracon's AVR series of assembly inductors offers advanced and cost-effective solutions for multiphase voltage regulation.

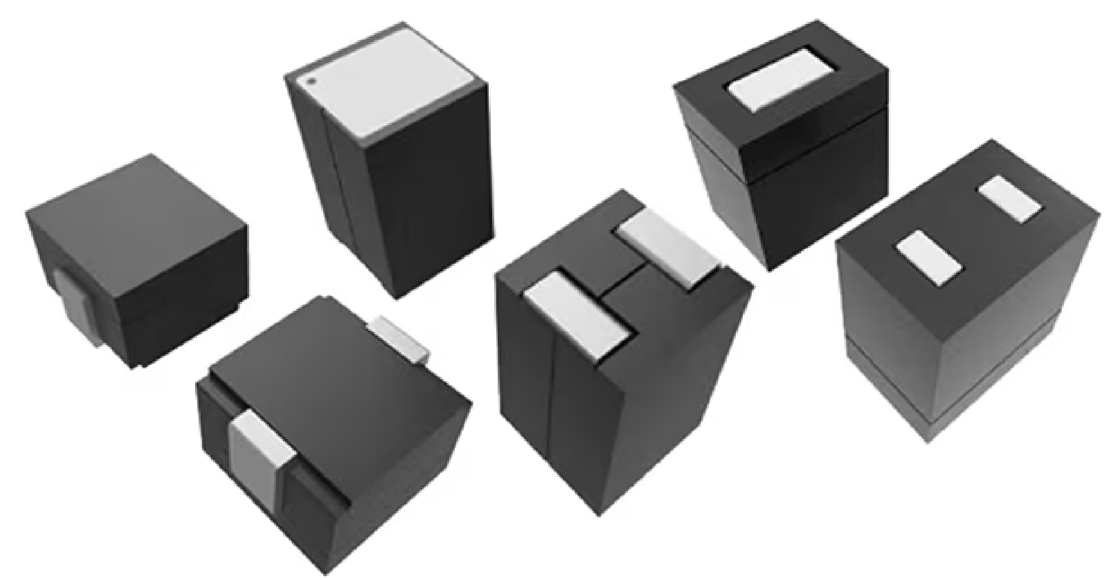
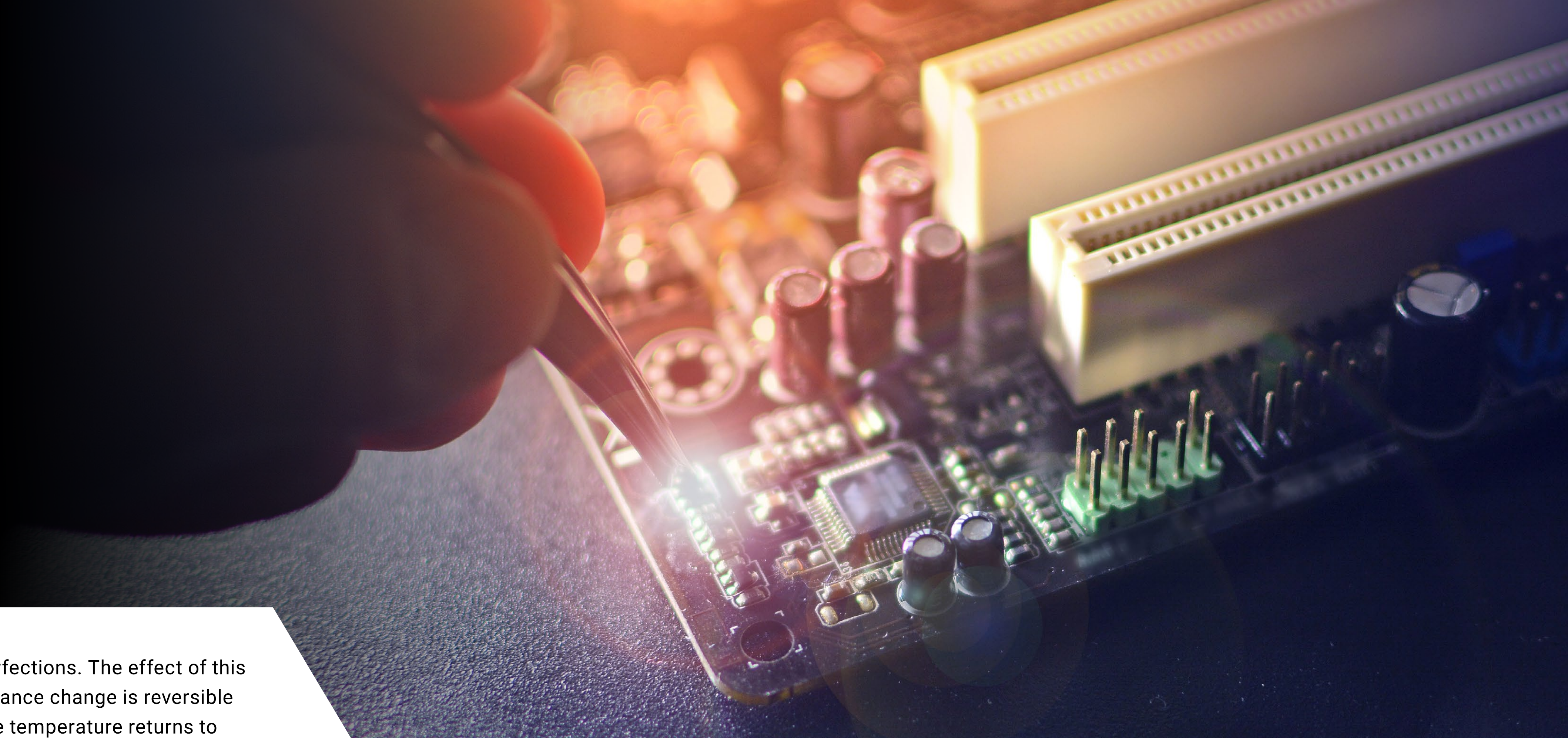


Figure 6: The AVR series of assembly inductors is specially designed, with construction, range of key parameter values, size, and more, to meet the unique needs of traditional DC/DC converters and for compensation in TLVR topologies. (Image source: Abracon)

Temperature coefficient of resistance for current sensing

By Vishay Intertechnology, Inc.



How temperature and construction affect resistance stability

The following topics will be discussed in the article.

1. What is TCR?
2. How is TCR determined?
3. How does construction affect TCR performance?
4. TCR in applications
5. How to compare datasheets

Cause and effect

Resistance is a result of a combination of factors that cause an electron's movement to deviate from an ideal path within a crystalline lattice of a metal or metal alloy. As an electron encounters defects or imperfections within the lattice it can cause diffusion. This increases the path traveled, resulting in increased resistance. These defects and imperfections can result from:

- Movement in the lattice due to thermal energy
- Different atoms present in the lattice, such as impurities
- Partial or complete absence of a lattice (amorphous structure)
- Disordered zones at the grain boundaries
- Crystalline and interstitial defects in the lattice

The temperature coefficient of resistance (TCR), sometimes referred to as resistance temperature coefficient (RTC), is a characteristic of the thermal energy component of the above imperfections. The effect of this resistance change is reversible as the temperature returns to reference temperature, assuming the grain structure was not altered from high temperatures resulting from an extreme pulse/overload event. For Power Metal Strip® and Power Metal Plate™ products, this would be a temperature that caused the resistance alloy to exceed 350°C.

This resistance change due to temperature is measured in ppm/°C, which widely varies among different materials. For example, manganese-copper alloy has a TCR of < 20 ppm/°C (for 20°C to 60°C), whereas copper used in terminations is approximately 3900 ppm/°C. Another way to represent ppm/°C that may be easier to consider is that 3900 ppm/°C is the same as 0.39 %/°C. These may seem like small numbers until you consider the change in resistance due to a temperature rise of 100°C. For copper that would cause a 39 % change in resistance.

An alternate method for visualizing the effect of TCR is to consider it in terms of the rate of expansion of a material with temperature (Figure 1). Consider two different bars, A and B, that are each 100 m in length. Bar A changes length at a rate of +500 ppm/°C and bar B changes length at a rate of +20 ppm/°C. A temperature change of 145°C will cause the length of bar A to increase 7.25 m, whereas bar B will only increase in length by 0.29 m. Below is a scaled (1 / 20) representation to visually demonstrate the difference. Bar A has a very noticeable change in length, whereas bar B has no visible change in length.

Figure 1: One method of visualizing the effect of TCR is to look at it the terms of rate of expansion of a material with temperature increase. (Image source: Vishay Dale)

This also applies to a resistor in that the lower TCR will result in a more stable measurement across temperature, which may be caused by applied power (causing the resistance element temperature to increase) or ambient environment.

How TCR is measured

TCR performance per MIL-STD-202 Method 304 is resistance change based on a reference temperature of 25°C. The temperature is changed and the device under test is allowed to reach equilibrium before the resistance value is measured. The difference is used to determine the TCR. For the Power Metal Strip WSL model, the TCR is measured at the low temperature of -65°C and then measured at +170°C. The equation follows below. Typically an increase in resistance with an increase in temperature results in a positive TCR. Also, note that self-heating causes a resistance change due to TCR.

Resistance - temperature coefficient (%):

$$\frac{R_2 - R_1}{R_1 \times (t_2 - t_1)} \times 100$$

Resistance - temperature coefficient (ppm):

$$\frac{R_2 - R_1}{R_1 \times (t_2 - t_1)} \times 1\,000\,000$$

Where:

R1 = resistance at reference temperature

R2 = resistance at operating temperature

t1 = reference temperature (25°C)

t2 = operating temperature

The operating temperature (t2) is often based on the application. For example, the temperature range for instrumentation is typically 0°C to 60°C, and -55°C to 125°C is the typical range for military applications. The Power Metal Strip WSL series provides TCR for its operating range of -65°C to +170°C, while the WSLT series has an extended temperature range to 275°C.

Table 1 below gives the TCR for some resistance materials used in the range of products associated with this article.

Figure 2 compares different TCR levels as a percentage change in resistance versus increasing temperature from 25°C.

The following equation calculates the maximum change in resistance value for a given TCR.

$$R = R_0 \times [1 + \alpha(T - T_0)]$$

Where:

R = final resistance

R0 = initial resistance

α = TCR

TCR, PPM/°C OF VARIOUS RESISTOR ELEMENT MATERIALS				
Temperature range	-55°C to +25°C	0°C to +25°C	+25°C to +60°C	+25°C to +125°C
Manganin	+50	+10	-5	-80
Zeranin	+20	±2.5	±5.0	+10
Evanohm	+5.0	+2.5	-2.5	-5.0
Foil	-1.0	-0.3	+0.3	+1.0
Thin film	-10	-5.0	+5.0	+10
Thick film	-100	-25	+50	+100

Table 1: Various resistor element material TCRs in ppm/°C. (Image source: Vishay Dale)

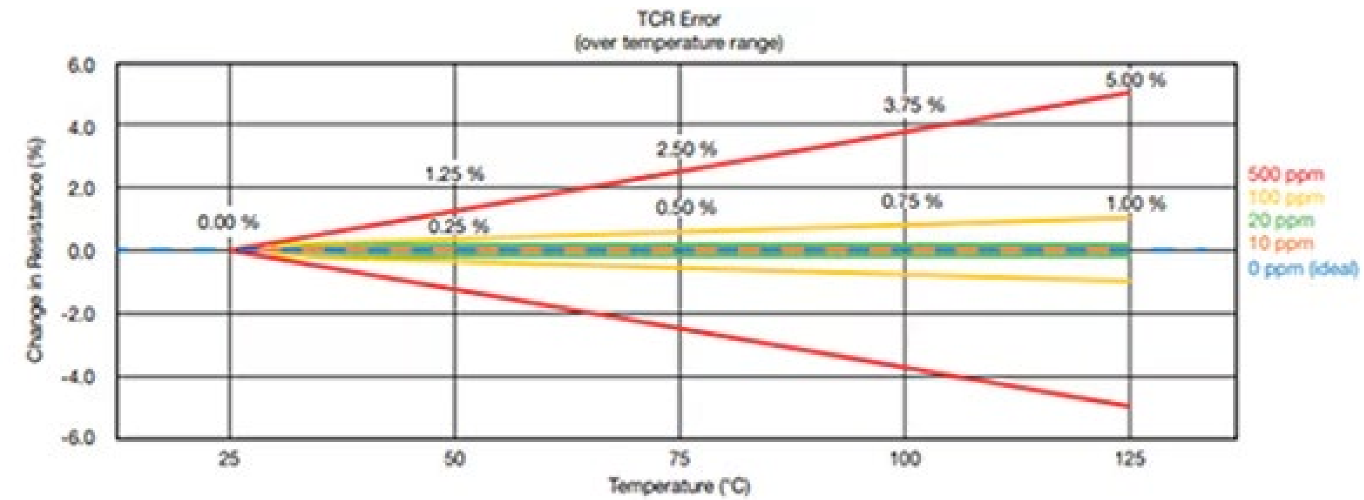


Figure 2: A comparison of different TCR levels as a percentage change in resistance over temperature. (Image source: Vishay Dale)

T = final temperature

T0 = initial temperature

Vishay offers an online TCR calculator at https://www.vishay.com/resistors/change-resistance-due-to-rtc-calculator/.

How construction affects TCR

The Power Metal Strip and Power Metal Plate series offer superior TCR performance when compared to traditional all-metal thick film current sense resistors. A thick film current sense resistor utilizes a material that is primarily silver, with terminals of silver and copper. Silver and copper have similarly large TCR performance values.

The Power Metal Strip resistor series uses a solid copper terminal (item 2 in Figure 4) that is electron beam welded to a low TCR resistance alloy (item 1), achieving low values down to 0.1 mΩ with low TCR. However, the copper terminal has a high TCR (3900 ppm/°C) compared to the resistance alloy (< 20 ppm/°C), which still plays a role in the overall TCR performance as lower resistance values are required.

The copper terminal provides a low resistance connection to the resistance alloy, which

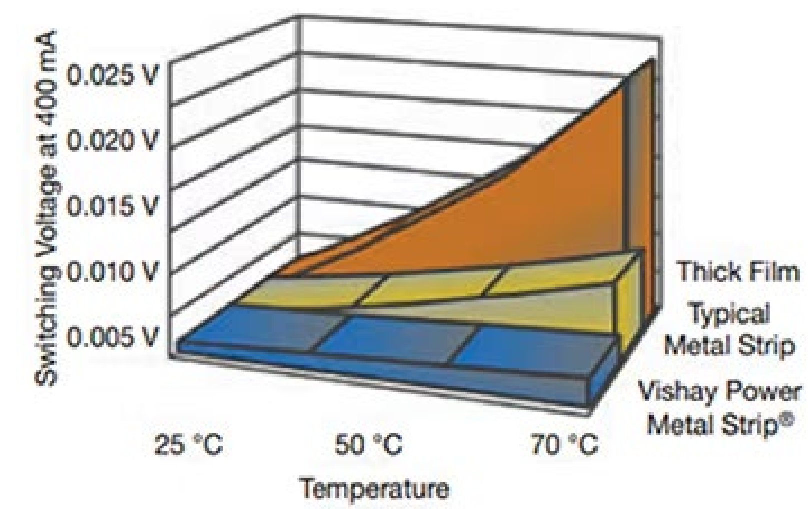


Figure 3: Comparison of Vishay Power Metal Strip resistors to typical metal strip and thick film resistors. (Image source: Vishay Dale)

enables uniform distribution of current flow to the resistance element for a more accurate current measurement for high current applications. However, the copper terminal has a high TCR (3900 ppm/°C) as compared to the resistance alloy (< 20 ppm/°C), which has a significant impact on the overall TCR performance at very low resistance values. This is portrayed in Figure 5 demonstrating how the total resistance is influenced by the combination of the copper terminal and the low TCR resistance alloy. For the lowest resistance values of a specific resistor construction, the copper becomes more significant in the TCR rating and performance.

