HISTORICAL LUCAS ALTERNATOR REGULATOR & IGNITION SCHEMATICS - MORE THAN MEETS THE EYE.

THIS ARTICLE IS A PHOTO GALLERY OF SOME OF LUCAS'S TRANSISTORIZED ALTERNATOR REGULATOR AND IGNITION SCHEMATICS. REMARKS ARE MADE ABOUT HOW THEY FUNCTION AND SUBTLE & CLEVER ASPECTS OF THEIR DESIGN.

(H. Holden. July 2018).

Introduction:

One issue that makes life more difficult for those with an engineering disposition, wanting to repair or restore vintage automotive electronic items, is that many semiconductor based automotive products have their circuitry encapsulated in hard resin to protect them from vibration and fumes in the engine compartment.

It is a tedious process to dig the device out of the resin and document it and this often destroys the device in the process. So any ***factory data*** on the design becomes more important to understand how the part or module works and to do things such as design a “test protocol” or “test machine” to evaluate the function.

(Some test machines are shown at the end of this article. These were built specifically for testing Lucas Distributors and Lucas Regulators and Ignition systems).

This article addresses some the technical creations and innovations Lucas were responsible for, over the time when Lucas moved to semiconductor controls for their car alternator and ignition systems in the mid 1960 to mid 1970 decade.

The images here, which are “Lucas factory diagrams” were found in the defunct Lucas factory in the UK and published online by a fellow who identified himself as an “Archivist” .Subsequently his website has closed down it appears.

Transistor Alternator Regulators; a general note on how they work:

The function of the transistor alternator ***voltage regulator*** was designed to emulate or replicate the earlier electro-mechanical regulators which were used for early alternators and dynamos. Dynamo regulators were more complex requiring ***current*** as well as ***voltage regulation***.

(Electronic dynamo regulators were not commercial products in the 1970’s era because dynamos were being phased out at the very time transistorized electronic controls matured. Although later, Bosch made the 30019 electronic dynamo regulator as a replacement for their earlier electro-mechanical design).

For voltage regulation of an alternator (or dynamo), there is a switching device (which was a physical contact in the electro-mechanical regulator) or an “output transistor switch” in the electronic regulator. This output transistor passes current to the field coil or rotor so as to magnetically energise it. The output voltage from an alternator is proportional to the magnetic field intensity of the rotor, as well as the rpm.

The regulator also contains a voltage sensing or "threshold device" (a relay coil in the mechanical regulator where a magnetic field opposes a spring force) or in the electronic regulator, the input transistor, typically the voltage drop of the base-emitter junction, is used as the "comparator" or threshold sensing device.

Once the set output voltage is reached (typically 14.3V for and alternator) the field current is interrupted. In the case of the mechanical regulator it is interrupted by the contact in series with the field coil circuit opening. In the case of the electronic regulator it is interrupted by the output transistor being taken out of conduction (switched off) by the input transistor/s removing its base current.

Once the field coil is turned off, then after a time the output voltage of the dynamo or alternator falls below the threshold voltage value. The field is then switched back on again because the output transistor again receives drive current. The cycle repeats rapidly with the field coil turning on and off, typically at a rate around 30 to 60 cycles per second.

The thing to understand about most dynamo and alternator voltage regulators is that they are switch-mode, not analog regulators. It is the switched field current which results in an average controlled output value from the alternator or dynamo. However, by necessity, there is a ripple on that average output voltage above and below the switching threshold of the regulator’s input.

Many people incorrectly assume, looking at the simple circuits for dynamo and alternator regulators, that they are analog or linear controllers. They are not and they oscillate in a switch mode because they reside inside a feedback loop with the alternator. It is largely the electrical delay through the alternator itself that ends up determining the actual switching frequency of the feedback loop with some delays and filtering added in the electronics of the regulator module.

These simple two or three transistor regulators are best called "Variable Frequency PWM (pulse width modulated) regulators". Of note, these respond very quickly to a change in load within a few switching cycles. This means a sudden increase in alternator load makes the alternator pulley suddenly more difficult to turn.

Also, in the case of variable frequency PWM regulators, such as the Lucas ones, the Engineer cannot tell you what frequency the loop would be operating on unless they had physically measured the electro-magnetic delay properties of the particular alternator and the filtering delays in the regulator. The running frequency depends on a number of factors including the winding resistances, inductances, magnetic properties of the core materials and the geometry of them in the specific type of alternator and the filter component values in the regulator. Also the frequency alters a little with loading. However the switching frequency, in use, is easily measured with an oscilloscope.

Later in history, the electronic controls for alternators moved to "Fixed Frequency PWM" where the electrical delay properties of the alternator do not affect the switching frequency of the field coil (or rotor). Instead, the switching frequency is controlled by an independent oscillator, or the car's CPU.

Fixed frequency PWM was employed to delay the response of an alternator to a sudden increase in load as electrical apparatus in cars, consuming large current power and current loads, increased in modern cars.

For example in a 1960's era small car the total electrical power load might be 400W. Later it could be over 1.5 to 3kW with additional electrical apparatus. This could cause the alternator to stall an idling engine when something switched on with a high load current. So LRC (load response control) was invented for a slow alternator current ramp up and this required fixed frequency PWM to implement it. Fixed frequency PWM is easy for modern Engineers to understand too, as it is the same technique used to power control many other electronic and electromechanical systems. Pre-made PWM IC’s are also very common now.

So despite the apparent simplicity of variable frequency PWM it is actually more difficult to model and understand than fixed frequency PWM.

Variable frequency PWM requires the close to the correct positive & negative feedback filtering components in the regulator circuitry(see below) to get clean and fast glitch free rotor coil (or field coil) switching of a sensible frequency without unnecessary switching events triggered by ripple or noise, while variable frequency PWM does not. This is why variable frequency PWM regulators are better designed with the aid of a real alternator (or dynamo) and test machine system. Fixed frequency PWM is easily modelled in Spice simulators, suiting modern design practices.

Since the conversion of Octane to mechanical energy of a rotating shaft is about 40% efficient and the conversion of rotational to electrical energy by the alternator is around 60% efficient, then the conversion of Octane fuel to electrical energy in the vehicle is only 24% efficient. So, by analogy, the "oxymoron" is that any added electrical apparatus to a petrol powered vehicle degrades its efficiency. And as a result, cars with simpler and lower power consumption electrical systems of yesteryear are more efficient in this respect than modern petrol powered cars with more electrical apparatus, despite claims that someone says "they have an efficient alternator".

Subtle details in Lucas's deceptively simple alternator regulators:

One can see subtle details embedded in the design of Lucas's simple two or three transistor variable frequency PWM regulators. Mostly these details are overlooked because the 2 or 3 transistor circuits appear so simple to the observer.

1) Since the voltage comparator is the base-emitter junction of a transistor (the input or threshold sensing transistor) it has a negative temperature coefficient of about -2.1mV/DegC. This has to be compensated for, or the input voltage threshold would drop with heating and the alternator's output voltage would fall too much with heating.

So Lucas divided down the sensed voltage with a resistive divider first, then placed a zener diode in the range of 7.5 to 9V in series with the input transistor's base.

Zener diodes in this voltage range have a positive temperature coefficient of a similar magnitude to the transistor’s negative tempco and cancel the transistor's negative coefficient. This clever trick temperature stabilizes the “comparator” without having to use an actual comparator or OP amp IC or more transistors in a differential amplifier configuration.

Also, Lucas were the only company I know of who realised that the zener diode should be well thermally coupled to the input transistor. Lucas were also semiconductor designers and manufacturers. They built an input transistor with the zener diode incorporated into the one package. This can be seen in photos later as "The Input Device"

The analogous compensation in the electro-mechanical regulator:

In this regulator, on the voltage sensing coil, as the copper wire heats up its resistance increases. This would increase the dynamo or alternator's output voltage with heating (because the magnetic field is weakened and there is less magnetic force on the armature against its return spring holding the contact closed). The compensation in this case is performed with special return springs (on the armature and its field coil contact) with the appropriate metallurgy and tempering, so that the spring force decreases proportionally with heating.

