How Outboard Motor Ignition Systems Work, Part 3
Ignition with No Battery: the Magic of the Magneto

<u>OutboardIgnitionPart3 W. Mohat Rev. 3.0 May 25, 2018</u>

The ignition systems in antique outboards are usually magneto systems, as opposed to battery, points, and coil systems. (If you don't remember how battery, points, and coil ignition systems work, please go back and read Parts 1 and 2 of this article series.)

At first glance, magneto ignition systems seem very simple; it appears you are just replacing the battery with a generator consisting of a coil of wire and a magnet in the flywheel. Simple, right? Well, from an electrical schematic point of view, this might appear to be the case (figure 3-1).

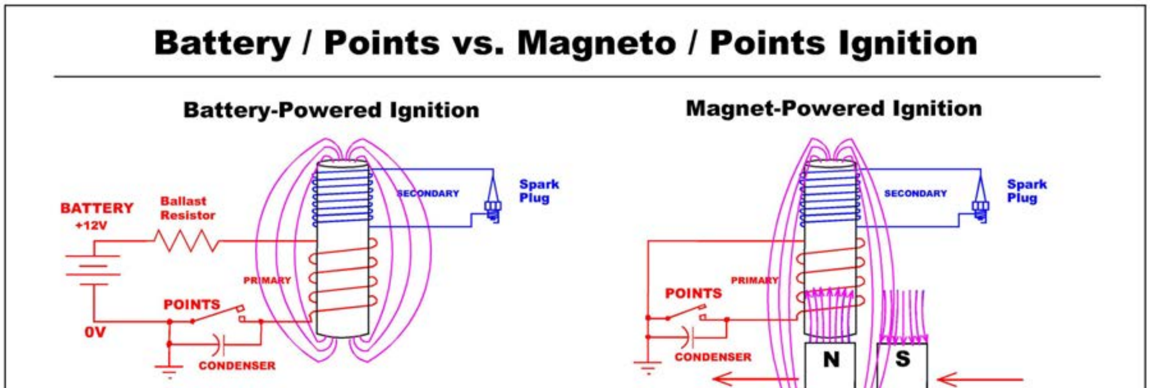


Figure 3-1

However, looks can be deceiving. In a battery-based system, the battery voltage is what is used to create current in the primary winding of the spark coil, whenever the points are closed. In a magneto, the magnets spinning in the flywheel are used to generate the voltage needed to create current in the primary winding. (Try to visualize this as the magnetic field creating a tiny battery inside the windings in the spark coil, and you'll have the right idea!)

In the battery-based system, you can measure +12 volts across the primary winding of the spark coil when the points are closed, and it is this voltage that drives the current in the spark coil. In the magneto-based system, you will measure almost zero voltage across the primary when the points are closed – and yet you get the same levels of primary current as you do with the battery-based system. The reason is that when the magnets spin past the primary of the spark coil, there IS a voltage generated – but it's generated inside the windings of the spark coil itself, where you can't measure it. By then connecting both sides of the magneto's primary together, this completes the circuit, and allows the voltage inside the coil to create the maximum current possible.

However, this is not the only difference we have to deal with. A battery provides direct current; that is, the +12 volt power is available all the time. In contrast, a simple generator or dynamo will create alternating current (AC), with the voltage alternating between positive and negative. (This looks like a “sine wave,” where the positive voltage you want is only available half of the time.) So, now you have to synchronize the AC voltage output to coincide with when you want the spark to be generated. By itself, that’s not a difficult challenge to overcome. However, magnetos produce a very odd output voltage pattern, where the positive and negative halves don’t look like each other at all. The positive voltage pulses generated are **much** higher in amplitude than the negative voltage pulses. In addition, the voltage pulses are all extremely narrow; the positive pulses we want to use only exist about 10% of the time. (See figure 3-2 for details. Compare the output voltage waveform you get from a bicycle generator to what is generated by a magneto. The magneto’s output voltage waveform looks very odd, but there are good reasons for this!)