This influence may occur at different resistance value ranges for different parts. For example, the TCR rating of the WSLP2512 is 275 ppm/°C at 1 mΩ, while the WSLF2512 is 170 ppm/°C at 1 mΩ. The WSLF has a lower TCR because the copper terminal has a lower resistance contribution for the same resistance value.

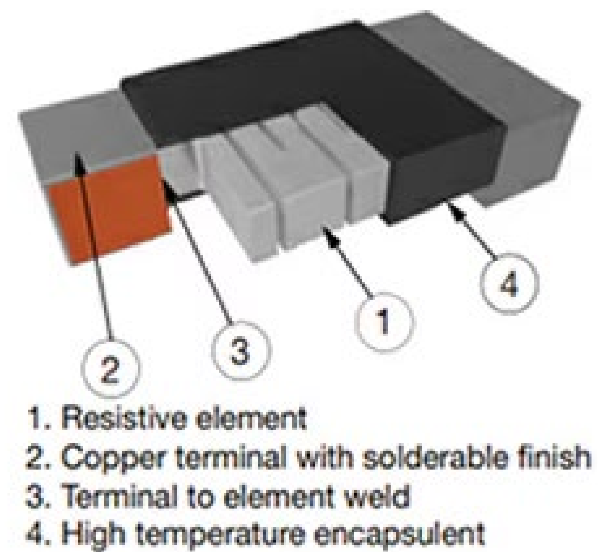


Figure 4: Typical construction of a Vishay Power Metal Strip resistor. (Image source: Vishay Dale)

Figure 5: For lower resistance values of a specific resistor construction, the copper becomes more significant in the TCR rating and performance. (Image source: Vishay Dale)

Kelvin terminal vs. 2 terminal

The Kelvin (4 terminal) construction provides two benefits: improved current measurement repeatability and improved TCR performance. The notched construction reduces the amount of in-circuit copper from the measurement. Table 2 illustrates the benefits of a Kelvin-terminated WSK2512 compared to the 2-terminal WSLP2512.

There are two key questions (The example in Figure 6 is of the WSL3637)

- *Why not notch all the way to the resistance alloy for the best TCR?*

This would introduce a new problem because the copper allows for a low resistivity connection to the region of current flow to be measured. Notching all the way to the resistance alloy would cause the measurement to be applied through a portion of the resistance alloy where there is no current flow. This would result in an increased measured voltage. It is a compromise between copper TCR effects and measurement accuracy and repeatability

- *Can I use a 4-terminal pad design to obtain the same results?*

No. While the 4-terminal pad design does offer better measurement repeatability, it does not remove the effects of copper from the measurement circuit. The resistor will still perform to the same rated TCR

Elevated construction

Kelvin terminal parts are not limited to a planar (or flat) type of construction. The WSK1216 and WSLP2726 are examples of resistors that use an elevated construction. The purpose is to save board space while still maximizing the portion of resistance that is contributed by the low TCR resistance alloy.

RESISTANCE RANGE (MΩ)		WSLP2512	WSK2512
0.5	0.99	400	350
1	2.9	275	250
3	4.9	150	75
5	200	75	35

Table 2: Comparison of the Kelvin-terminated WSK2512 to the 2-terminal WSLP2512. (Image source: Vishay Dale)

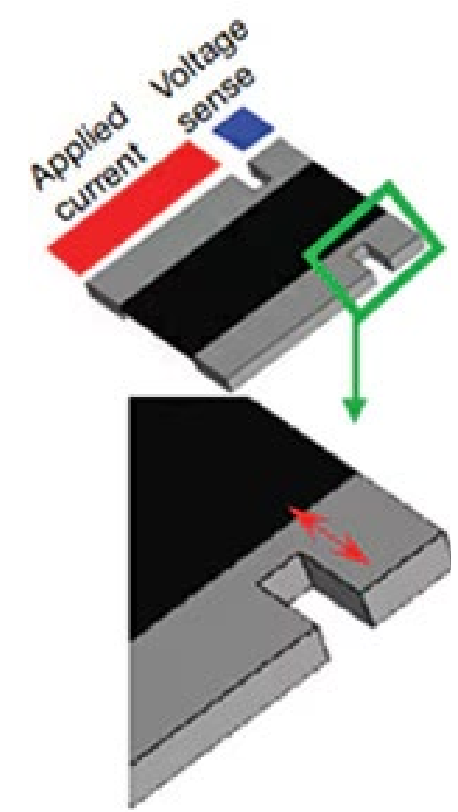


Figure 6: The notched construction (Vishay Dale's WSL3637 shown here) reduces the amount of in-circuit copper from the current sensing measurement. (Image source: Vishay Dale)

The combination of maximizing the resistance element and Kelvin termination provides a resistor with low TCR at very low resistance values (down to 0.0002 Ω), a small footprint, and high power rating.

Clad construction vs. welded

Terminals constructed by applying a thin copper layer to the resistive element will also affect TCR and measurement repeatability. The thin copper layer can be achieved by a clad construction or by electroplating. A clad construction is achieved by rolling sheets of copper and resistance alloy together under extreme pressure to create a uniform mechanical bond between the two materials. In both construction methods, the copper layer thickness is typically a few thousandths of an inch, which minimizes the effect of copper and provides an improved TCR. The tradeoff is that the resistor will shift slightly in value when mounted to the board because the thin copper layer does not permit a uniform distribution of current through the high resistance alloy. In some cases, the board-mounted resistance shift can be much greater than the effects from TCR between the resistor types being compared. For more information regarding clad construction, refer to https://www.vishay.com/doc?30333.

Another factor of construction can play a small role in a resistor's TCR characteristic in that the copper and resistance alloy properties may offset, providing a very low TCR characteristic. Detailed TCR testing for a specific resistor may be necessary to understand the full performance characteristic.

TCR in an application (ambient and applied power)

While TCR is typically considered in terms of how the resistor changes based on environmental or ambient conditions, there is another dimension to consider; temperature rise due to applied power. When power is applied the resistor heats due to converting electrical energy to thermal energy. This temperature increase due to applied power is also a component related to TCR, sometimes referred to as power coefficient of resistance (PCR).

PCR introduces another layer that is driven by construction, which is based on thermal conduction through the part or internal thermal resistance, R_{thi}. A resistor that has a very low thermal resistance on a high thermal conductivity board will maintain a lower resistor temperature. An example of this would be the WSHP2818, where the large copper terminal and internal construction provide a very thermally efficient construction that means the temperature will not rise significantly compared to the applied power.

Not all datasheets are created equally

Comparing specifications from multiple manufacturers can be difficult, as there are many ways to present TCR. Some manufacturers will list the element TCR, which is only part of the overall product performance as the termination effects are ignored. The most important parameter is the component TCR that includes the termination effects, which is how the resistor will perform in the application.

In other cases, the TCR characteristic will be presented for a limited temperature range, e.g. 20°C to 60°C, while another may present TCR characteristics across a wider operating range, e.g. -55°C to +155°C. When these resistors are compared, the resistor that is specified for a limited temperature range will present better performance than the resistor specified over a wider range. TCR performance is typically non-linear and worse in the negative temperature range. Detailed TCR curves specific to the resistor construction and resistance value may be available to support your design. Contact DigiKey or Vishay Dale at www2bresistors@Vishay.com.

Refer to the graphs in Figure 7 that show the non-linear TCR characteristic and how much difference the same resistor can present across a different temperature range.

If a datasheet lists TCR for a range of resistance values, better performance may be available. The lowest resistance value in the range will set the limit for the range due to termination effects. A resistor with the highest resistance value in the same range may have a TCR closer to zero because more of the resistance value is derived from the low TCR resistance alloy. For thick film, it is a combination of the silver content in the resistive film and the termination effect. One other point to clarify regarding this comparison of charts is that resistors do not always have this magnitude of slope, as some may be flatter, which is dependent upon the interactions of the TCR for both materials for the resistance value.

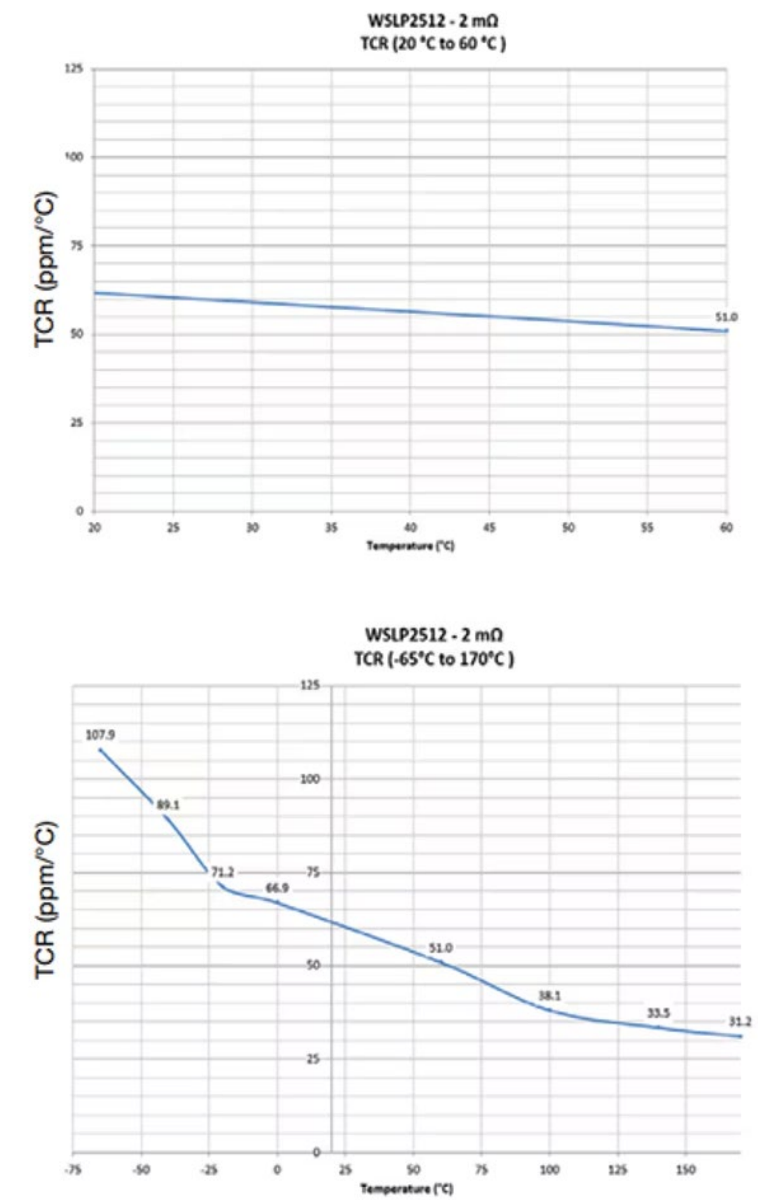


Figure 7: An example of the non-linear TCR characteristic and how much different the same resistor can present across a different temperature range. (Image source: Vishay Dale)

COMPARISON CHECKLIST

The purpose of this section is to offer a guide for comparing the TCR of one datasheet to another based on the details offered in this application note.

1. Are the resistor constructions similar?
   - Is the terminal construction clad, electroplated terminal, or a solid copper terminal?
   - Does the datasheet list the resistance alloy TCR or a component (total) TCR performance parameter? This is not always easy to determine
2. Temperature range
   - Is the temperature range for the specified TCR the same, such as 20°C to 60°C or wider?
   - Is the TCR value presented comparable for all resistance values?
3. Would the design benefit from a Kelvin termination for improved TCR performance?
4. Do you need more specific data for your design needs? www2bresistors@Vishay.com

Reference:

(1) Source: Zandman, Simon, & Szwarc Resistor theory and technology 2002 p. 23 - p.24

Additional resources

Overview: Power Metal Strip® Surface-Mount Current Sensing Resistors

Understanding and selecting film capacitors for power applications

By Art Pini
Contributed By DigiKey's North American Editors

Solar panel and electric vehicle (EV) use continues to increase. Their power systems rely on DC/DC converters and DC/AC inverters that require capacitors to reduce low-frequency ripple, filter high-frequency components that cause electromagnetic interference (EMI), and absorb transient load currents to prevent them from affecting the primary side of the power source. Capacitors for these power applications must be reliable, compact, lightweight, long-lived, and exhibit good high-frequency performance.

While film capacitors are a good option for these power applications, designers must understand their structure and characteristics to select the correct device.

This article provides a brief overview of film capacitors. It then discusses their selection and use in power applications using examples from Eaton-Electronics Division.

Film capacitors

Like all capacitors, film capacitors include two conducting plates separated by an insulating dielectric comprising a thin plastic film, typically made of polypropylene, a low-loss, high-strength dielectric (Figure 1). The conducting plates are thin metal foil or a thin layer of metal deposited on the dielectric. The foil and film are wound around a core, leads are attached, and the capacitor is enclosed in a plastic case and sealed with an epoxy resin, protecting the capacitor from the environment.

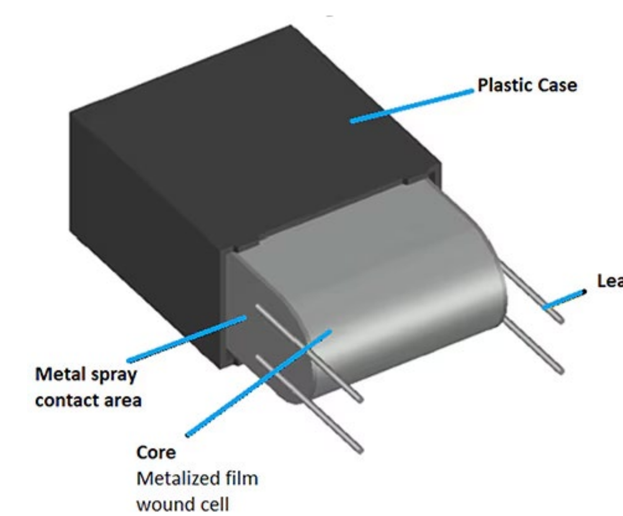


Figure 1: A film capacitor consists of a wound core containing alternating metal and dielectric layers, sealed in a protective plastic case. (Image source: Eaton-Electronics Division, modified by Art Pini)

While film capacitors have a relatively low energy density, they offer high capacitance density and several other features. First, film capacitors are nonpolar; they can be used in AC and DC circuits. Their dry, solid dielectric offers higher reliability than capacitors with liquid or semi-liquid electrolytes, and they have a stable capacitance value with excellent temperature stability. Lower equivalent series inductance (ESL) and equivalent series resistance (ESR) support the effective handling of high ripple currents and make film capacitors well-suited for high-frequency applications. Perhaps the most significant characteristic of film capacitors is that they are self-healing. If a dielectric breakdown occurs, a local hot spot is created that vaporizes adjacent metal, forming a non-conducting hole and allowing the capacitor to function normally, thereby extending its life.