2) To improve the noise immunity of their electronic alternator regulators, Lucas did something else. They placed a filter (or ***negative feedback***) capacitor from the collector to the base of the input transistor. This causes the input transistor to integrate any noise pulses presented to it. This reduces the chance of multiple unnecessary switching events of the rotor winding. However, this integration or filtering on its own, slows down the on-off or off-on time of the output transistor. To speed this up, they cleverly uses a series RC network from the field coil to the input transistor base circuit (***positive feedback***).

The combination of the two feedback types result in noise immune fast field coil switching and essentially replicates the type of response seen in a mechanical regulator with the limited frequency response (due to mechanical inertia) combined with magnetic hysteresis of the bobbin coils and their armatures.

3) Lucas's early electronic alternator regulators consisted of just two transistors, the input transistor which acted along with the input zener as a temperature stabilized comparator and a single output transistor.

This arrangement required a fairly heavy output transistor base-emitter bias current to get the output transistor into saturated conduction to switch the field coil, in the range of 60 to 120 Ohms with a 14V supply.

Later Lucas engineers realised that a Darlington transistor was a better option as the base current required to saturate it was 1/10 of the single BJT (bipolar junction transistor), so a bias resistor in the region of 1200 Ohms was satisfactory.

Some of the power savings in resistor heat dissipation unfortunately are offset by the increased power losses as the saturated Darlington which has about a 1.2V collector-emitter forward voltage drop compared to around 300mV for a single saturated BJT.

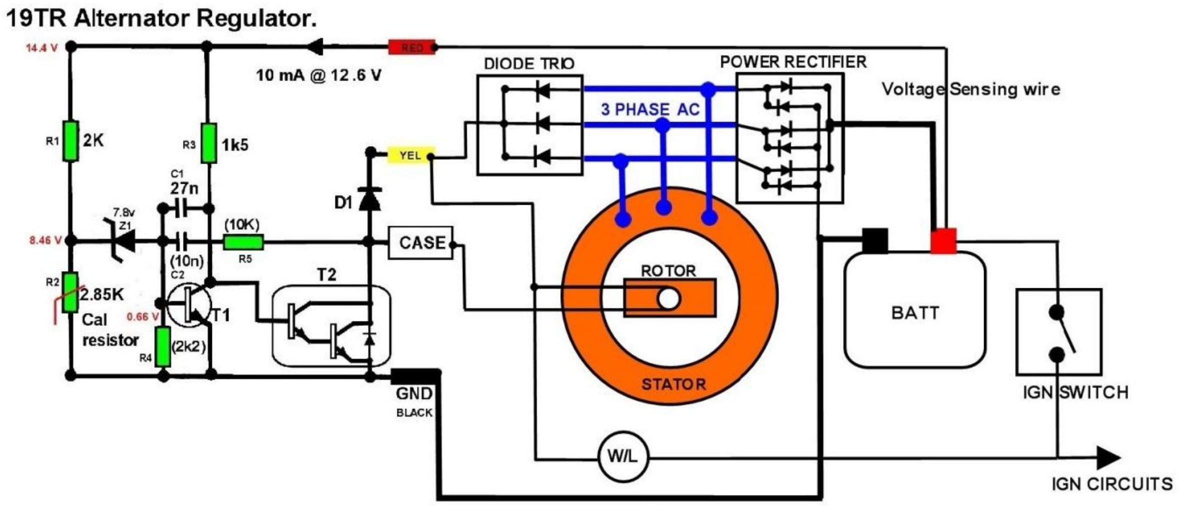
Therefore, with a 2A rotor current there is more heat loss in the Darlington output transistor itself, than a single BJT. However, a physical science power analysis (not presented here) proves that the overall efficiency comparing the single BJT to a Darlington output transistor switch, when the bias is derived from the same voltage source and the collector load, with any supply voltage over about 6 to 7V, its more efficient overall to use the Darlington than the BJT. Below 6V a single BJT is better. So Lucas did the right thing switching to a Darlington for most of their alternator regulators.

Lucas also used a dual output transistor arrangement with an additional driver transistor. It still required a resistor of around 80 Ohms to source enough bias current to adequately turn on (saturate) the output transistor, but there were lower demands on the input transistor and with a higher input resistances then allowed at the driver transistor’s input (base circuit) then smaller value and smaller physical size filter capacitors could be used.

Regulator variations, three terminal (2 wire) vs 4 terminal (3 wire) regulators:

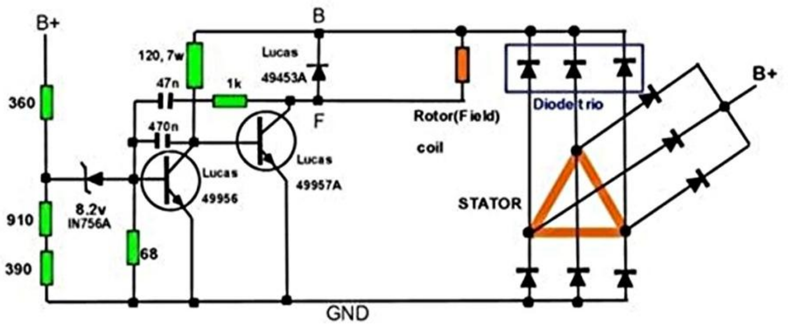
In the two wire regulator, the metal case is one contact and typically is the connection for the field coil (connected to the output transistor's collector which is one rotor connection). One wire often black is the ground and a green or yellow wire is the sense wire, connected to the alternators output from the main power three phase rectifiers. This is called **"machine Sensing"**. The other rotor connection is powered often by three smaller auxiliary rectifiers (the diode trio), so it is not powered unless the alternator is rotating.

Some regulators, for example the Lucas 19TR shown below have an extra sense wire (typically Red) which senses the battery voltage **"Battery Sensing"**, rather than the direct output from the alternator power rectifier output. This cancels the voltage drop (which depends on charge current) along the thick wire leading from the Alternators power rectifier pack to the battery positive terminal:

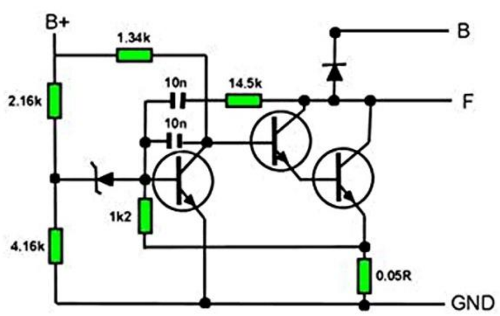


The diagram below shows the schematic of two Lucas regulators. Over the decade from the early 1960's to the 1970's Lucas had shifted to a Darlington output transistor, even though the regulator still had the same part number: Notice in the 1960's 4TR regulator required a 120 Ohm 7 Watt rated resistor. But the Darlington version in the 1970's unit required only a ¼ watt rated 1.34k (about 1k2) bias resistor.

Notice how both circuits have the characteristic input zener diode, the filter capacitor from the base to collector of the input transistor and the RC positive feedback network.