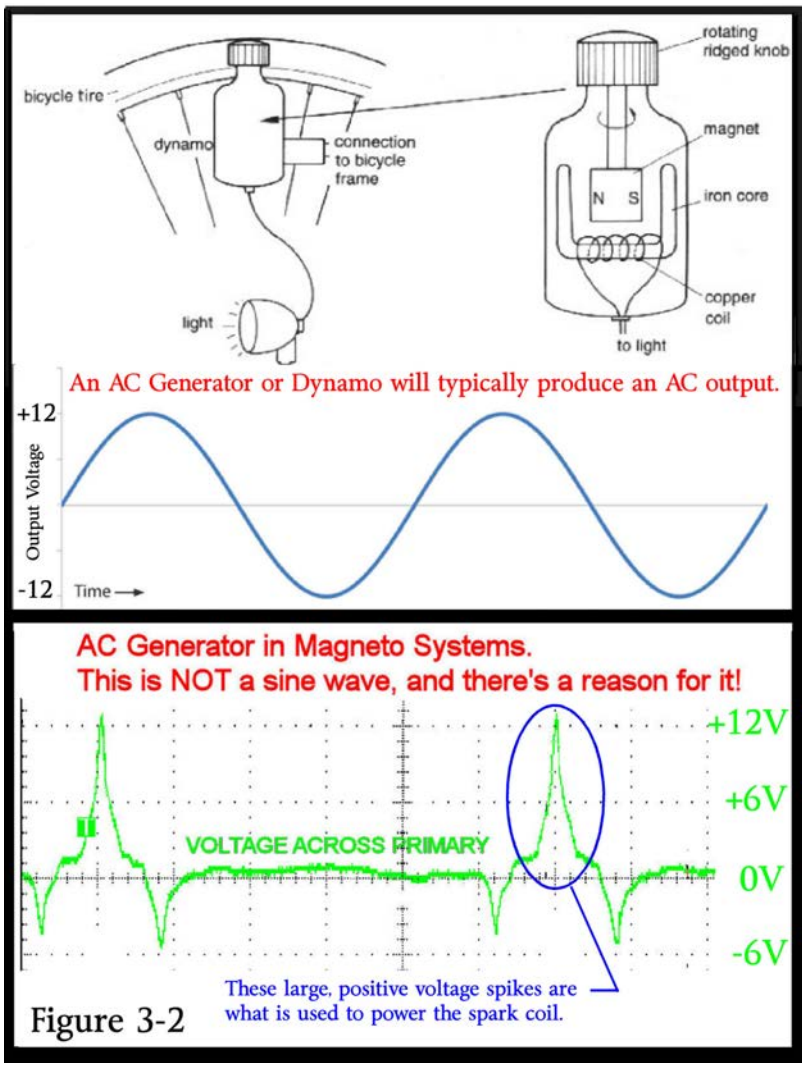


Figure 3-2

So, why do magnetos produce such an odd output voltage waveform? Well, here are the reasons:

1) Magnetos were designed before solid-state diodes were invented. Back in the 1920s and 1930s, only AC voltages could be easily generated. (Well, you COULD use a commutator and brushes system to give you only positive voltage pulses, creating a DC generator, but commutators and brushes are expensive to produce and a serious maintenance problem. Magnetos, especially in cheap devices like lawn mowers and chain saws, have to be inexpensive and very reliable. So, they have to deal with the AC voltage somehow.)

2) The magneto only uses the positive voltage pulses to create spark. The negative output pulses are not used (or worse, they can interfere with the positive voltage that we do want to use, so negative voltage output must be minimized if possible). Refer back to figure 3-2 to see which portion of the magneto's output voltage is actually used to create the spark. (Key point: this picture of the AC voltage created by the magneto is with the magneto's generator not connected to any load. You can see this if you disconnect the points and measure the AC voltage with no load. When the points are functioning, you will not be able to see this voltage across the magneto's primary winding).