Film capacitor types

Film capacitors are tailored for specific applications, and the common types are safety, DC link, AC filter, and pulse. Safety film capacitors are designed to attenuate conducted emissions in AC-line filtering applications. Many international safety standards have requirements for conducted EMI. Consider a line-powered DC charger for an EV. In fast-charging DC stations, common and differential-mode EMI filtering via capacitors serve as a low impedance to shunt noise signals with minimal power dissipation.

EMI suppression uses line filters comprising film capacitors between the power line and the switching power supply (Figure 2).

The capacitors marked C_X are placed line to line and reduce differential-mode EMI. The C_Y capacitors are wired from each line to ground, reducing common-mode EMI.

DC link capacitors serve as smoothing filters in DC circuits found between AC stages. An example is an inductor-capacitor (L-C) filter on the DC bus between a motor drive circuit's rectifier and inverter stages (Figure 3).

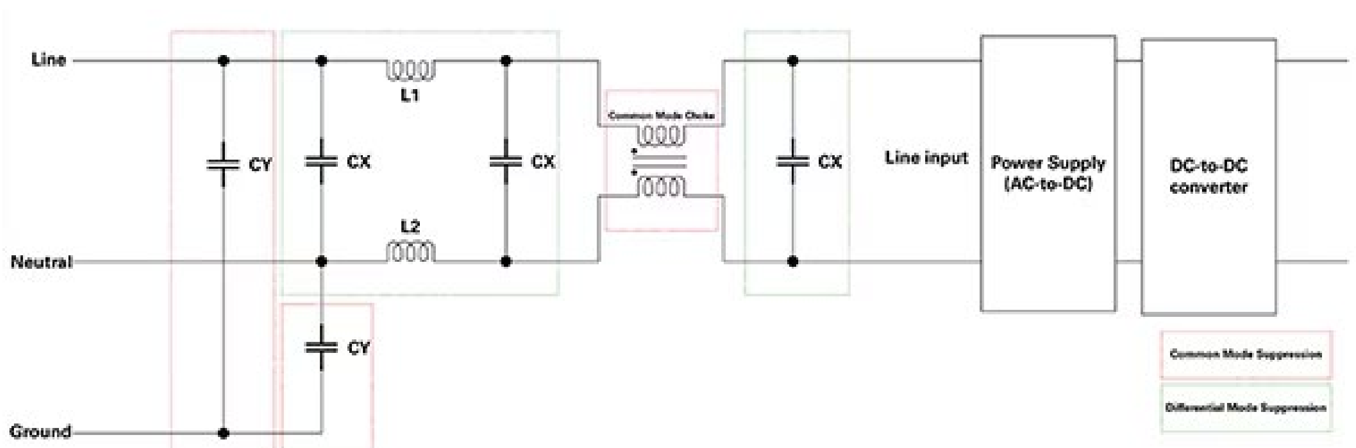


Figure 2: Safety film capacitors C_X and C_Y are incorporated into line filters to prevent EMI from propagating to the power line. (Image source: Eaton-Electronics Division)

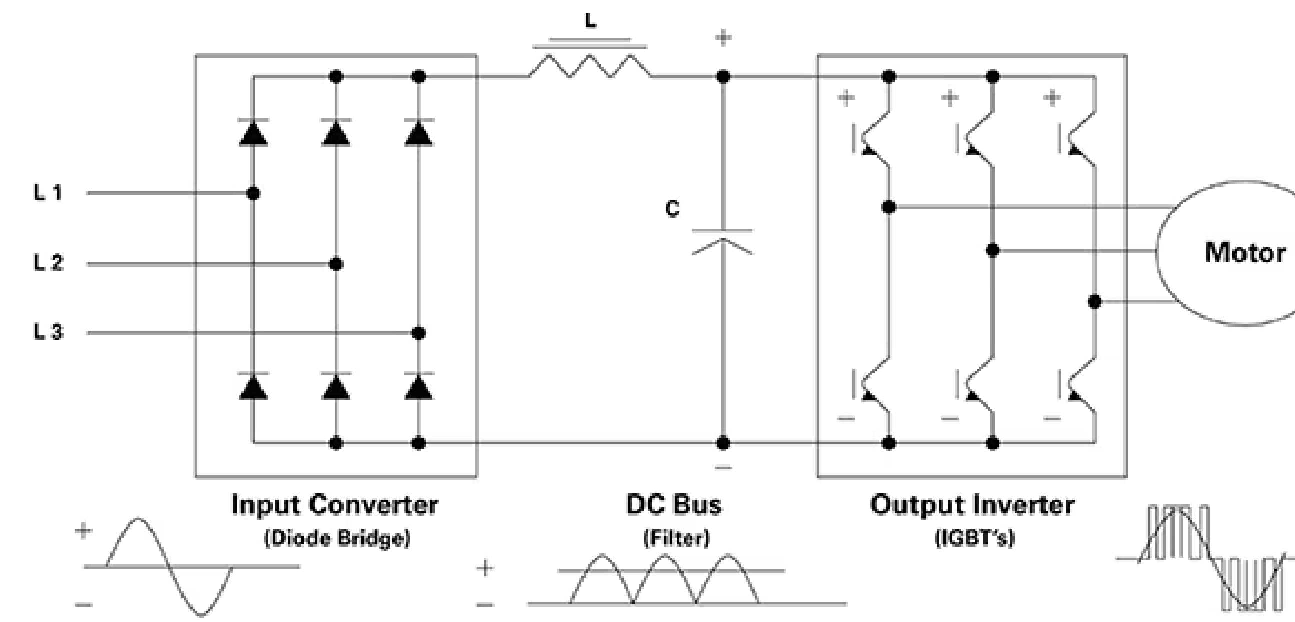


Figure 3: Shown is a DC link film capacitor used in an L-C filter between a motor drive circuit's rectifier and inverter stages. (Image source: Eaton-Electronics Division)

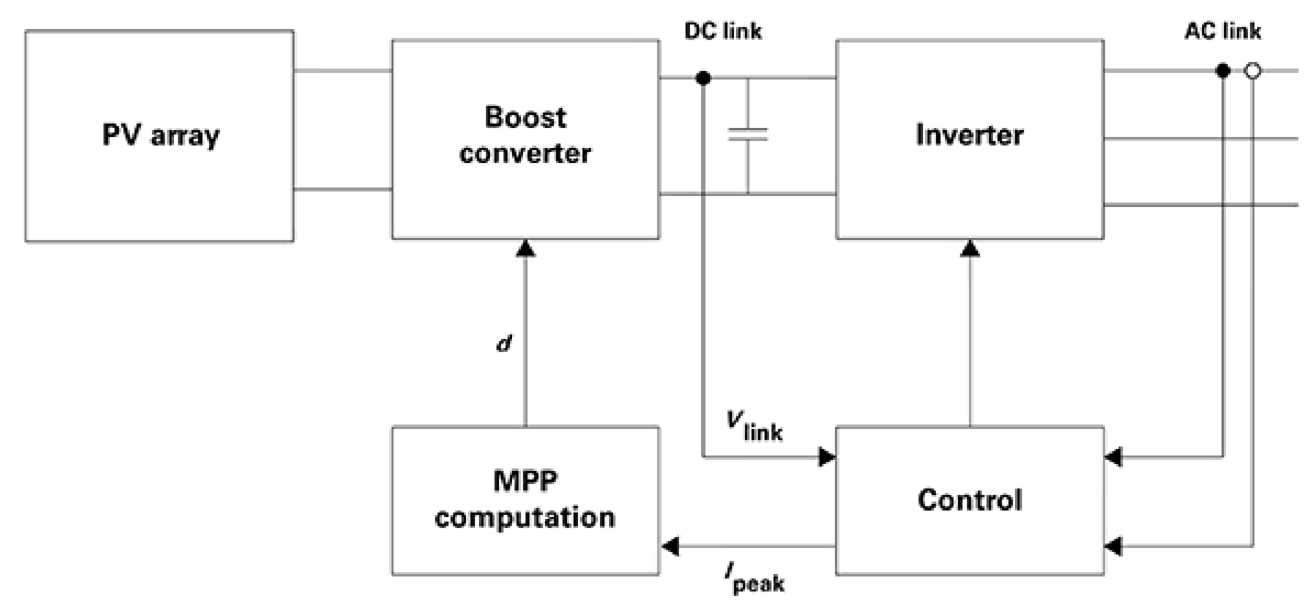


Figure 4: A DC link film capacitor suppresses noise and transients between a solar power system's boost converter and the inverter. (Image source: Eaton-Electronics Division)

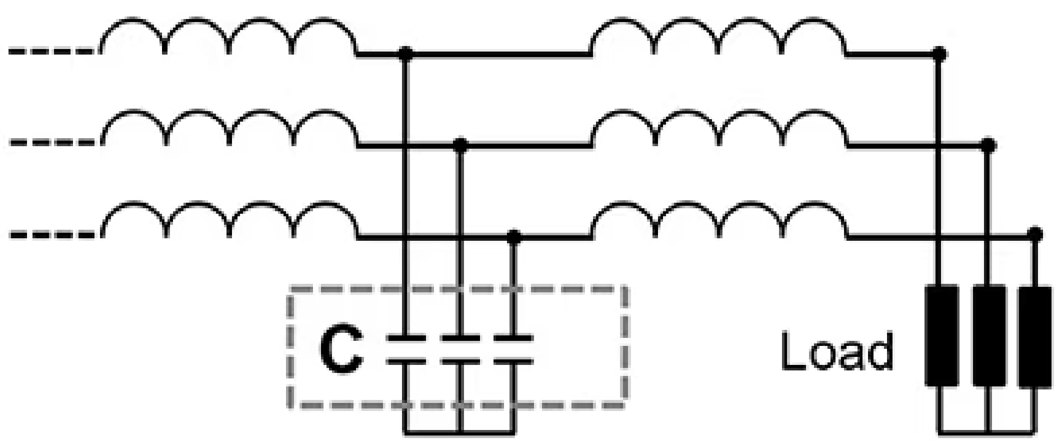


Figure 5: Shown are AC filter capacitors being used to filter a three-phase power source. (Image source: Eaton-Electronics Division)

Along with motor drives, these capacitors are also often found in power inverters and other high-power charging circuits where the AC input and AC output have different voltage levels. For example, consider a distributed inverter in a solar power system, where a DC link film capacitor is used to reduce noise and transients between stages (Figure 4).

The film capacitor reduces spurious signals at a point where the V_{link} line feeds information back to the control circuit, improving performance.

AC filtering capacitors help eliminate unwanted harmonic frequency content in applications such as three-phase AC power sources (Figure 5).

Film pulse capacitors are designed to protect sensitive components from high dV/dt voltage changes. They are used in pulsed electronic and power inverter applications. Designed for high energy density, they provide fast bursts of power in circuits such as resonant tank power converters (Figure 6).

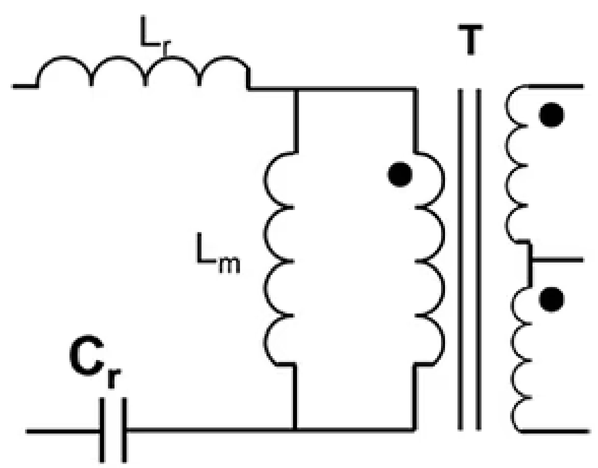


Figure 6: The pulse film capacitor forms a resonant tank circuit tuned relative to the switching frequency of the power converter, eliminating harmonics in the transformer secondary. (Image source: Eaton-Electronics Division)

Resonant tank circuits significantly improve the efficiency of inductor-inductor-capacitor (LLC) power converters. The pulse capacitor is used to tune the tank circuit relative to the switching frequency of a power converter. The resonant tank eliminates harmonics from the secondary of the transformer. Additionally, the resonant tank enables soft switching in the power converter switches, reducing losses and increasing efficiency.

Film capacitor construction

The characteristics of each type of film capacitor are determined by the materials used and the geometry of the film layers. For example, Eaton-Electronics Division's EFACA25J155D032LH AC filtering capacitor is a 1.5 microfarad (mF) ±5% capacitor with a maximum voltage rating of 250 V. It is AEC-Q200 qualified for automotive applications and has a THB type IIIB rating for humidity ingress.

Film capacitors are formed by alternating layers of the metalized dielectric. For the lowest voltage-rated capacitors (180 V_{AC} to 300 V_{AC}), the alternate layers are each connected to individual leads. Multiple layers in parallel increase the total capacitance, while placing two or more layers in series increases the voltage rating (Figure 7).

The leads are connected to each side of a split metallization for a higher voltage rating (350 V_{AC} to 500 V_{AC}. The alternate layer has a single metalized film isolated from the leads and serves as a common capacitor plate, resulting in two capacitors in series. This structure increases the breakdown voltage of the pair while lowering the capacitance. By placing multiple pairs in parallel, designers can increase the capacitance.

Using the same principle of isolated split segments, the 600 V_{AC} to 760 V_{AC}-rated capacitors create three series capacitors for every set of overlaid pairs.

Pulse capacitor applications and construction

Pulse capacitors are designed for applications that experience high dV/dt and currents. They exhibit low ESR and ESL, which improves their ability to absorb energy from transient voltage spikes. Their self-healing properties ensure reliable long-term operation.

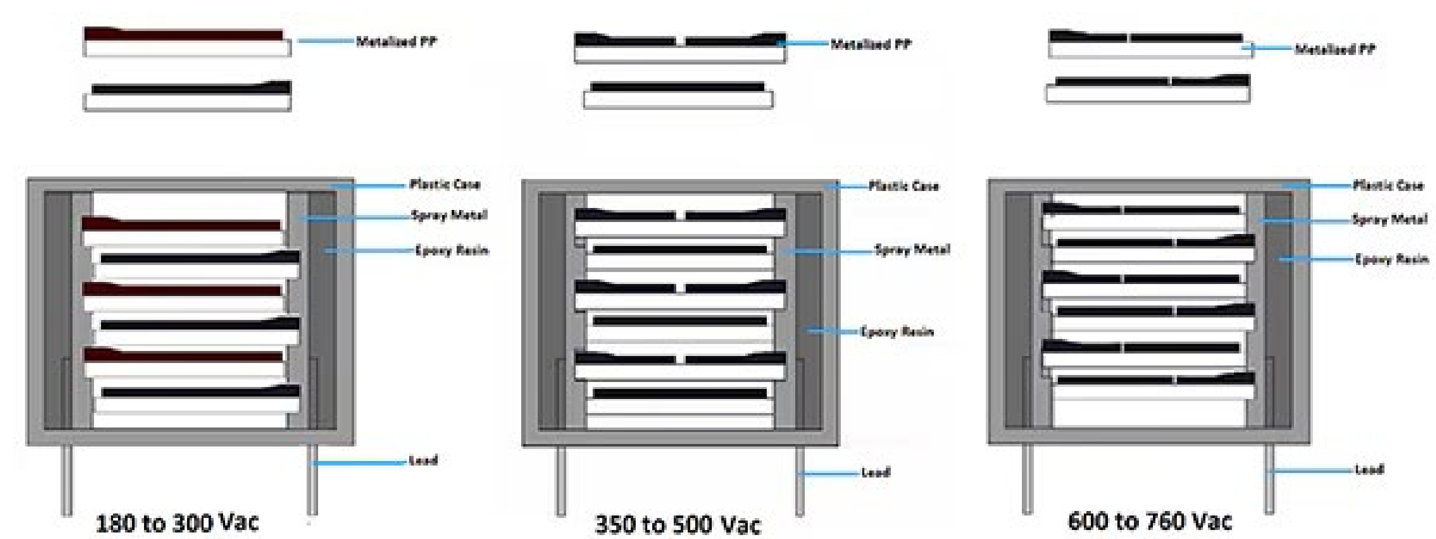


Figure 7: Adding multiple capacitors in series increases the voltage rating of a film capacitor. (Image source: Eaton-Electronics Division, modified by Art Pini)

Pulse film capacitors are well-suited for snubber applications in switched-mode power supplies, where they protect active switching devices from voltage spikes and ringing that occur during switching. For example, in Figure 8, a pulse film capacitor (C1) combined with a resistor (R1) and a diode (D1) forms a snubber that absorbs voltage spikes generated by the parasitic inductance of the transformer during the turn-off of the MOSFET switch.