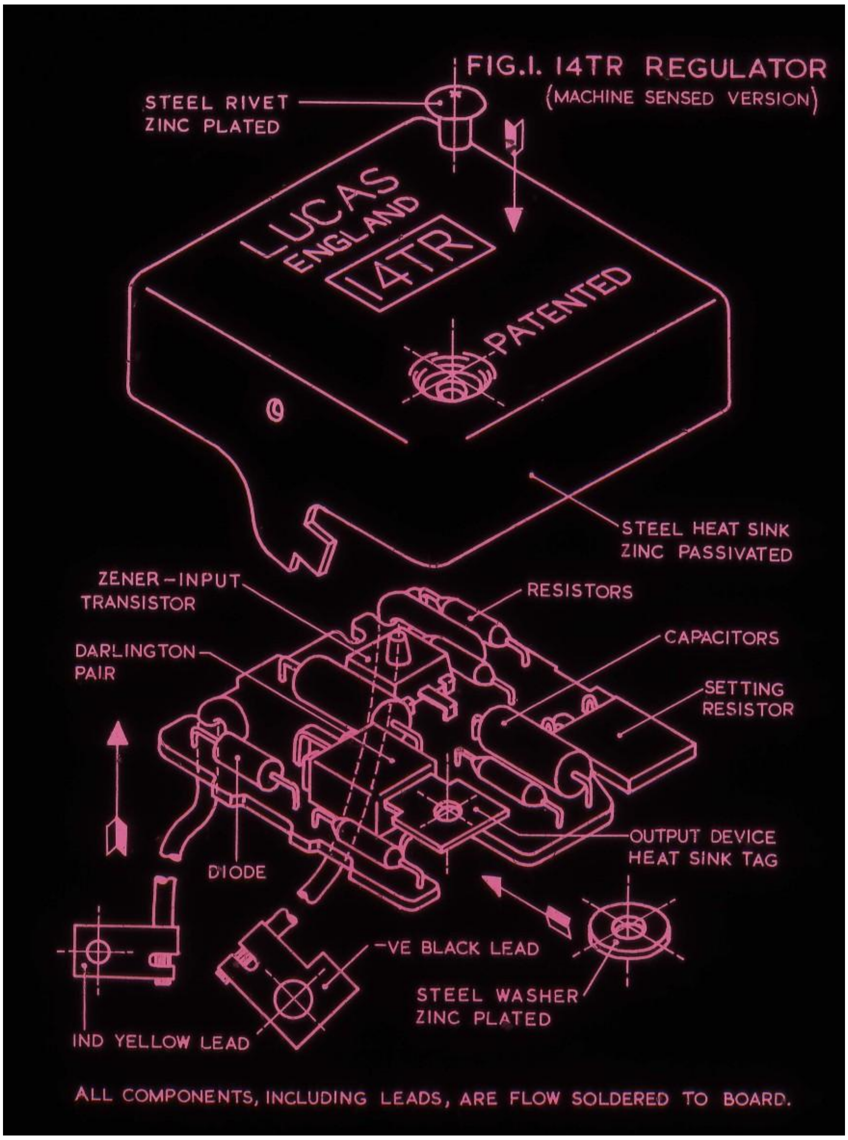


1960's 4TR REGULATOR

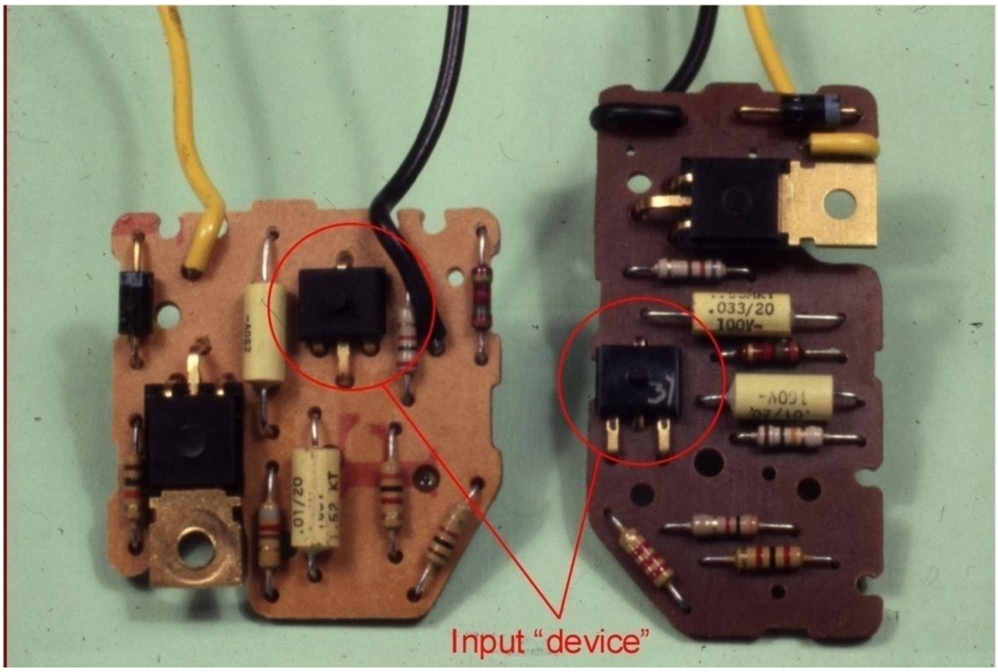


1970's 4TR REGULATOR

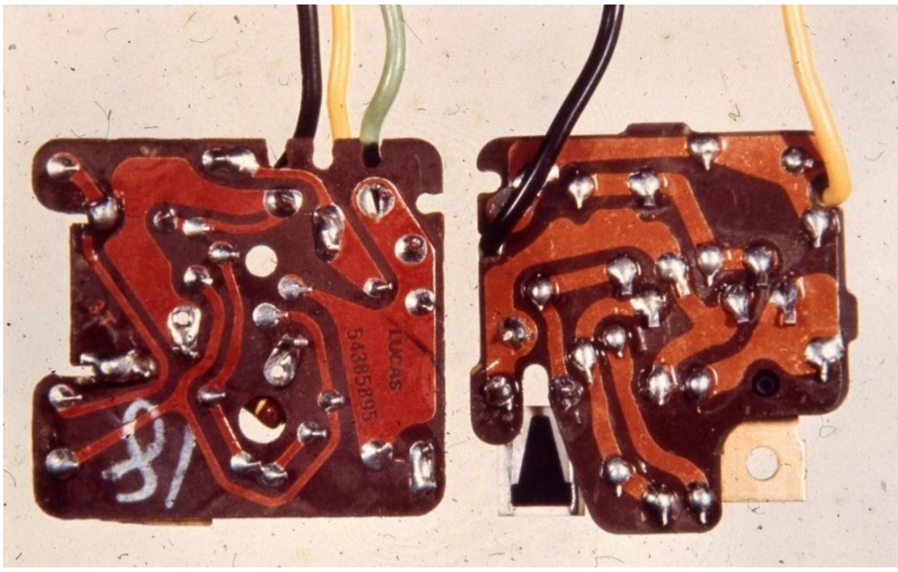
The factory diagram below shows the typical construction of a 14TR type:

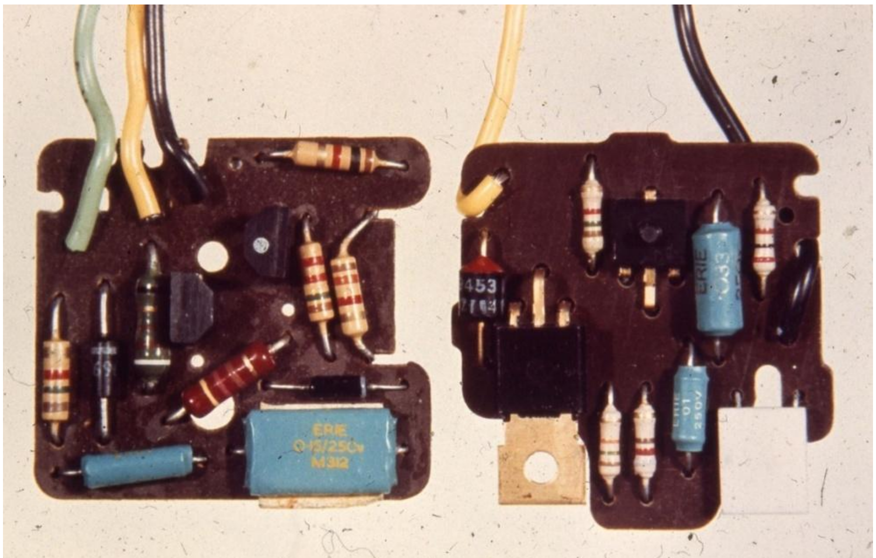


The photos below show typical PCB's that are inside the Lucas regulators like the 14TR and similar types. Notice that they use a Darlington output transistor and Lucas had combined the Zener diode and the input transistor into one 4 legged device labelled as "The input Device". This is a custom part, manufactured by Lucas. These were not available elsewhere. In the diagram above they label it as the "zener-input transistor". Normally these views are not available as the pcb’s are potted in resin, luckily the Archivist found these at the defunct Lucas factory.