3) We want the positive voltage generated to be at the maximum level possible, at exactly the time when the spark needs to be generated. When spark is **not** being generated, the voltage is of no use to us so magnetos are designed in such a way that they concentrate the positive voltage generated into a narrow, tall "spike" of voltage, to maximize the energy possible right at the exact instant when the coil needs to produce a spark. At the same time, negative voltage spikes are minimized as much as possible, so they won't interfere with the positive voltages that we want to use.

And now for the two really big questions: First, how is this odd waveform created, and second, how is it used to drive the spark coil? The "overview" answer to the first question is that the armature core in the spark coil and the pole pieces on the magnet(s) in the flywheel are specifically designed to produce this odd waveform. ("Poles" on magnets and armatures are pieces of metal from which the lines of magnetic force are directed.)

If you look closely at the magneto in an outboard motor, you will find that there are more magnets in the flywheel and poles in the armature cores than would seem to be necessary. Johnson and Evinrude magnetos have <u>two</u> magnets in the flywheel, and <u>three</u> poles in the armatures. (Refer to figure 3-4 for details.) Other systems may have <u>three</u> magnets in the flywheel and <u>two</u> poles in the armatures. It is this difference between the number of poles in the magnets and in the armature cores that is responsible for the creation of this odd waveform, with two small negative voltage pulses around every large, positive voltage pulse that is generated.

The "overview" answer to the second question is that when the output voltage is positive and the points are closed, the circuit is completed and current is driven through the primary winding in the magneto's primary coil. This appears identical to the battery, points, and coil based systems except that the "battery" here is voltage generated inside the coil (where you can't measure it) instead of being provided by an external battery, where it's easy to measure the voltage across the coil.

Now, to understand exactly how magnetos produce this output power waveform, it's necessary to first understand the basics of magnets, inductors, and transformers along with how a battery, points, and coil ignition system works (if you have not already done it, go back and review Parts 1 and 2).

Faraday's Law states that if you apply a voltage to a coil of wire, current will start to flow. As this current increases, it will create a magnetic field around the coil (forming an electromagnet). As the field increases in strength, it increases in size, causing the field to appear to move. However, the opposite is also true: if you take a magnet (with the magnetic field that surrounds it), and you move it past a coil of wire, then a voltage will be created in that coil of wire. If that voltage is connected to a load of some sort, current will flow (figure 3-3). It is the MOVEMENT of magnetic fields that creates voltage!

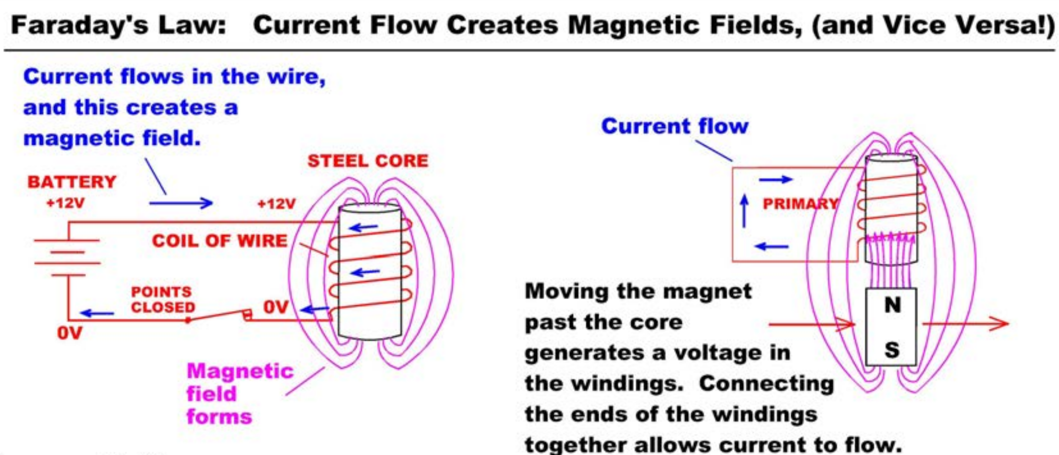


Figure 3-3

Also according to Faraday's Law, the faster the rate of change in the magnetic field, the larger the output voltage you will get; if the field changes VERY quickly, you can create very high voltages in the coil windings. (Remember the bicycle generator? The faster you pedal, the faster the generator spins and the brighter your bicycle's headlight will shine because of the increased output voltage.)