When the MOSFET opens in a flyback switched-mode power converter, the drain current is at its maximum. The inductance of the transformer operates to maintain that current and rapidly raises the voltage. Initially discharged, the capacitor in the snubber circuit absorbs the inductive spike energy, protecting the MOSFET switch. The response time of the capacitive action is reduced by keeping the ESL low, allowing the snubber to handle the high dV/dt of the transient. The low ESR permits the high currents needed to absorb the transient energy during the switch turn-off.

The construction of the pulse film capacitor is optimized to handle high dV/dt and resulting currents (Figure 9).

Eaton-Electronics Division film pulse capacitors use a double-sided metalized dielectric film, effectively doubling the contact area between the capacitor plate and lead connection, thereby lowering the capacitor's ESR and increasing its current capability. For example, the EFPLS1GJ223B072LH is a 0.022 mF ±5% pulse film capacitor rated for a maximum voltage of 1600 V. It has an ESR of 30 milliohms (mΩ) and an ESL of 12 nanohenries (nH). It has a maximum dV/dt specification of 6,000 V per microsecond (V/µs) and an RMS current rating of 3.2 A, with a peak current rating of 132 A.

The related EFPLA series includes pulse film capacitors for severe environments, such as automotive, and conforms to THB Grade IIIB and AEC-Q200 specifications. The Eaton EFPLA2AJ153B092LH, for example, is a 0.015 mF ±5% pulse film capacitor rated for 2,000 V. It has an ESR of 45 mΩ and an ESL of 12 nH. It has a maximum dV/dt specification of 4,500 V/µs and an RMS current rating of 3 A, with a peak current rating of 142.5 A.

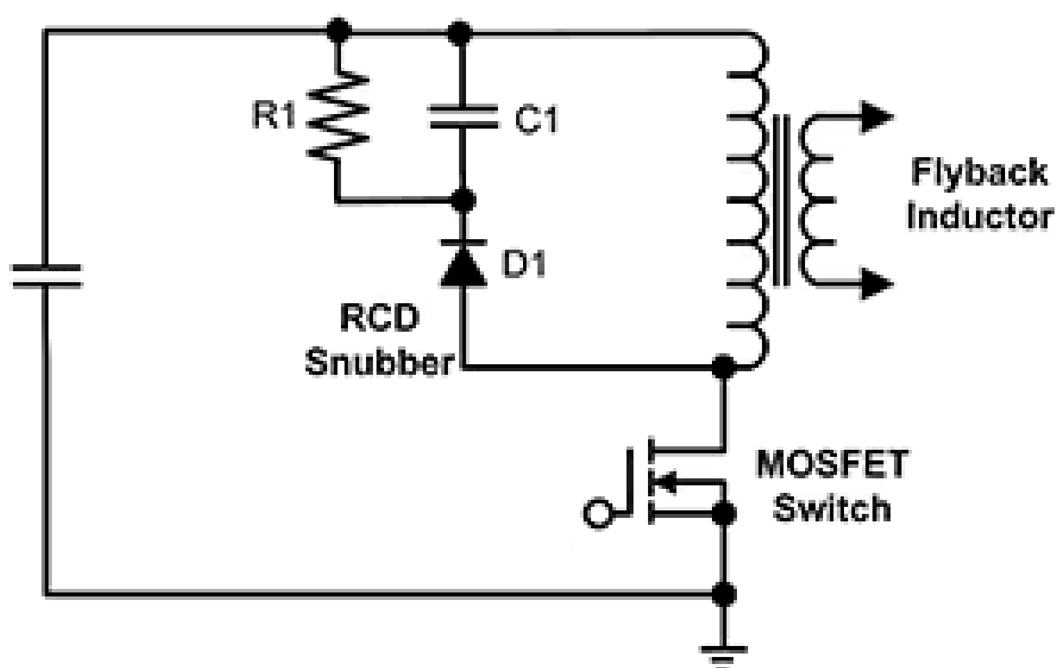


Figure 8: Pulse film capacitors such as C1 are well-suited to snubber applications in switched-mode power supplies, where they absorb voltage spikes generated by the parasitic inductance of the transformer during the turn-off of the MOSFET switch. (Image source: Art Pini)

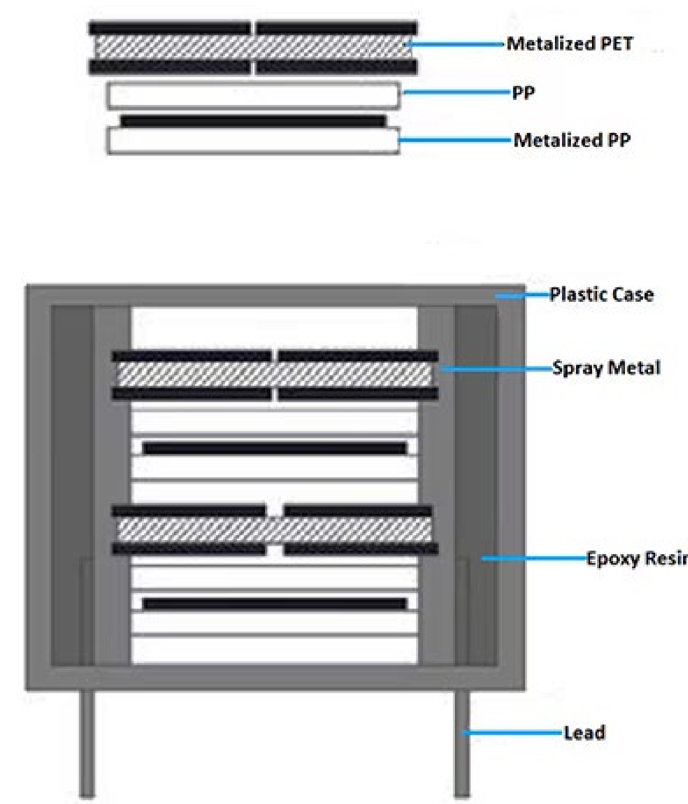
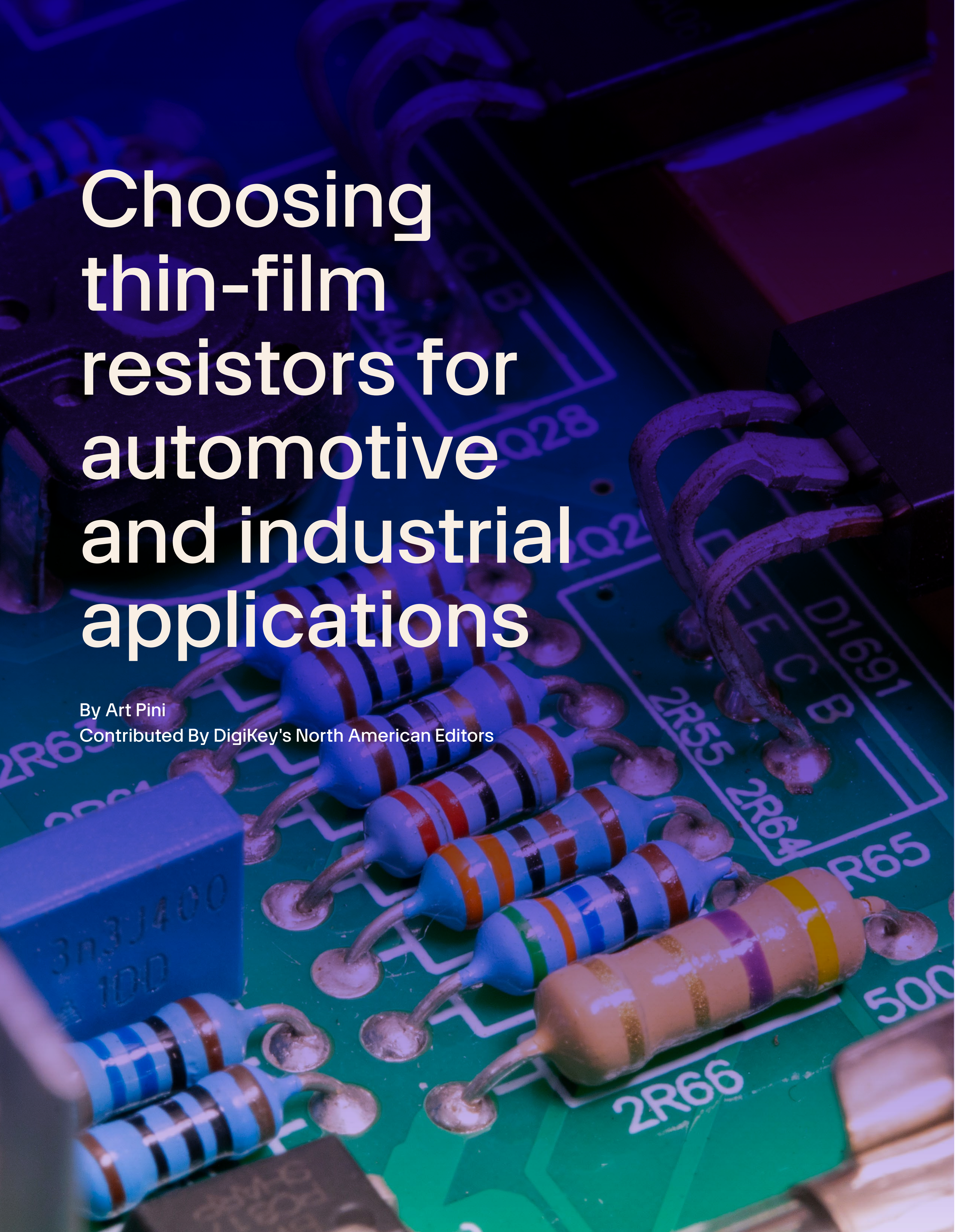


Figure 9: The internal structure of a pulse film capacitor employs a double-sided metalized dielectric film to reduce ESR. (Image source: Eaton-Electronics Division)

Conclusion

Film capacitors utilize dry, non-polarized technology and feature high capacitance density. They offer stable capacitance over temperature, handle high ripple currents and pulse and surge voltages, and are suitable for high-frequency and power applications. Their metalized construction also provides a self-healing capability, enhancing reliability and operational life and facilitating a more graceful failure mechanism. Eaton-Electronics Division offers a broad and growing range of metalized polypropylene film capacitors functionally optimized for multiple distinct applications and operating environments.



Choosing thin-film resistors for automotive and industrial applications

By Art Pini
Contributed By DigiKey's North American Editors

SMD PACKAGE	DIMENSIONS (INCHES)	DIMENSIONS (MM)	POWER RATING (W)
0402	0.039 x 0.02 x 0.014	1.0 x 0.5 x 0.35	0.063 (1/16)
0603	0.063 x 0.031 x 0.022	1.6 x 0.8 x 0.55	0.10 (1/10)
0805	0.79 x 0.049 x 0.024	2 x 1.25 x 0.6	0.125 (1/8)
1206	0.122 x 0.063 x 0.026	3.1 x 1.6 x 0.65	0.25 (1/4)

Table 1: Shown are the dimensions and power ratings for the four package sizes of the RP and AT chip resistor series components. (Table source: Art Pini)

Electronic applications such as automotive, industrial, and telecommunications require precision components that tolerate harsh environments, including high humidity and erosive atmospheres. Passive components are fundamental to the success of these advanced designs and require constant innovation to ensure reliable performance.

For example, metal film chip resistors must be designed and tested to ensure accuracy, stability, and reliability in challenging environments. One significant issue affecting the design of chip resistors for the automotive and industrial markets is their long-term reliability in the presence of sulfur compounds. These environments, where oils, lubricants, fuel, and other sulfur-rich compounds are extant, can degrade contacts and reduce the reliability of chip resistors.

This article discusses the challenges facing designers when choosing resistors for harsh automotive and industrial environments. It then presents two families of sulfur and moisture-resistant surface-mount resistors from YAGEO and shows how they can be used to meet the challenges of these applications.

Chip resistor characteristics

Chip resistors are a key component in modern electronics, including automotive, industrial, and telecommunication devices. Their small size, accuracy, stability, and reliability fit perfectly into high-density circuits. They come in a wide range of resistances, tolerances, temperature coefficients of resistance (TCRs), and power ratings. Two YAGEO chip resistor families are the AT and RP series. Both series are rated for automotive applications with AEC-Q200 qualification; this specification tests passive electronic components for temperature, humidity, resistance to soldering heat, thermal shock, and board flex tolerance. It also tests for low moisture sensitivity and sulfur resistance.

Comparing electrical specifications

The AT and RP series of surface-mount device (SMD) resistors are available in four standard surface-mount packages: 0402, 0603, 0805, and 1206. The numerical code for each package contains the device's nominal length and width in inches (Table 1).

The power ratings vary directly with the package volume, ranging from 1/16 W to 1/4 W.

These package sizes offer varied values of resistance, resistive tolerance, TCR, and voltage ratings. The specifications of the AT series resistors are summarized in Table 2.

The table lists the available range of resistor values for each package size, TCR, and tolerance.

AT Series Electrical Characteristics

TYPE	Operating Temperature Range	Power Rating	Max. Working Voltage	Max. Overload Voltage	Dielectric Withstanding Voltage	T.C.R. (ppm/°C)(2)	±0.01% (L)	±0.02% (P)	±0.05% (W)	±0.1% (B)	±0.25% (C)	±0.5% (D)	±1% (F)
							Resistance Range (E-24/E-96 series)(Ω) & Tolerance(1)						
AT0402	–55 °C to +155 °C	1/16W	50 V	100 V	100 V	±50 (E)				10 ≤ R ≤ 100K			
						±25 (D)				10 ≤ R ≤ 100K			
						±15 (C)	50 ≤ R < 11K			10 ≤ R < 11K			
						±10 (B)				50 ≤ R < 11K			
						±5 (A)				50 ≤ R < 11K		---	
AT0603		1/10W	75V	150 V	100 V	±50 (E)				10 ≤ R ≤ 330K			
						±25 (D)				10 ≤ R ≤ 330K			
						±15 (C)	50 ≤ R < 14K			10 ≤ R < 14K			
						±10 (B)				50 ≤ R < 14K			
						±5 (A)				50 ≤ R < 14K		---	
AT0805		1/8W	150 V	300 V	300 V	±50 (E)				10 ≤ R ≤ 1M			
						±25 (D)				10 ≤ R ≤ 1M			
						±15 (C)	50 ≤ R < 17K			10 ≤ R < 17K			
						±10 (B)				50 ≤ R < 17K			
						±5 (A)				50 ≤ R < 17K		---	
AT1206		1/4W	200 V	400 V	500 V	±50 (E)				10 ≤ R ≤ 1M			
						±25 (D)				10 ≤ R ≤ 1M			
						±15 (C)	50 ≤ R < 20K			10 ≤ R < 20K			
						±10 (B)				50 ≤ R < 20K			
						±5 (A)				50 ≤ R < 20K		---	

NOTE : 1. Global part number (code 7)
2. Global part number (code 9)

Table 2: Shown are the electrical characteristics of the AT series resistors. (Table source: YAGEO)

Similarly, the specifications for the RP series are summarized in Table 3.