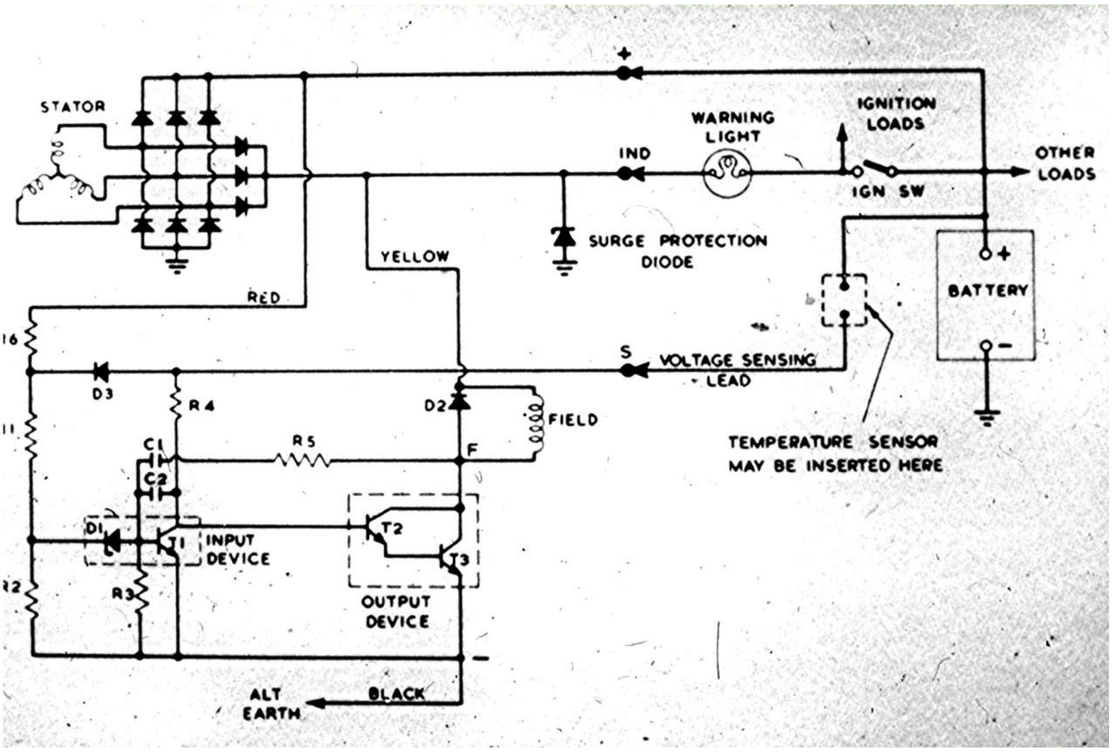
The images below show typical views of Lucas regulator pcb's, prior to potting:





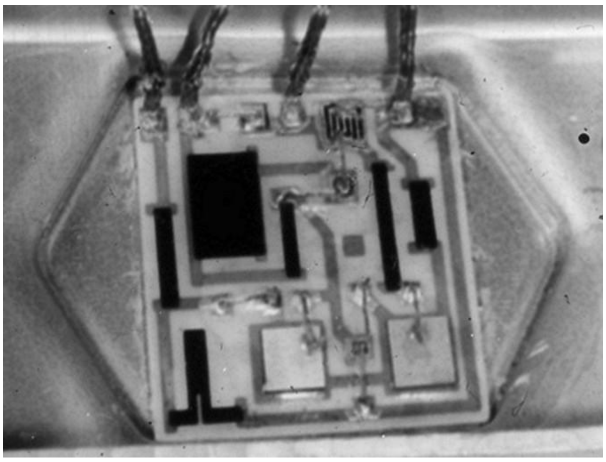
The transistors on the left pcb are “lockfit” types and this pcb mated with the base and emitter connections of a power output transistor.

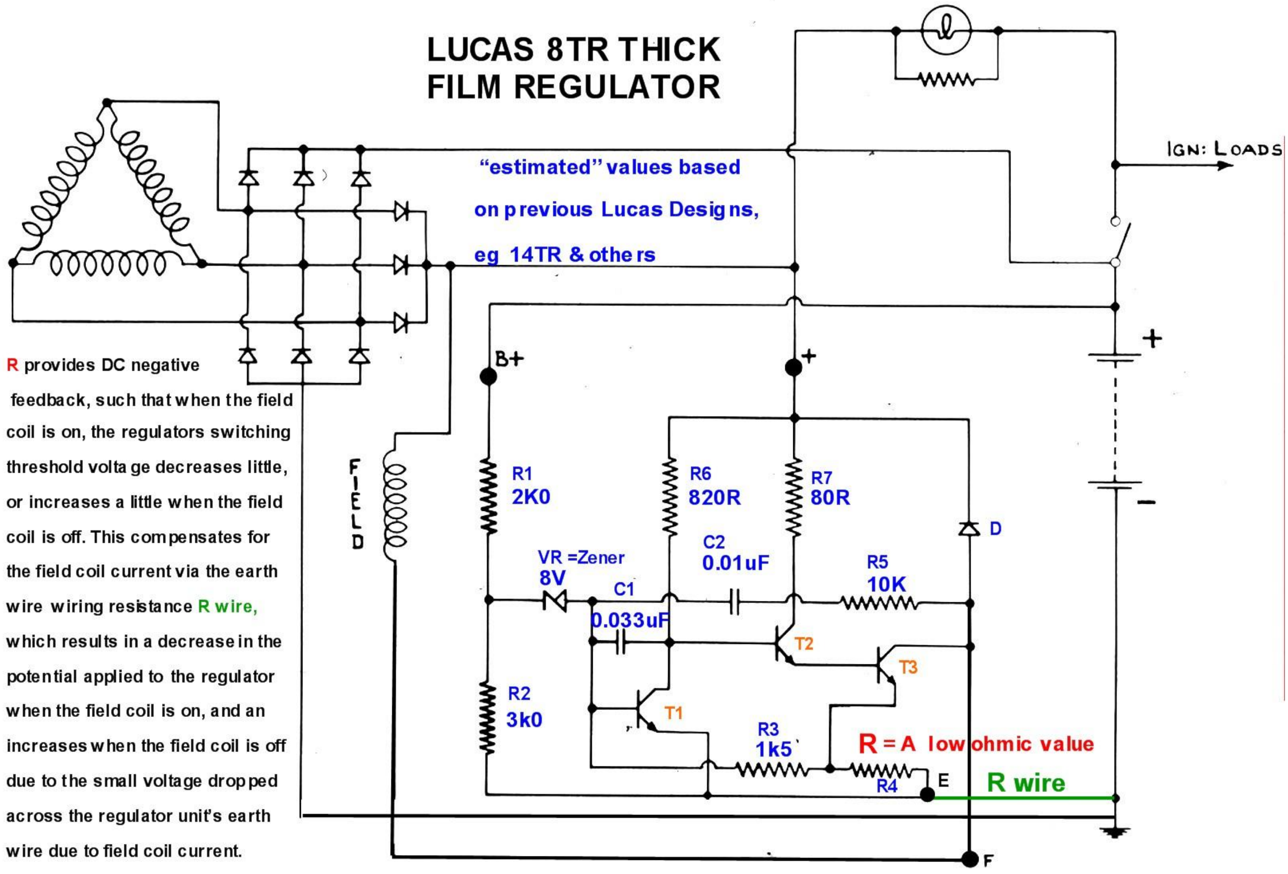
The diagram below shows a version with a combination of machine and battery voltage sensing:



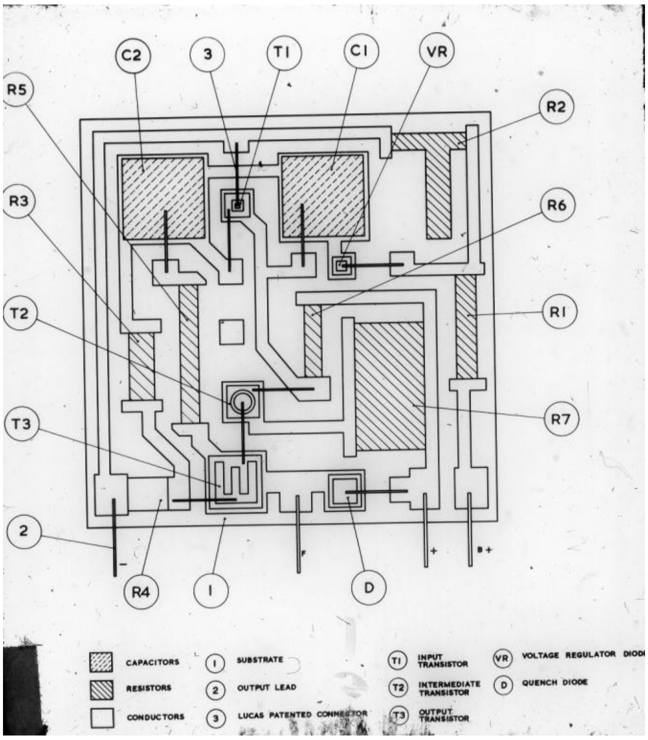
8TR Alternator regulator:

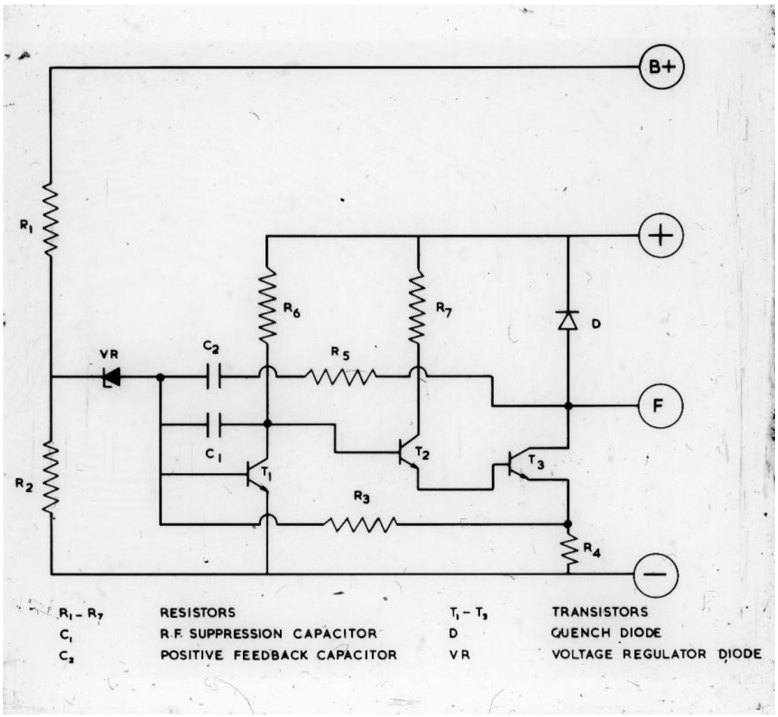
This regulator is a “thick film” type. This has the transistor crystals bonded to a white ceramic substrate and uses screened resistors. One resistor is trimmed with a cut for calibration. The same design was used in the later Lucas 37565A regulator module.



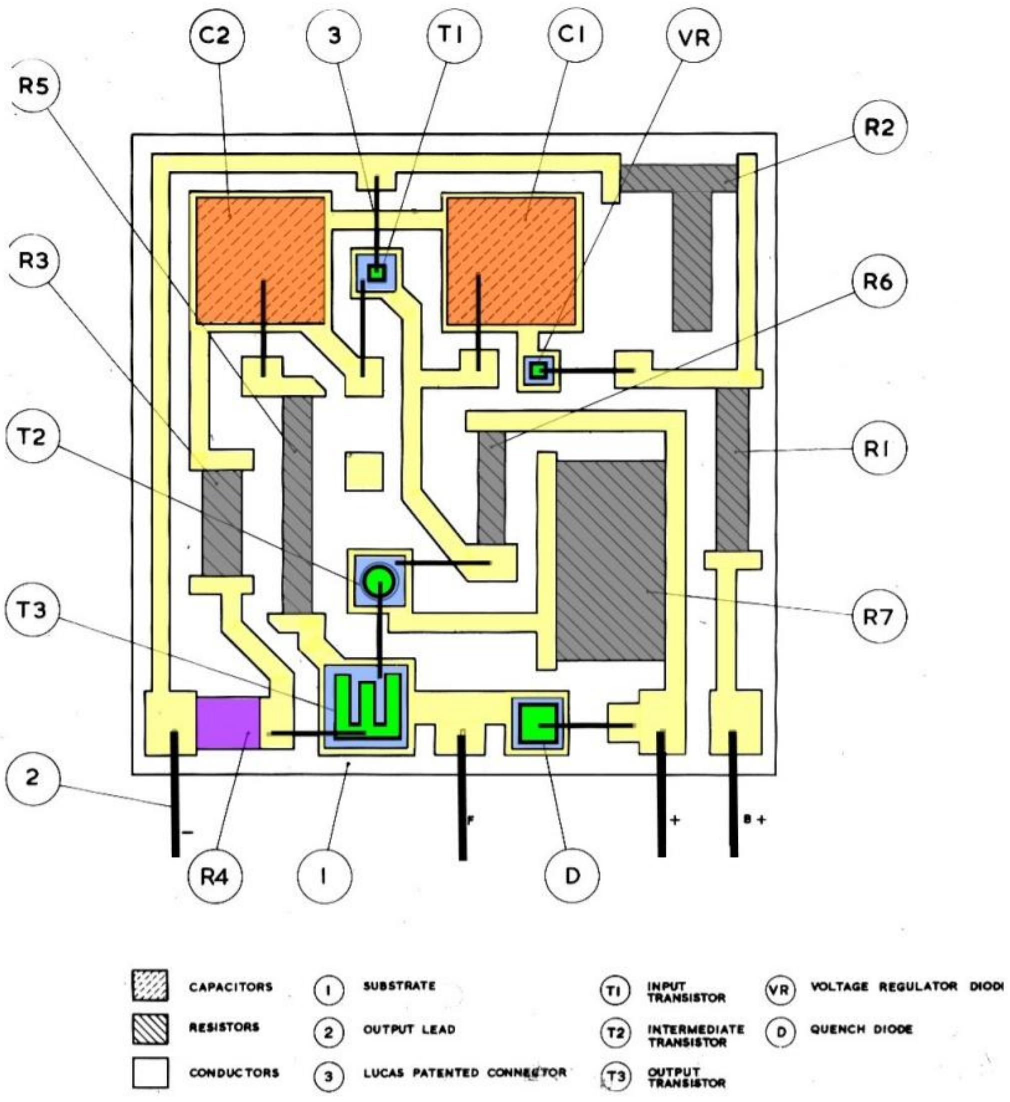


The coloured writing above indicates some of the probable component values based on previous Lucas designs and explains the purpose of R4 which is not present in many alternator regulator designs. This appears to have been a unique Lucas idea.





The thick film regulators were quite revolutionary as the construction was extremely heat resistant and they were also potted in silicone rubber with made them very vibration resistant. Lucas designed most of their alternator regulators to reside inside the alternator body, where it can get very hot especially with heat from the engine and radiator nearby combined with heat from the full wave three phase bridge rectifier, also nearby inside the alternator.

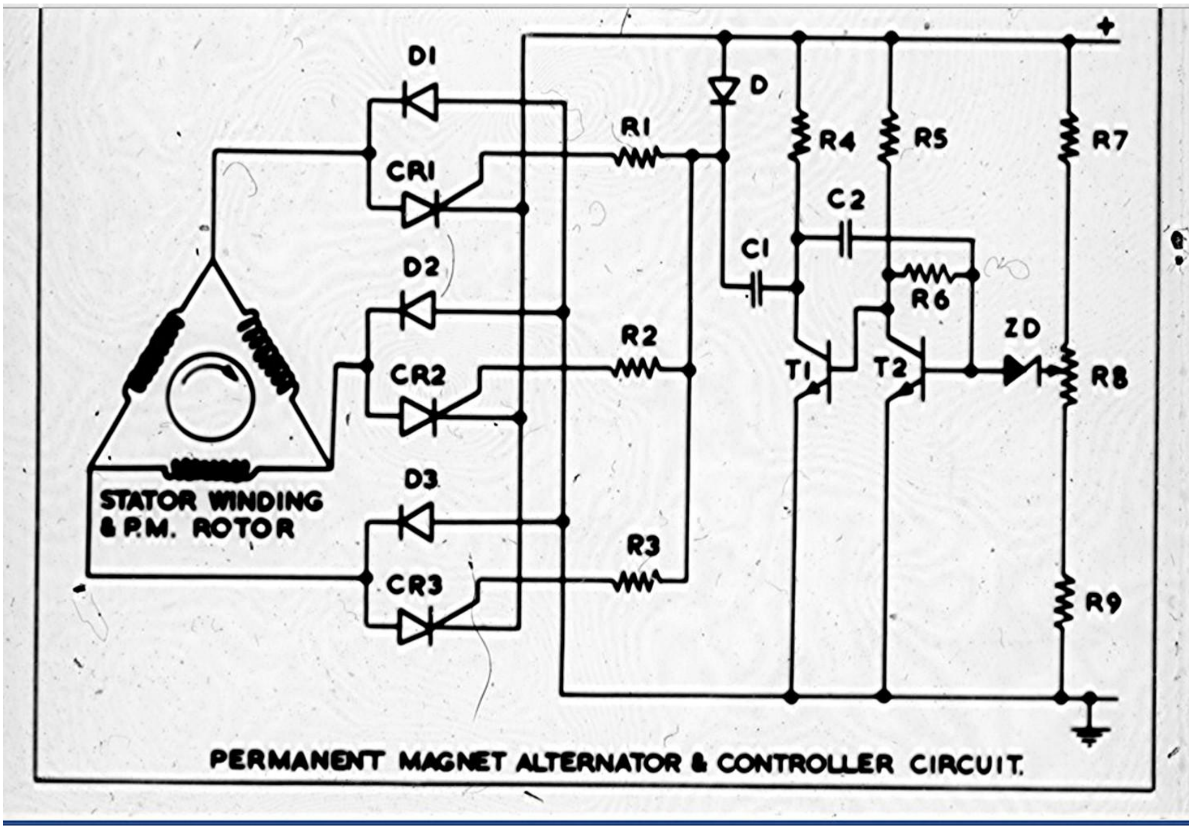


Lucas sets the tone for Permanent Magnet Alternator Regulators:

The circuit below shows Lucas's solution to the regulation of a permanent magnet alternator. In this type of alternator, there is no hope of regulating the rotor's magnetic field intensity, as a means of controlling the output voltage, because it is a permanent magnet. So an entirely different solution is required.

Lucas chose to sense the output voltage in the usual way with a resistive divider, zener & input transistor (for temperature compensated voltage sensing).

However, this time, the transistor circuit controls three of the rectifiers that make up the three phase bridge, which have been replaced with SCR's. (These are silicon controlled rectifiers). Their switch on duration controls the portion of the cycle (of the alternator's AC output waveform) that the rectifiers are conducting. In this way the average output voltage is controlled. The design is simple and very effective.



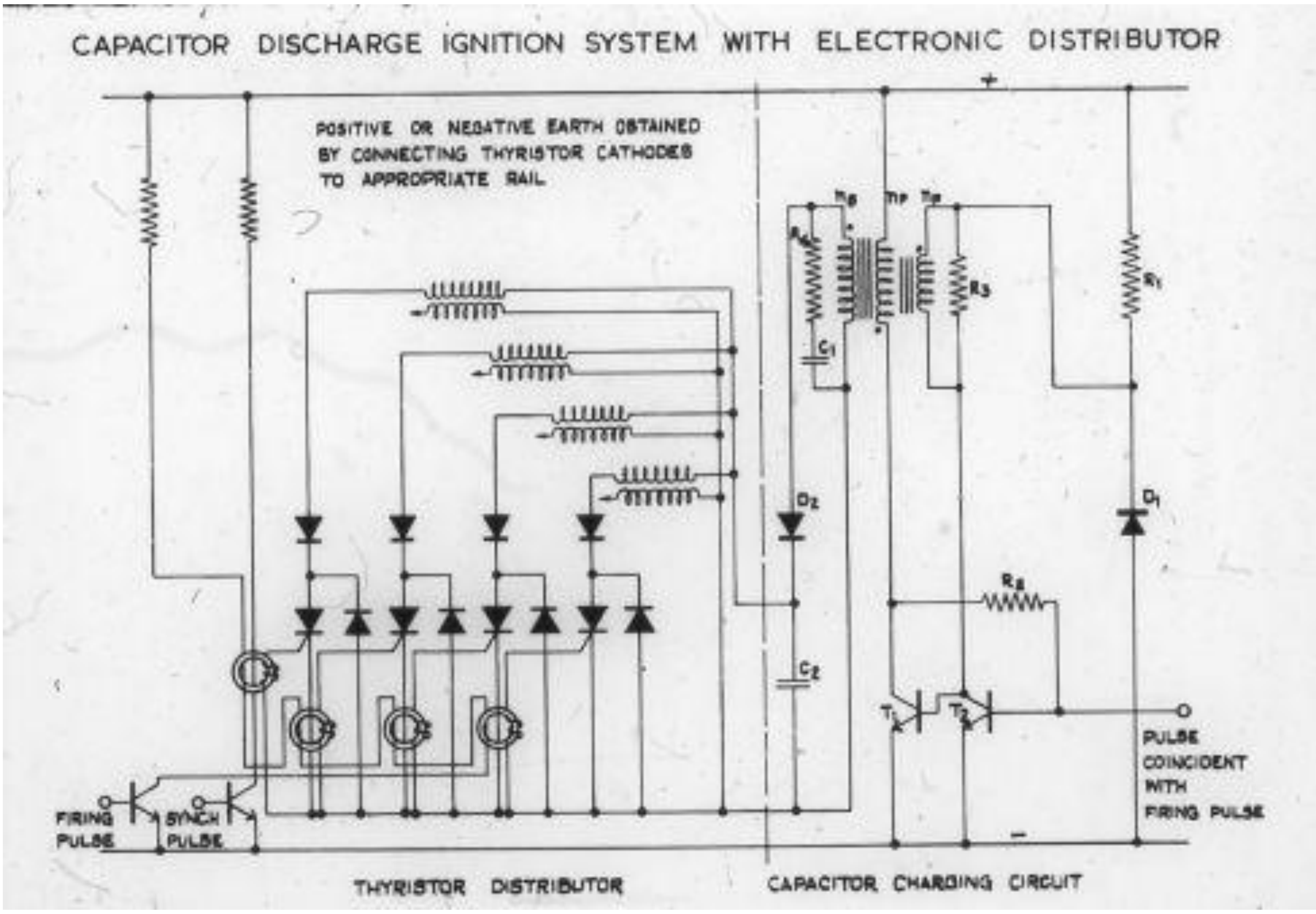
LUCAS IGNITION SYSTEMS:

Unfortunately many of Lucas's early transistor ignitions systems were not wonderful for reliability, but they were nonetheless creative. The common ones were the Opus series. I'm not going to present those here as there is a lot of data out there on the net on these.

Instead I'll present this creative Lucas circuit of a CDI (capacitive discharge ignition). It has a DC:DC converter which charges C2 to a high voltage in the order of 400V.

There are individual coils for each cylinder (a distributor-less system) and it uses "Magnetic Memory" to create a "shift register". This task would now be performed by more transistors or IC's, but I think it was ingenious the way Lucas designed this without resorting to more semiconductors. The design shows how skilled the Lucas Engineers were at electromagnetism and its principles.

I have no record that this unit was ever made into a commercial product, it was probably just a design that was stuck on their drawing board:



The magnetic rings (toroids) would be made out of a magnetic material such as Alnico in an initial non magnetized state. A firing pulse current passes through one turn of all the magnetic rings.

Depending on the magnetization state of the individual ring, a gate pulse will be transformed into the gate of the SCR or will not depending on whether the ring is magnetized or not and the polarity of the magnetization. If an applied firing pulse attempts to increase the magnetic field in the same direction then no gate pulse for the SCR is generated. If it reverses the magnetization, a gate pulse is generated.

The sync pulse sets the correct polarity magnetic field in the first ring on the left hand side, so that when the firing pulse occurs that ring can reverse its magnetic state and therefore generates a gate pulse for the first SCR (left SCR on the diagram).

Once a ring has transmitted one pulse it remains in a deactivated state from the point of view of behaving as a pulse transformer, as its core is now magnetized with one polarity and cannot transmit another gate pulse until its “remembered magnetic field” is reversed again by a current pulse in the opposite direction.

The cathode current of the left hand SCR passes through the second ring and sets its field so it is able to transmit one pulse after that. Therefore on the next firing pulse the SCR (second on the left) is triggered and it also prepares the next ring to fire on the next firing pulse.

So the SCR's fire in a sequence from left to right. When the far right hand SCR fires, or after that, all the rings are in a "won't transmit a gate pulse” state. But then the sync pulse occurs, conditioning the left hand ring to be ready to trigger the left hand SCR, then the cycle repeats. It is ***a magnetic shift register***.

Also, when there is a firing pulse, as often is the case in CDI designs, the DC:DC converter is inhibited (T2 inhibits T1). This is because the firing of the SCR shorts out the DC:DC converter output (the charged capacitor C2) across the ignition coil primary.

Lucas Goes American:

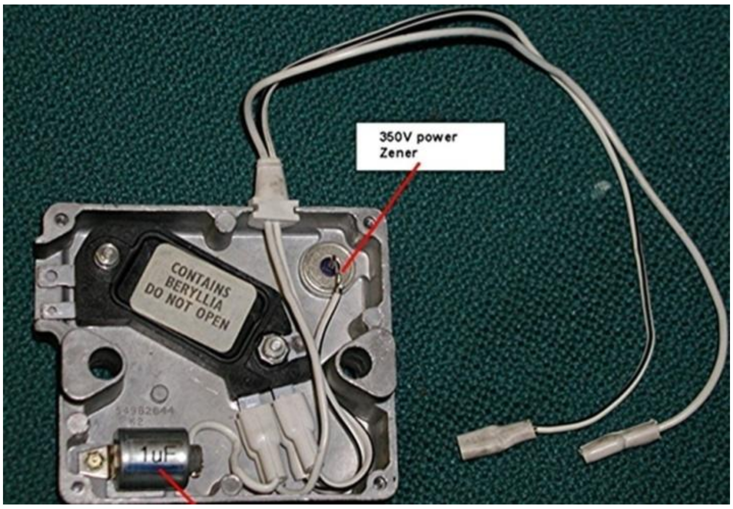
Due to the difficulties Lucas had with their own electronic ignitions, they decided to produce and an electronic ignition unit (for MG's and the like) with reluctor distributors that contained the proven and reliable General Motors HEI module.

This unit was the AB14 (an MDI = Magnetic Discharge ignition unit) and it was also used in Jaguars. Lucas actually improved the reliability of it by adding a 350V power clamp zener diode on the ignition coil connection. This addition also has other benefits in improving the high voltage rise time because it clamps the initial primary voltage to a fixed value at the initiation of the spark. Then the ignition coil high voltage rise time then assumes the same rate that it does in a CDI unit, where an initial fixed voltage (from a capacitor) is applied to the coil primary. The rate of rise of voltage is then determined by the properties of the ***ignition coil*** such as its resistances, leakage inductance and associated capacitances.

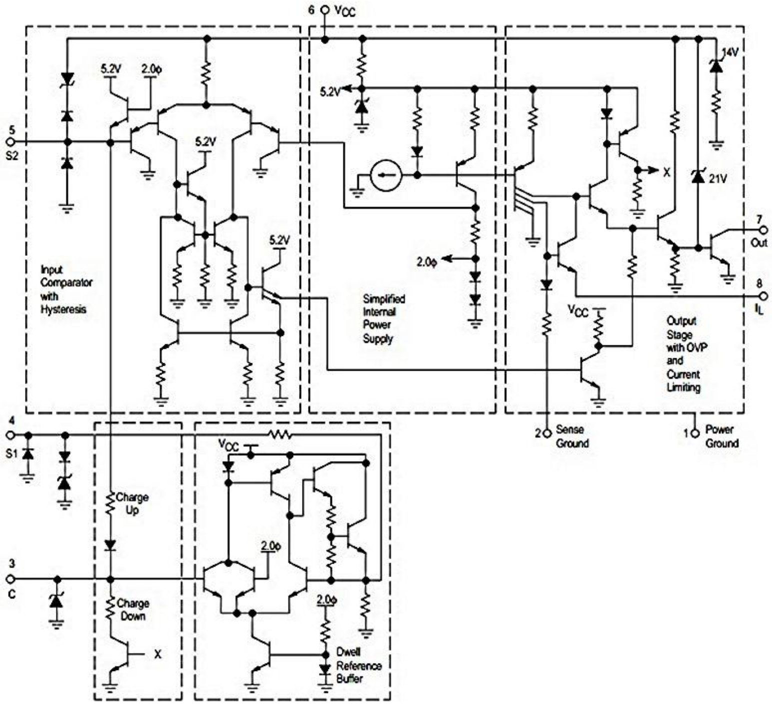
It is not widely appreciated that if an ignition coil's high tension lead is unplugged from the ignition coil, and a spark does not form, not only does the coil's secondary voltage rise very high, but so does the primary voltage. This can cause the output transistor, even in the robust GM HEI module to fail, because, depending on the ignition coil type, the collector voltage on the transistor can go well over 700V.