Components of either product series are selected based on package size, TCR, resistance tolerance, and resistance. The range of available resistance values varies with each of the other specifications.

The TCR values for the RP series are available in steps of ±50, ±25, ±15, and ±10 parts per million per degree Centigrade (ppm/°C).

The AT series adds an additional lower TCR of ±5 ppm/°C.

Note that the range of available resistance values for the RP series devices is greater or equal to those of the AT resistors for each TCR step.

Both series offer tolerance values of 0.1%, 0.25%, 0.5%, and 1%, which are the most used resistor tolerances. However, the AT series offers three additional tolerance ranges: 0.05%, 0.02%, and 0.01%.

These precise tolerances are less frequently called for, and the resistor values offered have a more restricted range.

Comparing the AT and RP series resistors

The YAGEO AT0402FRE0710KL is a 10 kiloohm (kΩ), 1/16 W AT series resistor with a TCR of ±50 ppm/°C in an 0402 package. The RP series equivalent is the RP0402FRE0710KL, which has the same specifications. The difference in products is that the RP series offers resistance values of 10 Ω to 240 kΩ in this TCR range compared to the AT series range of 10 Ω to 100 kΩ. The RP series provides this range of resistance over all the TCR values, whereas the AT series reduces the range for TCR values of ±10 ppm/°C and ±5 ppm/°C.

The AT0603DRE0710KL is a 10 kΩ, 1/10 W AT series resistor in an 0603 package. Its TCR is ±50 ppm/°C. The RP0603DRD0710KL is an RP 0603 series resistor with the same nominal specifications except for the TCR, which is ±25 ppm/°C. The range of available resistances in the RP series is from 10 Ω to 910 kΩ. The AT resistors have values ranging from 10 Ω to 330 kΩ for the two highest TCR specifications and a much more restrictive range for the lower TCR selections.

In an 0805 package, the AT series AT0805BRD0710KL is a 10 kΩ, 1/8 W resistor with a TCR of ±25 ppm/°C. The equivalent RP entry, the RP0805BRD0710KL, has the same resistance, tolerance, and TCR. Again, the RP series has a broader resistance range over the full range of TCR selections, while AT resistors have a more restricted range for the lower three TCR selections.

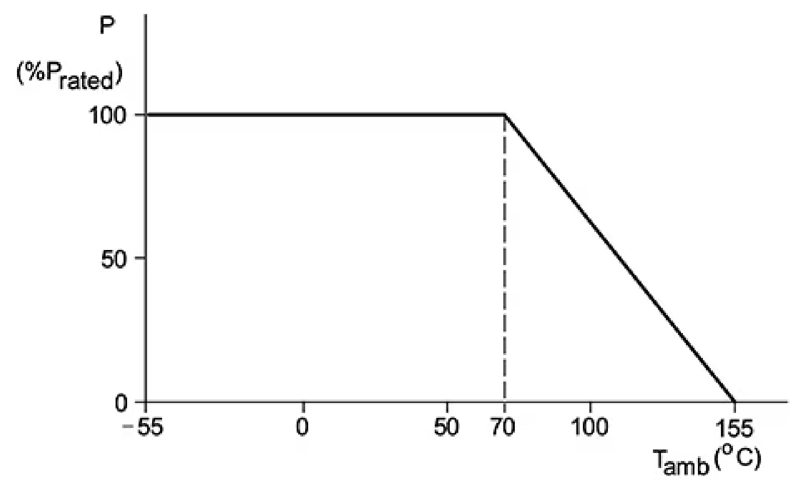
The AT1206BRD0710KL is a 10 kΩ, 1/4 W resistor in a 1206 package. Its RP equivalent is the RP1206BRD0710KL, with identical specifications.

RP Series Electrical Characteristics

TYPE	Operating Temperature Range	Power Rating@70°C (3) 07	Power Rating@70°C (3) 7W	Max. Working Voltage	Max. Overload Voltage	T.C.R. (ppm/°C)(2)	±0.1% (B)	±0.25% (C)	±0.5% (D)	±1% (F)	Unit weight (mg/pcs)
							Resistance Range (E-24/E-96 series)(Ω) & Tolerance(1)				
RP0402	–55 °C to +155 °C	1/16 W	--	50 V	100 V	±50 (E) ±25 (D) ±15 (C) ±10 (B)	10 ≤ R ≤ 300K				0.572
		--	1/8 W				10 ≤ R ≤ 240K				
RP0603		1/10 W	1/5 W	75V	150 V	±50 (E) ±25 (D) ±15 (C) ±10 (B)	10 ≤ R ≤ 1M				2.128
RP0805		1/8 W	1/4 W	150 V	300 V	±50 (E) ±25 (D) ±15 (C) ±10 (B)	10 ≤ R ≤ 1M5				4.642
RP1206		1/4 W	2/5W	200 V	400 V	±50 (E) ±25 (D) ±15 (C) ±10 (B)	10 ≤ R ≤ 1M5				10.116
RP1210		1/4 W	--	200 V	400 V	±50 (E) ±25 (D)	10 ≤ R ≤ 1M				15.805

NOTE : 1. Global part number (code 7)
2. Global part number (code 9)
3. Global part number (code 10-11)

Table 3: Shown are the electrical characteristics of the RP series resistors. (Table source: YAGEO)



Maximum dissipation (P_{max}) in percentage of rated power as a function of the operating ambient temperature (T_{amb})

Figure 1: The power derating curve for both series requires reduced power at temperatures above 70°C. (Image source: YAGEO)

Based on the electrical specifications, these resistor families are similar and would fit into many applications. The RP series offers a broader range of resistance values, making it more applicable. The AT series offers closer tolerances for some resistance values and a lower TCR range, and both of these characteristics would be applied in applications requiring greater precision and accuracy. Both series operate over a temperature range of -55°C to +155°C for their rated power levels. Note that the rated power must be derated if the ambient temperature rises above +70°C (Figure 1).

Environmental safety and protection

Both the AT and RP product families are qualified for use in automotive and industrial environments. The epoxy compounds used in their manufacture are halogen-free. Additionally, they are lead-free and meet RoHS specifications. These resistors also reduce environmentally hazardous waste production by using non-forbidden materials.

Both resistor product lines have low susceptibility to moisture and corrosive gases common in vehicular and industrial conditions. One aspect of moisture resistance is the moisture sensitivity level (MSL). This rating system used by the electronics industry identifies how long a component can be exposed to a humidity level of 60% to 85% relative humidity, and at a temperature below +85°F before it absorbs too much moisture to be wave soldered. During wave soldering, trapped moisture expands rapidly, damaging the component and possibly the circuit board. The AT and RP series resistors are rated at MLS 1, indicating an unlimited floor storage life. They are also tested for moisture resistance under AEC-Q200, and both series have variations in resistance of less than ±(0.1% + 0.05 Ω) due to exposure to humidity.

Contamination due to exposure to sulfur compounds is an increasing area of sensitivity for passive components like chip resistors. Oil, lubricants, oil-based fuels, and rubber components or coatings emit sulfur-based fumes. These sulfur compounds react with metals, especially silver, and can damage chip resistors.

The test (ASTM-B-809-95, modified) for sulfur resistance involves exposing test components to a sulfur-rich atmosphere created in a closed vessel by adding a measured amount of powdered sulfur. The vessel is heated to +105°C, and the components are exposed to this atmosphere for 750 hours. The resistors under test are measured to ensure their resistance changes less than a prescribed limit. Both series of resistors exhibit superior resistance to sulfur.

Differences between the AT and RP series resistors

The AT and RP series resistors have different designs. The AT series is an earlier design that uses a more traditional approach to moisture and sulfur resistance. The RP series is a more recent design incorporating newer construction techniques and materials (Figure 2).

Both series use a resistive metal film deposited on a ceramic substrate like all chip resistors. The AT resistors use copper as the top side electrode (C1) to reduce the corrosive effects of sulfur vapors, as copper's reaction with sulfur is not as strong as silver's. The resistive layer and the electrode are sealed using an epoxy overcoat. The end caps are made of tin-coated nickel to ensure solderability. They seal and provide connection points to the silver electrode on the bottom of the resistor.

Based on years of experience with related chip components, the RP devices add a polymer silver layer (C3) on top of the C1 inner electrode to prevent sulfur contamination. This allows the inner electrodes to be made of silver. A thin passivation layer is a barrier between the metal film and corrosive elements. Passivation is a chemical process that coats the resistive layer to make it less likely to corrode or be affected by its environment. An epoxy overcoat completes the sealing process.

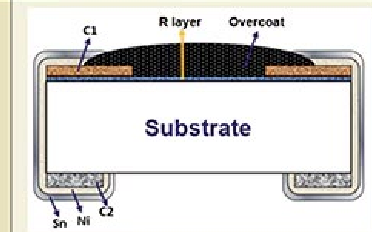
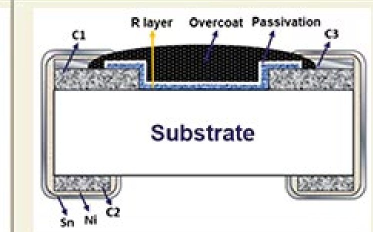
Product series		AT	RP
Structure			
Inner Electrode	C1	Cu	Ag
	C2/C3	Ag	Ag
Protective layer		Overcoat (Epoxy)	Overcoat (Epoxy) + Passivation
Substrate		High Grade Ceramic	High Grade Ceramic

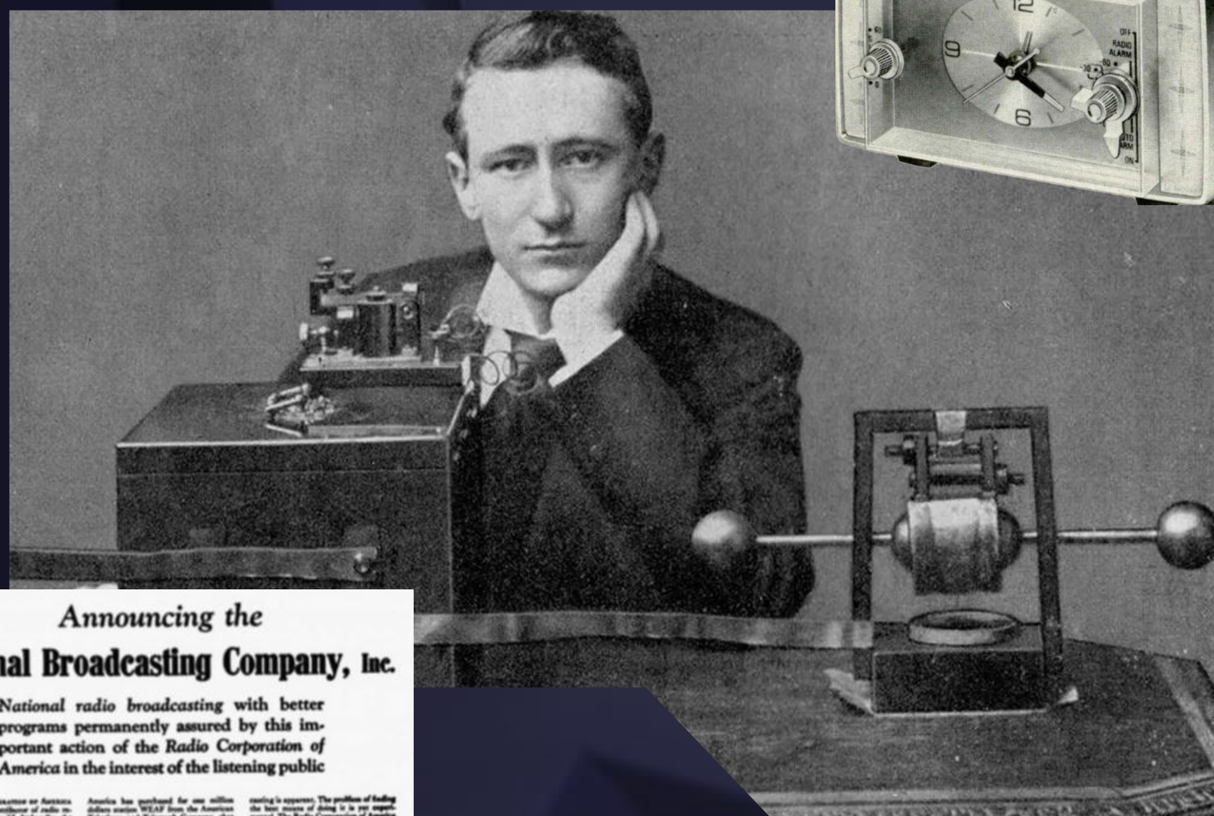
Figure 2: A comparison of the construction of the AT and RP series chip resistors shows the differences in how the devices are protected from moisture and sulfur. (Image source: YAGEO)

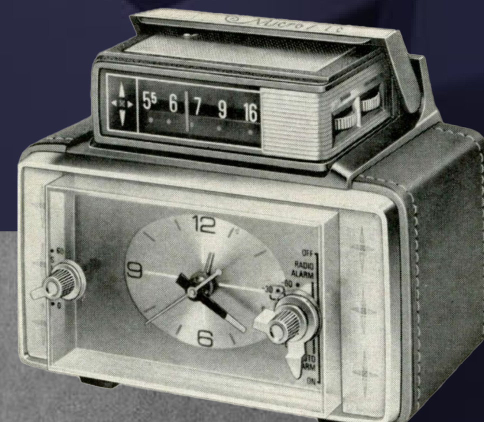
The RP series has better sulfur resistance than the AT series due to its improved sealing process. The sulfur test specification for the RP devices has a tighter limit of ±(2.0% + 0.05 Ω) compared with the AT limits of ±(4.0% + 0.05 Ω). This means a smaller change in resistance due to sulfur exposure.

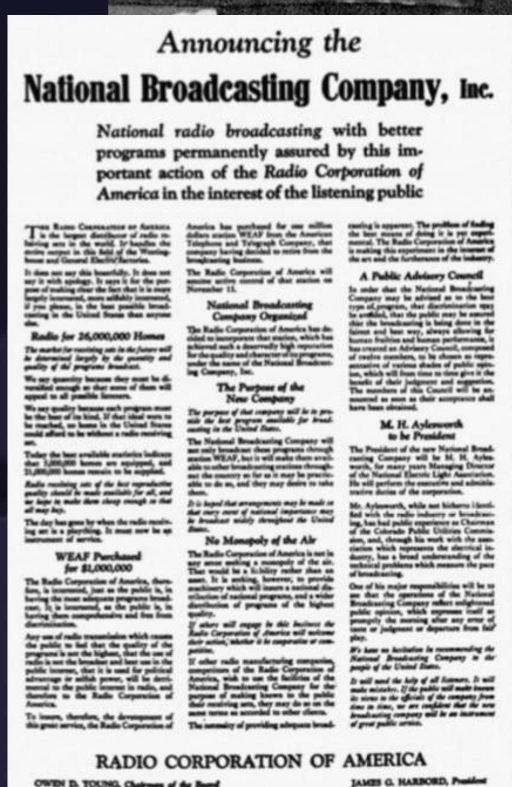
The newer resistor structure has also improved production efficiency, with lower costs and shorter lead times.

Conclusion

Automotive, industrial, and telecommunications systems require precision components that can reliably perform in harsh environments, including high humidity and erosive atmospheres. The AT and RP series resistors are AEC-Q200 qualified and well-suited to these applications. The RP series has improved humidity and sulfur tolerance, lower pricing, and shorter lead times. The AT series offers selective resistor values with lower tolerances of ±0.01%, ±0.02%, and ±0.05%.



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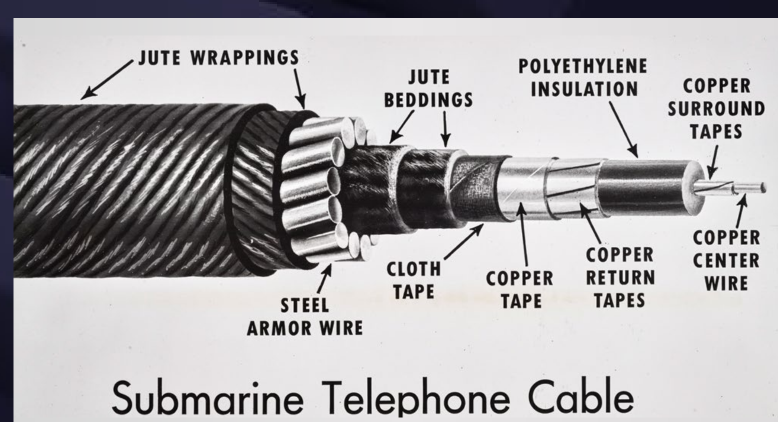


Two centuries of technology (1826-2026)

By David Ray, Cyber City Circuits

Happy New Year

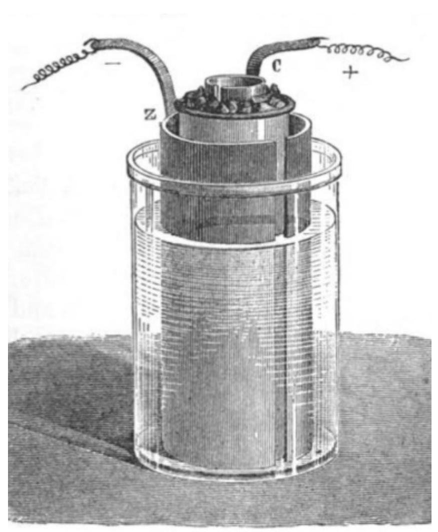
Happy New Year. 2026 is here and it marks two hundred years since Ampère first published his new Theories of Electro-Dynamics, essentially creating the new field of the study of electricity. As tribute to that event, the writer has collected twenty events, one for each decade, that came and shaped the coming years.

1826 –Theory of Electrodynamic Phenomena

André-Marie Ampère's 1826 publication "Théorie des phénomènes électrodynamiques, uniquement déduite de l'expérience" (Theory of Electrodynamic Phenomena, Uniquely Deduced from Experiment) marked a foundational moment in the history of electromagnetism. In this work, Ampère systematically codified the laws of interaction between electric currents, establishing a mathematical and conceptual framework that explained how currents produce magnetic effects. Building on Hans Christian Ørsted's discovery that a current-carrying wire can deflect a compass needle, Ampère demonstrated that magnetism was not a distinct force but rather a consequence of electric current in motion. His formulation of what is now known as Ampère's law described the force between two elements of current and introduced the concept of electrodynamic interactions as fundamentally mechanical and directional.

Retro Electro Fun Fact: Did you know that Ampère's father was beheaded during the French Revolution, while Ampère was a teenager? Learn more about that story in the Retro Electro Article 'Genius and Tragedy.' (Link: https://www.digikey.com/en/emedia/emagazine/2024/connectors?page=20)

What set Ampère's work apart was his insistence on deriving all conclusions directly from experiment, rather than from speculative models. By treating current elements as interacting along their lengths rather than just at discrete points, he laid the groundwork for later developments in field theory. Ampère's publication not only offered one of the earliest attempts to unify electricity and magnetism but also introduced concepts such as the electrodynamic moment and internal current loops to explain magnetic behavior. His rigorous experimental approach and mathematical formalism greatly influenced James Clerk Maxwell, whose own synthesis of electromagnetism expanded on Ampère's theories. In this way, Théorie des phénomènes électrodynamiques represents not just a milestone in 19th-century physics but a cornerstone in the modern understanding of electromagnetic fields.



1836 –John Daniell invents the Daniell Cell Battery

Before 1836, the best available source of electricity was Volta's 1800 "voltaic pile," a stack of zinc and copper discs separated by brine-soaked cloth. Though groundbreaking, it suffered from rapid voltage drop as hydrogen bubbles accumulated on the copper plate, along with corrosion and noxious acid fumes. These limitations made it unreliable for sustained work, a fatal flaw as telegraphy and laboratory research demanded a constant current. John Frederic Daniell's answer, introduced in 1836, was the "constant battery." His design involved placing zinc in dilute sulfuric acid within a porous earthenware cup, which was nested inside a copper container filled with copper sulfate. The key innovation was that the copper sulfate absorbed the hydrogen that once crippled Volta's pile, depositing copper metal instead. The result was a steady one-volt output with vastly reduced corrosion, fumes, and increased reliability.

The Daniell cell quickly became the foundation of 19th-century electrification. By the 1850s, telegraph networks relied on it, with the British General Post Office maintaining about 20,000 cells at its London station, and Western Union's New York hub housing racks of thousands on its own. Daniell himself demonstrated 70 cells powering an electric arc in 1839, an effect so intense it caused burns from ultraviolet exposure. By the 1860s, one Daniell cell was roughly defined as one volt, when establishing the first electrical standards. Safe, portable, and reliable, the Daniell cell powered telegraphs, electroplating shops, and scientific experiments throughout the Victorian era, remaining widely in use for the rest of the century.

1846 – Gutta Percha insulated cable first produced for commercial sale

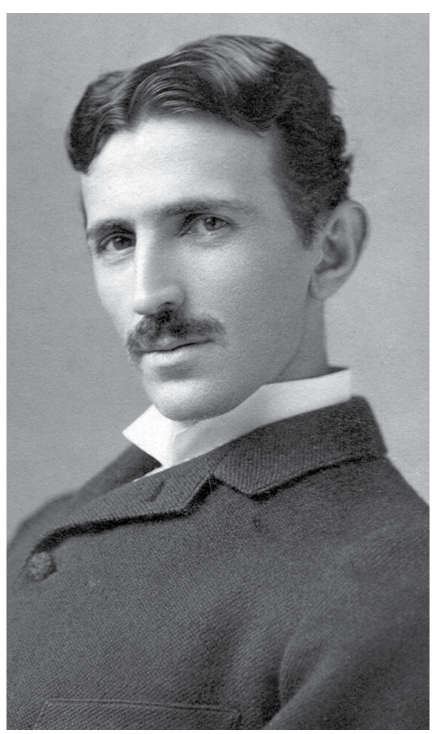
Telegraph cables with insulation made of gutta-percha were first sold on the British cable market in 1846. Gutta-percha, a natural latex extracted from the sap of the Palaquium gutta tree native to Southeast Asia, was used by local populations for various practical purposes long before Western scientists 'discovered' it in the 1840s. In 1843, Scottish surgeon Dr. William Montgomerie, working in Singapore, sent samples to London, demonstrating its malleable and waterproof properties, which sparked interest among inventors and engineers. Originally explored for medical and decorative uses, such as dental fillings and golf balls, gutta-percha's thermoplastic nature, softening when heated and hardening when cooled, made it highly versatile. Its introduction to Europe coincided with the rapid expansion of telegraphy, where early tests demonstrated its superior insulating qualities compared to materials like rubber, which degraded in the presence of moisture.

The use of gutta-percha in cable insulation, especially for submarine cables, allowed for the global telecommunications revolution of the 19th century. Proven to be an ideal non-conductive, waterproof, and durable insulator, it was first employed for submarine telegraph

Retro Electro Fun Fact: The Daniell cell became the initial standard for one volt, in the 1860s, following the propositions of a young telegraph engineer named Latimer Clark. It was internationally recognized in 1881. You can read the whole story in the Retro Electro article 'Ohm's Day.' (Link: https://www.digikey.com/en/emedia/emagazine/2024/power?page=14) cables in 1848 by the Gutta Percha Company, which quickly ramped up production to meet the growing demand. Its ability to protect copper wires from seawater corrosion and electrical leakage was crucial for long-distance underwater cables, leading to successes like the 1858 transatlantic cable that drastically cut communication times between continents from weeks to minutes. Without gutta-percha, the growth of international telegraph networks would have been severely hindered, delaying global connectivity advancements until synthetic materials like polyethylene were developed in the mid-20th century.

1856 – The birth of Nikola Tesla

Nikola Tesla, born on July 10, 1856, in Croatia (then part of the Austrian Empire), emerged as one of the most visionary inventors and engineers in the history of electrical science. His significant contributions include pioneering work that laid the foundation for modern electrical power systems and wireless technologies, revolutionizing humanity's ability to harness and distribute energy. Tesla's innovative thinking challenged the status quo, particularly during the "War of the Currents" between George Westinghouse and Thomas Edison, where he promoted alternating current (AC) over direct current (DC). This not only proved more efficient for long-distance transmission but also facilitated the widespread electrification of the world, powering homes, industries, and cities on an unprecedented scale. Beyond his technical achievements, Tesla's forward-looking ideas on renewable energy and global communication continue to inspire modern advancements in sustainable technologies and the Internet of Things.



1866 – the successful completion of the 'second' trans-atlantic cable

The failure of the 1858 transatlantic cable left Europe and America without a working link for nearly a decade. While engineers like Charles Bright and William Thomson (later Lord Kelvin) pushed for a second attempt, the outbreak of the American Civil War in 1861 diverted funding, ships, and public attention away from the project. It was not until 1865 that a new expedition was launched using the giant ship Great Eastern, which carried the entire cable in its holds. That attempt failed when the line snapped and was lost on the ocean floor, but the experience proved invaluable for planning the next mission.

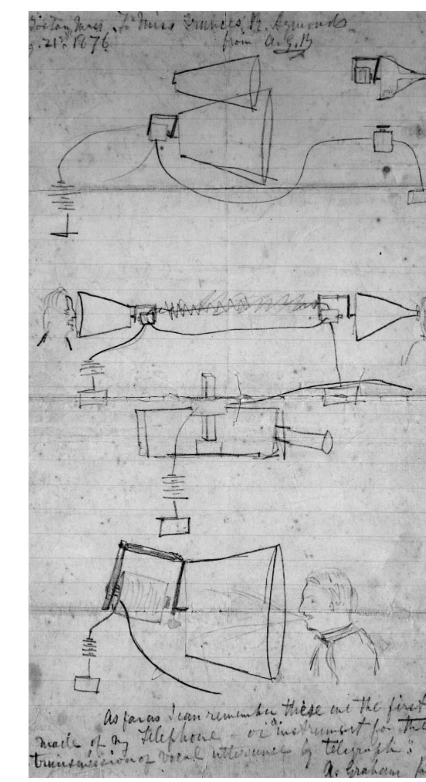
In 1866, the Great Eastern set out once again, this time with improved cable design, better manufacturing controls, and Thomson's mirror galvanometer to detect faint signals. The expedition not only succeeded in laying a continuous cable between Ireland and Newfoundland but also recovered and spliced the broken 1865 cable, leaving two working transatlantic lines in service.

Messages that once took weeks by ship could now be exchanged in minutes. This triumph marked the true beginning of global communications between Europe and the New World.

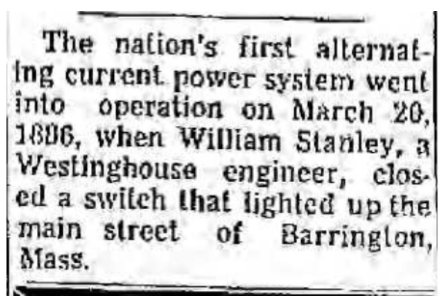
1876 – Alexander Graham Bell is awarded the patent for the telephone

The invention of the telephone resulted from decades of experimentation with the telegraph, as inventors aimed to transmit not just clicks and codes, but the full range of the human voice. Alexander Graham Bell, a Scottish-born teacher of the deaf, pursued this vision by exploring how sound waves could be converted into varying electrical currents and then transformed back into sound at the other end of a wire. Working with his assistant, Thomas Watson, in Boston, Bell developed a working prototype by 1876 that could clearly transmit recognizable speech. His famous first words, "Mr. Watson, come here, I want to see you", marked the beginning of a communications revolution.

Bell's achievement didn't happen in isolation. Other inventors, like Elisha Gray, were also working towards the same goal, submitting patents for similar devices within hours of Bell's patent. The close timing led to years of legal disputes, but Bell's claim was ultimately upheld in court, cementing his place in history. Within a few years, the telephone shifted from a laboratory curiosity to a commercial enterprise, with the Bell Telephone Company laying wires across cities and towns. This invention revolutionized business, government, and daily life, reducing distances and changing the way people connected in the modern world.



Retro Electro Fun Fact: Did you know that William Stanley Jr also invented the all-metal vacuum-insulated bottle, today known as 'the Stanley cup'? Learn more in the Retro Electro Article 'Forgotten Genius: William Stanley Jr's Legacy in Electrical Engineering.' (Link: https://www.digikey.com/en/emedia/emagazine/2025/power?page=12)


The nation's first alternating current power system went into operation on March 20, 1886, when William Stanley, a Westinghouse engineer, closed a switch that lighted up the main street of Barrington, Mass.

1886 – The electrification of Great Barrington, Massachusetts

The electrification of Great Barrington in 1886 marked a major achievement in electrical engineering, led by William Stanley Jr., who showed the world's first practical alternating current (AC) power distribution system. Stanley transformed a closed-down rubber mill into a testing lab in his childhood home of Great Barrington. There, he set up a 25-horsepower Westinghouse steam engine and a 500-volt Siemens alternator, building transformers to increase voltage to 3,000 volts for transmission and reduce it to 100 volts for safe use at each 'subscriber' location. On March 20, 1886, this system successfully powered 26 businesses and 400 incandescent lamps along Main Street, using over 4,000 feet of wire strung along elm trees. This proof-of-concept solved the major problems of Thomas Edison's direct current (DC) systems, which experienced large voltage drops over short distances, needing heavy conductors and many pollution-causing power stations. Stanley's innovations, such as a closed magnetic core in his transformers, boosted efficiency and stability, making long-distance power transmission practical and scalable.