The addition of the 350V power zener diode snubs off that voltage spike if that scenario occurs and saves the HEI module. One other way to reduce the voltage peaks on the transistor is to leave a 0.2uF capacitor in the coil primary circuit (as in standard Kettering ignition with a contact breaker). This limits the amplitude of the high voltage rise time and slows the rise time. Without this capacitor (HEI units normally don't have it), the high voltage rise times of the electronic drive to the coil from an HEI (Zener clamped MDI module) ***are equally fast to those of CDI***, and the actual high voltage rise time depends largely not on the electronics itself (MDI or CDI), but the largely design of the particular ignition coil and parameters such as its leakage inductance. These facts still appear to remain generally ill understood in ignition system folklore and there are many myths and legends relating to CDI vs MDI.

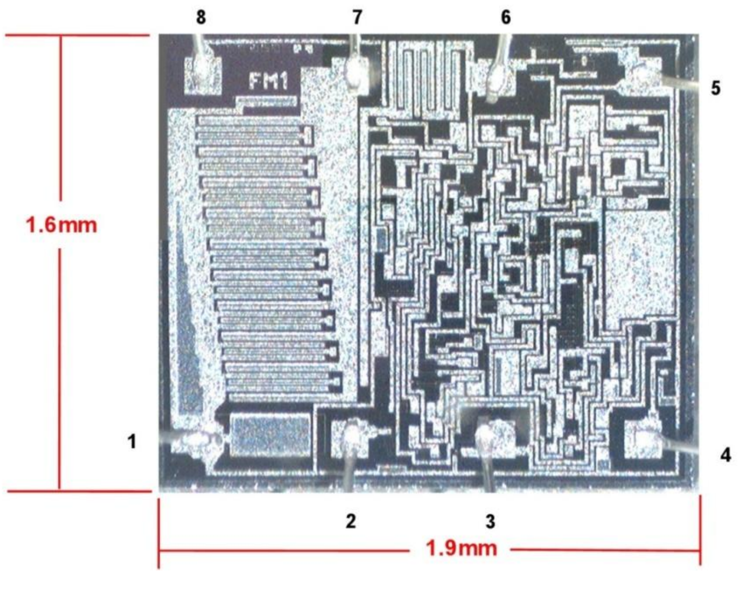
The photo below shows Lucas's AB14 ignition module with the GM HEI module inside it:



The HEI module itself is based on a specialized or custom Motorola IC, the MC 3334, which was designed to be used with a reluctor distributor, the idea being to dynamically alter the Dwell, so as to have uniform spark energy across the full RPM range. The circuit of the inside of the MC3334 is shown below. Included with this IC are some support components and a Darlington output transistor inside the HEI module. So while this is not a Lucas designed part, Lucas saw fit to use it in their ignition systems.



THE MC3334 IC DIE: Microscope photograph taken inside the HEI module



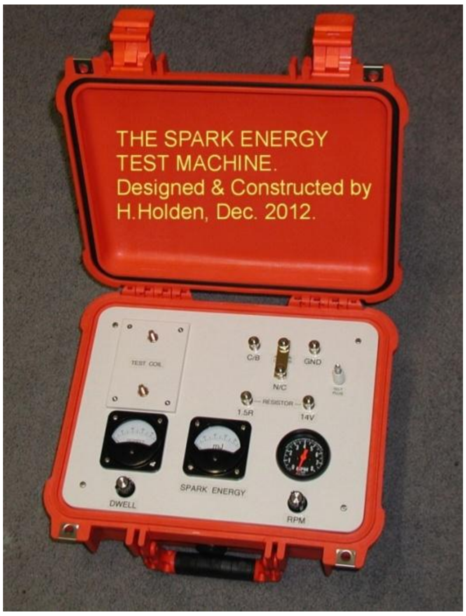
TESTING LUCAS REGULATORS, IGNITION CIRCUIT & DISTRIBUTORS:

Unfortunately, when the Lucas factory closed, much of their test gear and laboratory equipment was lost.

To test ignition modules, alternator regulators and distributors ideally requires dedicated test machines. I built a few machines dedicated to testing & adjusting Lucas products.

The test machine below was developed to test Lucas RB106 electro-mechanical regulators and electronic equivalents. It also tests C40 Dynamos and alternator regulators.

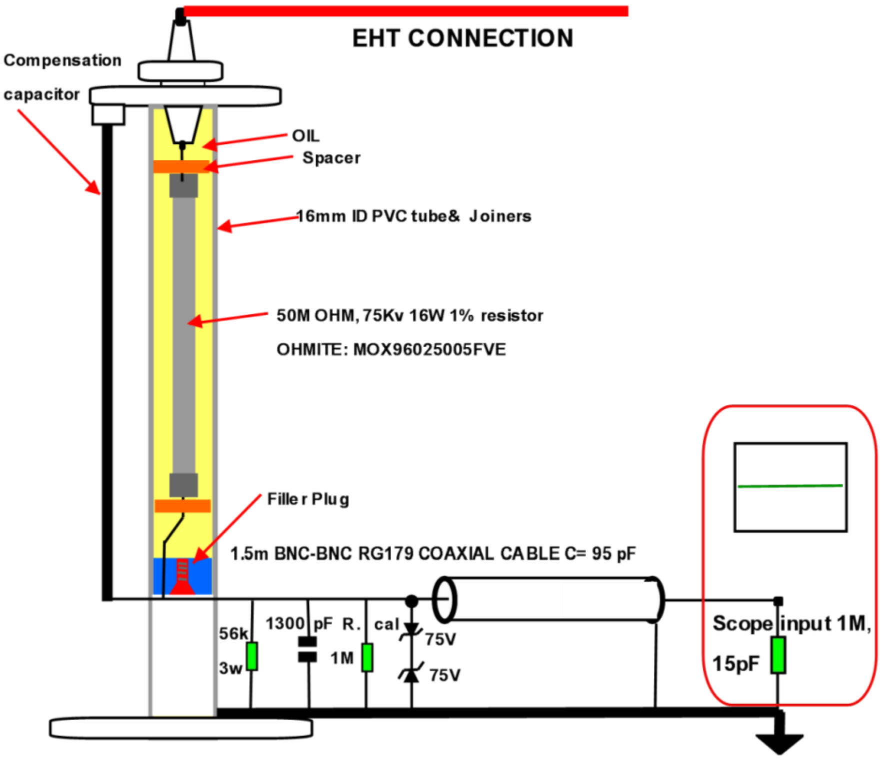
The Spark Energy Test Machine was designed to test the spark energy from ignitions coils and electronic ignition modules and CDI units for a scientific evaluation. There are many myths and legends comparing CDI to Magnetic ignition systems.



The Distributor test machine was designed to test Lucas 25D & 45D Distributors:

50 Kilovolt capable high voltage probe:

This sort of probe is not an off the shelf item. A 50kV capable high voltage probe was designed and built to measure ignition coil output voltages by giving a faithful calibrated recording without loss of high frequency detail. The bandwidth of the probe is over 1.5 MHz. The highest frequencies in an ignition coil output waveform rarely exceed 300kHz. Without this probe it is not possible to adequately study the output voltage waveforms of CDI and MDI systems and make any meaningful judgements about them, especially about voltage rise times. (So if somebody makes a claim about the performance of CDI and MDI systems, without a probe like this, or a spark any test machine, for accurate scientific recordings, you can take their conclusions with a grain of salt).



Further reading:

There are multiple articles on the topic of CDI (capacitive discharge ignition) and MDI (magnetic discharge ignition) and the advantages and disadvantages of each on the www.worldphaco.net website.

On this site are also designs for electronic versions of the Lucas RB106 Dynamo regulator and how to restore the original units. In addition the www.worldphaco.com site has an article on histrical electronic RB106 regulators that led to the final design.