1896 – first public demonstration of wireless telegraphy

Guglielmo Marconi, born in 1874 in Bologna, Italy, stands as a pivotal figure in the history of electrical

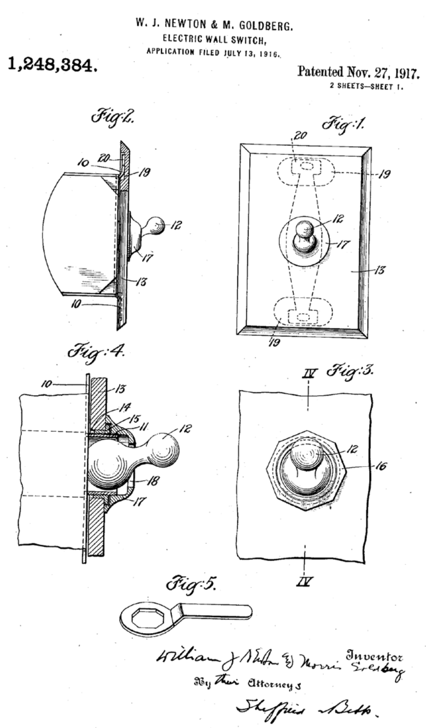
science due to his groundbreaking work in developing wireless telegraphy, which revolutionized global communication. His vision to transmit signals through the air without wires transformed the possibilities of long-distance communication, laying the groundwork for modern radio, television, and satellite technologies. Marconi's relentless experimentation with electromagnetic waves, building on the theoretical work of James Clerk Maxwell and Heinrich Hertz, enabled him to create practical systems for wireless transmission. His contributions earned him the 1909 Nobel Prize in Physics, shared with Karl Ferdinand Braun, and his innovations were instrumental in maritime safety, military communication, and the eventual rise of broadcasting. Marconi's ability to combine scientific inquiry with entrepreneurial drive made wireless technology a reality, connecting the world in ways previously unimaginable.

On December 12, 1896, Marconi conducted his first public demonstration of radio at Toynbee Hall in London, a landmark event in the history of electrical communication. During this demonstration, he transmitted Morse code signals wirelessly across the lecture hall, causing a bell to ring on the receiving end without any physical connection, an astonishing feat for the audience. This event, facilitated during a lecture by his supporter William Preece of the British Post Office, showcased the practical potential of his wireless telegraphy system, which he had been refining since his initial experiments in Italy. Marconi's demonstration marked a turning point, proving that electromagnetic waves could reliably carry signals over distances, and it garnered significant public and scientific interest, paving the way for further advancements like his 1901 transatlantic transmission. This 1896 milestone solidified Marconi's reputation as a pioneer and set the stage for the wireless revolution.

1906 – Reginald Fessenden's Christmas Eve radio broadcast

On Christmas Eve of 1906, Canadian-American inventor Reginald Fessenden achieved what is widely recognized as the first radio broadcast of voice and music. Transmitting from a station in Brant Rock, Massachusetts, he amazed ship operators and amateur listeners, accustomed only to Morse code clicks, by playing an Edison cylinder phonograph recording of Handel's Largo, performing "Silent Night" on the violin, and reading from the Gospel of Luke. The broadcast was received on ships and stations nearby, while there are reports of it being heard as far away as Scotland.

Fessenden's demonstration was a major technological breakthrough. Despite the primitive receivers of the time, primarily crystal oscillators and electrolytic detectors, the broadcast was clear enough to understand, demonstrating that radio could carry actual voice communication rather than just telegraph signals. This simple holiday transmission marked the launch of broadcasting, offering a glimpse of the worldwide networks of music, news, and storytelling that would characterize the twentieth century.



1916 – the modern wall switch

In 1916, inventors William J. Newton and Morris Goldberg of Lynbrook, New York, patented an innovation so simple and practical that it quietly reshaped daily life: the modern toggle wall switch. Before their design, switching household electric lights often meant handling clunky knife switches or rotary knobs, devices that were awkward, dangerous, and prone to excessive wear. Newton and Goldberg's switch enclosed the live contacts inside a protective housing and introduced a small lever that snapped between on and off positions. This not only reduced the risk of electrical shock but also provided users with the reassuring tactile feedback we still associate with flipping a light switch on today.

The toggle switch quickly became a standard fitting in American homes as electrical wiring spread in the early 20th century. Its intuitive design required no explanation, helping electricity shed its reputation as a hazardous novelty and integrate seamlessly into everyday life. More than just a convenience, it represented a subtle but important step toward safer and more reliable electrical infrastructure, ensuring that even a child could control a light without danger.


Announcing the
National Broadcasting Company, Inc.
National radio broadcasting with better programs permanently assured by this important action of the Radio Corporation of America in the interest of the listening public
RADIO CORPORATION OF AMERICA

1926 – RCA creates the National Broadcasting Company (NBC)

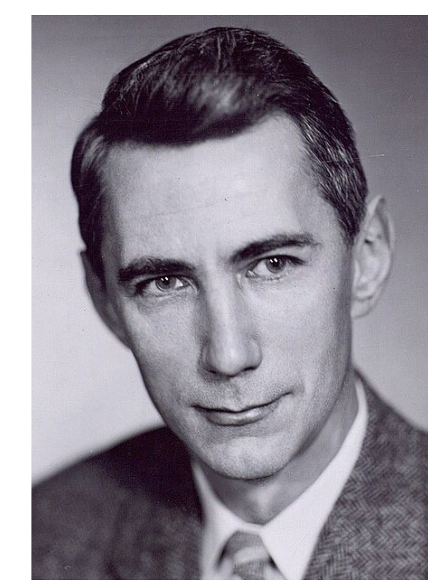
In the early 1920s, American radio was a patchwork of local stations, each operated independently and mostly owned by companies like Westinghouse, GE, or AT&T. Programming was regional and inconsistent, with nothing resembling a stable national service. This changed in 1926 when the Radio Corporation of America (RCA) purchased AT&T's flagship station WEAF and its broadcast assets, then merged them with its own stations. From this merger, the National Broadcasting Company (NBC) was formed, becoming the first major American radio network.

Retro Electro Fun Fact: RCA held a lot of influence in the electronics industry in the early twentieth century. So much so it is credited for creating the standards that became the naming conventions used for discrete semiconductor devices, like the 1N4004 diode and the 2N2222 transistor. Learn that story in this Retro Electro article about the origins of semiconductor part designators. (Link: https://www.digikey.com/en/emedia/emagazine/2024/sensors?page=17)

NBC's innovation was to knit dozens of stations across the United States using leased long-distance trunk lines from AT&T and 'clear-channel stations' at 50 kilowatts. For the first time, a listener in San Francisco could hear the same broadcast as a family in New York, and overnight, radio turned into a national communication medium. NBC's dominance was so complete that in the 1940s, the government forced RCA to sell off a large portion of its network, which reemerged as the American Broadcasting Company (ABC). In less than twenty years after Fessenden's first audio broadcast, there was a true nationwide broadcast radio network.

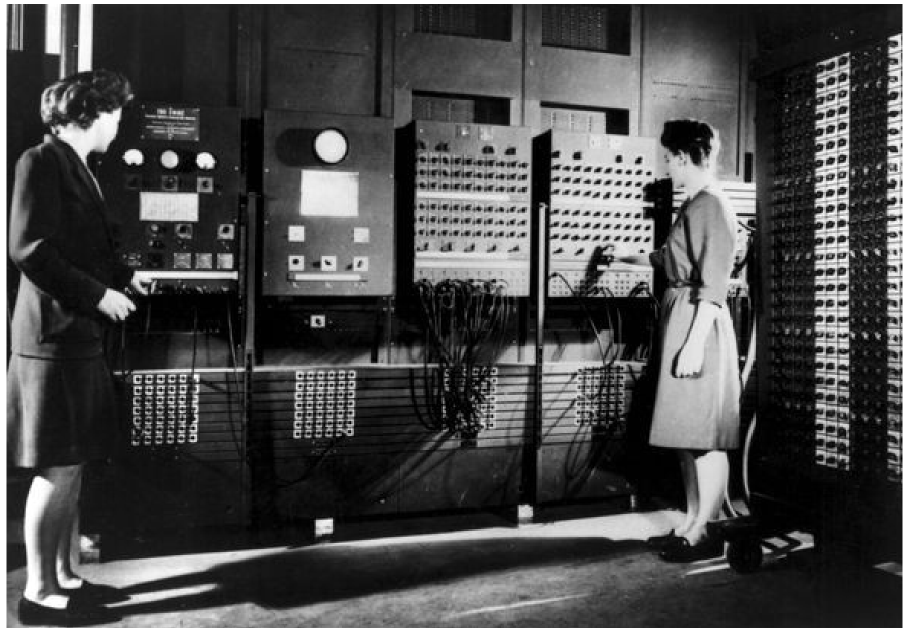
1936 – Claude Shannon begins work on his master's thesis

Claude Shannon's master's thesis, A Symbolic Analysis of Relay and Switching Circuits, is widely regarded as one of the most influential documents in modern technology. In this work, Shannon demonstrated that the algebraic methods developed by George Boole in the mid-1800s could be directly applied to the design and analysis of electrical switching circuits, such as those using relays and telephone exchange hardware. By demonstrating that logical propositions could be represented using circuit diagrams, and vice versa, Shannon unified two previously distinct fields: abstract symbolic Boolean logic and practical electrical engineering. This insight meant that any logical function could be systematically realized with a combination of relays, paving the way for a rigorous, mathematical approach to digital circuit design.



Retro Electo Fun Fact: Claude Shannon played a key part in the milestone 1955 Dartmouth Summer Research Project on Artificial Intelligence. Learn more in the Retro Electro article 'Programming a Calculator to Form Concepts.' (Link: https://www.digikey.com/en/emedia/emagazine/2024/edge-ai?page=11)

His thesis established the conceptual foundation for digital computers, demonstrating that binary logic was not just a mathematical curiosity but a powerful engineering tool. Every digital circuit in use today, from microprocessors and memory chips to control systems, is based on the principles outlined by Shannon in 1937. His work offered both a new theoretical framework and a practical design method that engineers could adopt, facilitating the shift from ad hoc relay designs to systematic, scalable digital systems. In hindsight, A Symbolic Analysis of Relay and Switching Circuits served as the blueprint for the digital age, often cited as the most important master's thesis in history.



1946 - ENIAC: Electronic Numerical Integrator and Computer

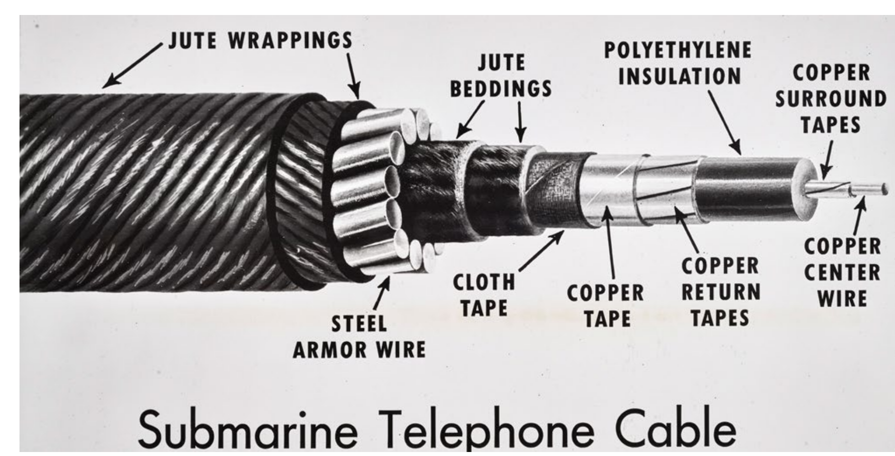
In February 1946, the University of Pennsylvania unveiled the ENIAC, the Electronic Numerical Integrator and Computer, to the public as the world's first general-purpose electronic computer. Built by John Mauchly and J. Presper Eckert under a $500,000 U.S. Army contract, the machine was originally intended to speed up the calculation of artillery firing tables during World War II. ENIAC was massive, using nearly 18,000 vacuum tubes; it was 100 feet long and weighed about 30 tons.

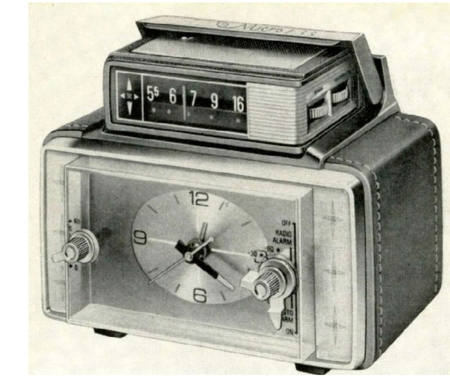
Though it wasn't completed before the end of WWII, it was used afterward to run hydrogen bomb simulations and weather forecast calculations. It was later moved to the Aberdeen Proving Ground, where it was finally used to produce the ballistics tables it was designed for and remained in operation until 1955. It is reported that it could perform over 5,000 addition problems per second, making it far faster than mechanical calculators, though programming it required physically rewiring the machine and setting switches.

1956 – The first transatlantic telephone cable 'TAT-1'

In the summer of 1956, TAT-1 (Transatlantic No. 1), the first of its kind submarine telephone cable, was strung across the ocean to carry voice conversations between North America and Europe, not via choppy radio, but through a continuous, high-fidelity line stretching nearly 2,000 miles from Oban, Scotland, to Clarenville, Newfoundland. It was a feat of both engineering and diplomacy. For the first time, someone in London could pick up a phone and speak directly to someone in New York with a clarity and immediacy that radio had never quite delivered. Designed to carry just 36 simultaneous calls, TAT-1's capacity now seems quaint, but at the time, it was a technological triumph that connected continents in real time.

What made TAT-1 possible wasn't just cable, it was amplification. Roughly every 40 miles along the ocean floor, sealed repeaters powered by vacuum tubes re-energized the signal, ensuring that a human voice wouldn't get attenuated into noise halfway across. The design drew heavily from wartime research into radar and long-range communications, and its successful deployment represented the culmination of decades of development in telegraphy, telephony, and electronics.





1966 – General Electric releases the first single-IC radio

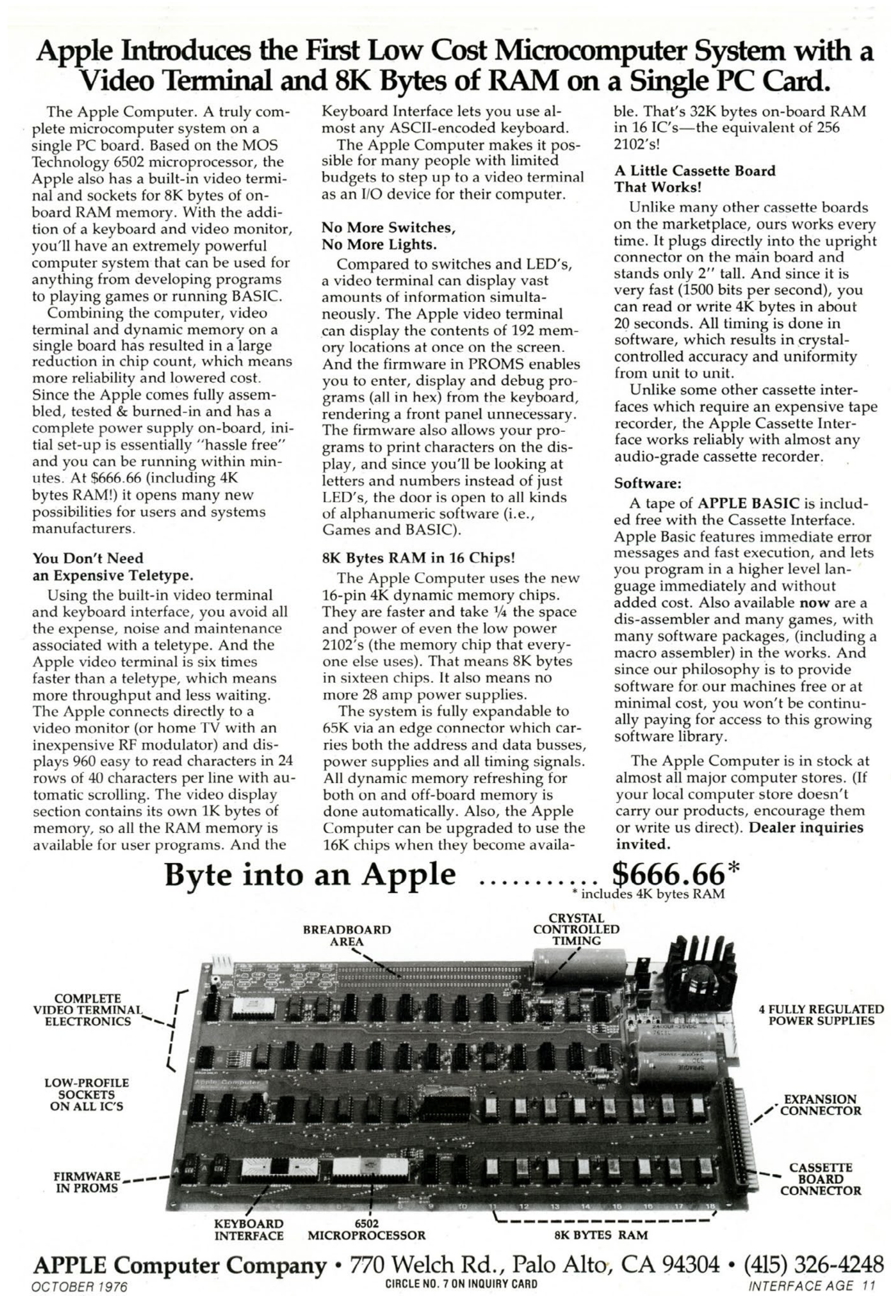
In November 1966, General Electric unveiled the P1740, the world's first mass-produced AM radio built around a single integrated circuit. Instead of dozens of discrete transistors and resistors, the design was squeezed into a monolithic silicon chip just 35 by 40 mils in size, about the footprint of a single audio transistor. Marketed with a three-year warranty and powered by a rechargeable nickel-cadmium battery, the P1740 promised reliability and portability at a price point that would eventually fall below six dollars.

The P1740 marked a turning point: the integration of consumer radio electronics onto a single chip. Although external components, such as inductors, transformers, and capacitors, were still required, the heart of the receiver was now an IC "black box." For engineers, it demonstrated how affordable integrated circuits could be scaled for consumer products. In hindsight, this little AM set was a harbinger of the pocket calculators, digital watches, and eventually microcomputers that would carry integrated circuits into every corner of daily life.

1976 – No more switches, no more lights – The Apple computer

The Apple-1 computer was released in 1976, marking Apple Computer's first commercial product and an important turning point in the history of personal computing. Designed by Steve Wozniak and marketed by Steve Jobs, it differed from other hobbyist machines of the era because it was sold as a fully assembled circuit board rather than a kit of parts. Running on the newly introduced MOS Technology 6502 microprocessor, the Apple-1 featured 4 KB of RAM, composite video output for a standard television, and support for an external keyboard, removing the intimidating front panels of switches and lights that characterized earlier systems like the Altair 8800.

The Apple-1 sold for $666, and its simplicity made it one of the first computers that an average enthusiast could set up and use at home. Fewer than 200 Apple-1s were ever produced, but the sales gave Apple the momentum to develop the Apple II, launched in 1977, which became one of the defining machines of the early personal computer era.



Apple Introduces the First Low Cost Microcomputer System with a Video Terminal and 8K Bytes of RAM on a Single PC Card.

The Apple Computer. A truly complete microcomputer system on a single PC board. Based on the MOS Technology 6502 microprocessor, the Apple also has a built-in video terminal and sockets for 8K bytes of on-board RAM memory. With the addition of a keyboard and video monitor, you'll have an extremely powerful computer system that can be used for anything from developing programs to playing games or running BASIC.

Combining the computer, video terminal and dynamic memory on a single board has resulted in a large reduction in chip count, which means more reliability and lowered cost. Since the Apple comes fully assembled, tested & burned-in and has a complete power supply on-board, initial set-up is essentially "hassle free" and you can be running within minutes. At $666.66 (including 4K bytes RAM!) it opens many new possibilities for users and systems manufacturers.

You Don't Need an Expensive Teletype.

Using the built-in video terminal and keyboard interface, you avoid all the expense, noise and maintenance associated with a teletype. And the Apple video terminal is six times faster than a teletype, which means more throughput and less waiting. The Apple connects directly to a video monitor (or home TV with an inexpensive RF modulator) and displays 960 easy to read characters in 24 rows of 40 characters per line with automatic scrolling. The video display section contains its own 1K bytes of memory, so all the RAM memory is available for user programs. And the Keyboard Interface lets you use almost any ASCII-encoded keyboard.

The Apple Computer makes it possible for many people with limited budgets to step up to a video terminal as an I/O device for their computer.

No More Switches, No More Lights.

Compared to switches and LED's, a video terminal can display vast amounts of information simultaneously. The Apple video terminal can display the contents of 192 memory locations at once on the screen. And the firmware in PROMS enables you to enter, display and debug programs (all in hex) from the keyboard, rendering a front panel unnecessary. The firmware also allows your programs to print characters on the display, and since you'll be looking at letters and numbers instead of just LED's, the door is open to all kinds of alphanumeric software (i.e., Games and BASIC).

8K Bytes RAM in 16 Chips!

The Apple Computer uses the new 16-pin 4K dynamic memory chips. They are faster and take ¼ the space and power of even the low power 2102's (the memory chip that everyone else uses). That means 8K bytes in sixteen chips. It also means no more 28 amp power supplies.

The system is fully expandable to 65K via an edge connector which carries both the address and data busses, power supplies and all timing signals. All dynamic memory refreshing for both on and off-board memory is done automatically. Also, the Apple Computer can be upgraded to use the 16K chips when they become available. That's 32K bytes on-board RAM in 16 IC's—the equivalent of 256 2102's!

A Little Cassette Board That Works!

Unlike many other cassette boards on the marketplace, ours works every time. It plugs directly into the upright connector on the main board and stands only 2" tall. And since it is very fast (1500 bits per second), you can read or write 4K bytes in about 20 seconds. All timing is done in software, which results in crystal-controlled accuracy and uniformity from unit to unit.

Unlike some other cassette interfaces which require an expensive tape recorder, the Apple Cassette Interface works reliably with almost any audio-grade cassette recorder.

Software:

A tape of **APPLE BASIC** is included free with the Cassette Interface. Apple Basic features immediate error messages and fast execution, and lets you program in a higher level language immediately and without added cost. Also available **now** are a dis-assembler and many games, with many software packages, (including a macro assembler) in the works. And since our philosophy is to provide software for our machines free or at minimal cost, you won't be continually paying for access to this growing software library.

The Apple Computer is in stock at almost all major computer stores. (If your local computer store doesn't carry our products, encourage them or write us direct). **Dealer inquiries invited.**

Byte into an Apple $666.66*
* includes 4K bytes RAM

APPLE Computer Company • 770 Welch Rd., Palo Alto, CA 94304 • (415) 326-4248

OCTOBER 1976 CIRCLE NO. 7 ON INQUIRY CARD INTERFACE AGE 11

Retro Electro Fun Fact: The Apple 1 used the MOS6502 microprocessor which released just six months earlier. You can read the story of Chuck Peddle and the MOS6502 in the Retro Electro article "The Birth of the Microprocessor and Chuck Peddle." (Link: https://www.digikey.com/en/emedia/emagazine/2025/embedded-and-mcus?page=18)

1986 – Microsoft initial public offering raised $61M

In March 1986, Microsoft went public with one of the most successful technology IPOs of its time. The company was best known then for developing operating systems and programming languages for the rapidly expanding personal computer market, especially MS-DOS, which had become the basis of IBM-compatible PCs. The IPO was set at $21 per share, raising about $61 million and instantly valuing Microsoft at over $500 million. The debut drew huge attention on Wall Street, both because of the company's strong stance in the booming PC industry and because it was led by a young, ambitious Bill Gates, who was only 30 years old at the time.

The impact of Microsoft's IPO extended beyond just raising capital. It solidified the company's status as a leading player in the software industry and made Gates and some of his early employees millionaires overnight. More importantly, the influx of resources allowed Microsoft to expand aggressively into new markets, develop future versions of Windows, and build the infrastructure necessary to dominate the desktop computing era. In hindsight, the 1986 IPO marked the point when Microsoft transitioned from a promising software company into a global technology giant, laying the foundation for decades of influence over the computing landscape.

1996 – The first USB devices hit the market

The release of the Universal Serial Bus (USB) standard and the introduction of the first USB devices in January 1996 marked a significant milestone in electronics and computing, fundamentally simplifying device connectivity. Developed by a group that included Intel, Microsoft, and Compaq, USB introduced a standardized, plug-and-play interface that replaced the diverse range of proprietary ports, such as serial and parallel connections. With a data transfer rate of up to 12 Mbps (USB 1.0) and the ability to power devices, USB enabled seamless connections for peripherals such as keyboards, mice, printers, and storage devices. This standardization reduced user complexity, lowered manufacturing costs, and encouraged broad adoption across PCs and other electronics, creating a universal connectivity ecosystem that remains vital to modern technology.

The importance of USB's 1996 debut went beyond immediate convenience, shaping the evolution of consumer electronics and data transfer. By offering a single, versatile interface, USB helped spread portable devices like flash drives and external hard drives, which became common in the early 2000s. Its backward compatibility and scalability ensured its long-term relevance, with later versions (e.g., USB 2.0, 3.0) building on the original standard. USB's influence also extended beyond computing, impacting mobile devices, cameras, and even power delivery standards like USB-C. In 1996, USB's introduction sparked a move toward 'plug-and-play' functionality and user-friendly design, setting a precedent for future connectivity standards and establishing its role as a key element of modern electronics.

2006 – Blu-Ray optical format is released

The introduction of the Blu-ray disc drive in 2006 marked a pivotal moment in consumer electronics, revolutionizing high-definition media storage and playback. Developed by the Blu-ray Disc Association, led by Sony, Blu-ray offered a significant step forward from DVDs with its 50 GB storage capacity, made possible by a blue-violet laser that allowed for denser data packing. This technology addressed the increasing demand for high-definition content, fueled by the spread of HDTVs, providing superior video resolution (1080p) and audio quality. The Blu-ray drive's debut at CES 2006 and the subsequent release of players like the Sony PlayStation 3 set a new standard for home entertainment, enabling not only better movie experiences but also larger data storage for computing and gaming. Its influence extended beyond consumer use, shaping content creation and distribution by offering a robust platform for high-quality digital media, solidifying its role in the transition to HD ecosystems.

The importance of the Blu-ray drive was increased by its role in the high-definition format war against Toshiba's HD DVD, a competition that influenced the electronics industry in 2006. Blu-ray's eventual win, confirmed by

2008, was due to its larger storage capacity, wider industry support from companies like Panasonic and Samsung, and strategic use in gaming and movie distribution. This victory established Blu-ray as the main optical disc format, affecting hardware manufacturing and software development for years. However, its long-term importance was reduced by the rise of streaming services, which started to challenge physical media. Still, in 2006, the Blu-ray drive was a key technological advancement, expanding the limits of data storage and media use, and setting the stage for future innovations in optical and digital storage.

2016 – Apple removes the headphone jack from their flagship product

In September 2016, Apple announced the iPhone 7 with a controversial change: the removal of the 3.5 mm headphone jack. The company explained the decision as a move toward promoting wireless audio and freeing up internal space for larger batteries and better components. Instead of the analog jack, Apple suggested users switch to Lightning-connected headphones or wireless options, especially its newly released AirPods. At the time, many people criticized the decision, viewing it as a frustrating departure from a standard that had been in place for decades. Critics said it forced extra purchases, made compatibility more complicated, and reflected Apple's closed-ecosystem approach.

Despite the backlash, Apple's decision established a strong precedent in the tech industry. Initially, competing smartphone manufacturers mocked the move, but they soon followed suit, with many flagship models removing the headphone jack in later years. The change sped up the growth of the wireless audio market, increasing demand for Bluetooth

headphones and true wireless earbuds, which have now become a multibillion-dollar industry. It also signaled a larger trend in consumer electronics toward minimalism, sealed designs, and ecosystem lock-in, strengthening Apple's influence over hardware design standards. Looking back, while inconvenient for some users, removing the headphone jack changed how people interact with their devices and paved the way for a wireless-first audio future.

2026 – The future

In 2026, quantum computing is set to reach important milestones that could mark its shift from theoretical potential to practical use, bringing tangible benefits across various industries. Surveys show that most experts expect quantum systems to offer clear advantages, such as faster computation and better problem-solving abilities, by this year. Companies like IBM are updating their roadmaps to achieve quantum advantage in 2026, focusing on improving qubit stability and error correction to develop fault-tolerant systems capable of outperforming classical computers in many tasks. This progress is especially important for fields like materials science and pharmaceuticals, where quantum simulations could speed up discoveries in new battery chemistries and drug development, possibly cutting research timelines from years to months and encouraging innovations in sustainable energy and healthcare. The key significance is quantum computing's ability to solve complex optimization problems that are impossible for traditional electronics, opening the door to a new era of computational power.

Suggested Reading

1826 – Theory of Electrodynamic Phenomena

1836 – Daniell Cell – Primary Batteries by Henry S. Carhart

1846 – The Gutta Percha Company by Bill Burns

1856 – "The Birth of Nikola Tesla" by The Tesla Science Center

1866 – " The Transatlantic Telegraph Cables 1865-1866" by The Institution of Engineering and Technology

1876 – "Who is Credited for Inventing the Telephone?" on The Library of Congress

1886 – "The Great Barrington Electrification" by The Edison Tech Center

1896 – Marconi's First Public Demonstration of Radio

1906 – Actual Recording of Reginald Fessenden's Christmas Eve Radio Broadcast

1916 – Patent for Electric Wall Switch

1926 – RCA Creates the National Broadcasting Company (NBC)

1936 – "A Symbolic Analysis of Relay and Switching Circuits" by Claude Shannon

1946 – ENIAC: Electronic Numerical Integrator and Computer

1956 – The First Transatlantic Telephone Cable 'TAT-1'

1966 – World's First Single Chip Integrated Circuit Radio by J.A. Cacciola and E.Q. Carr

1976 – "Apple I Microcomputer" by the National Museum of American History

1986 – "A Look Back at Microsoft's IPO" by Network World

1996 – Universal Serial Bus (USB), 1996

2006 – "Blu-Ray Disc" by the Museum of Obsolete Media

2016 – "Fans Angry Over 'Missing' iPhone 7 Headphone Socket" by Jane Wakefield for the BBC

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