Always remember that in a magneto, the magnetic field applied to the coil's primary winding must be changing in size (or appearing to move) in order for any output voltage (and, hence, current) to be generated. If the magnetic field is not changing (specifically, if there is no magnetic field present, or if the magnetic field is at some maximum value but is NOT increasing or decreasing in strength,) then no output voltage will be generated. This is an important concept, and is absolutely key to understanding how a magneto generates that odd output waveform.

So, now that we have reviewed the basic principles, let's see how magnetos use them to create their rather odd AC voltage output. We'll start by looking at the Johnson/Evinrude 3-pole armature system, since it's a little easier to explain. NOTE: In the figures that follow, the points will be held open, so the voltage generated will not be affected by the spark coil's normal operation. For now, we just want to visualize how a magneto functions as an AC generator. Note also in these figures that the cam, which normally operates the points, is not shown because that's not important right now. And finally, the piston in the engine is at top dead center (TDC) when the magnets are just past the 12 o'clock (0 degrees) position in these figures.

Top dead center is when the piston is all the way up at the very top of the cylinder, at maximum compression, where we usually want the spark to occur. In figure 3-4, this condition will be met when the TDC arrow on the flywheel aligns with the Center pole on the 3-pole armature. Some outboards have timing marks on the flywheel to show where this is, but many do not.

Note in figure 3-4 that there is one magnet in the flywheel, with two pole pieces (a North pole and a South pole) pointing in toward the armature. The armature has three poles on it, which we will simply name Left, Center, and Right.

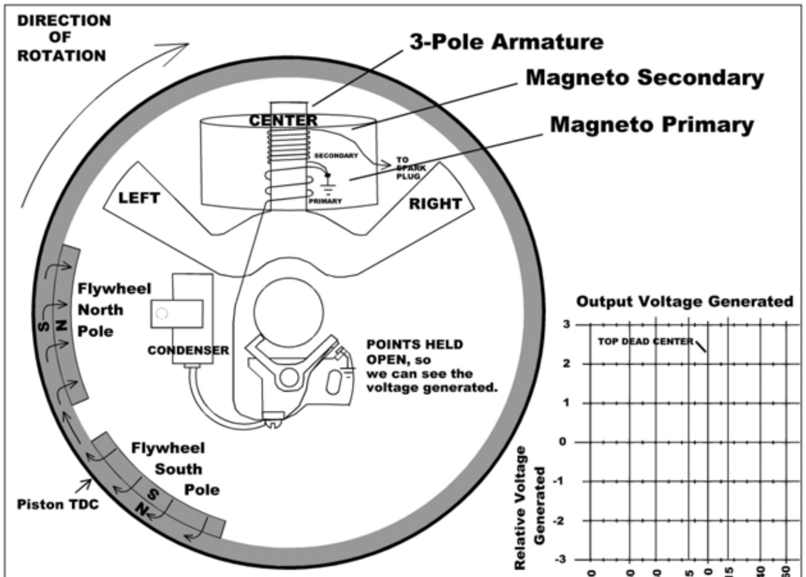


Figure 3-4

For about ¾ of the flywheel's rotation, the magnets are nowhere near the poles on the armature, so no voltage is generated at all. Let's keep rotating the flywheel, and see what happens!

Before we begin, let's look at figures 3-4 through 3-11. In these drawings, we have a graph of the output voltage that will be generated. However, we are not showing specific output voltages, just "relative voltages." The reason is that a relative voltage of 1 on this graph might represent an actual voltage of 1 volt (if the flywheel is turning slowly) or it might represent 10 or 20 volts or more, if the flywheel is spinning much faster. This is just like the higher voltage output you will see when you spin a bicycle generator faster.

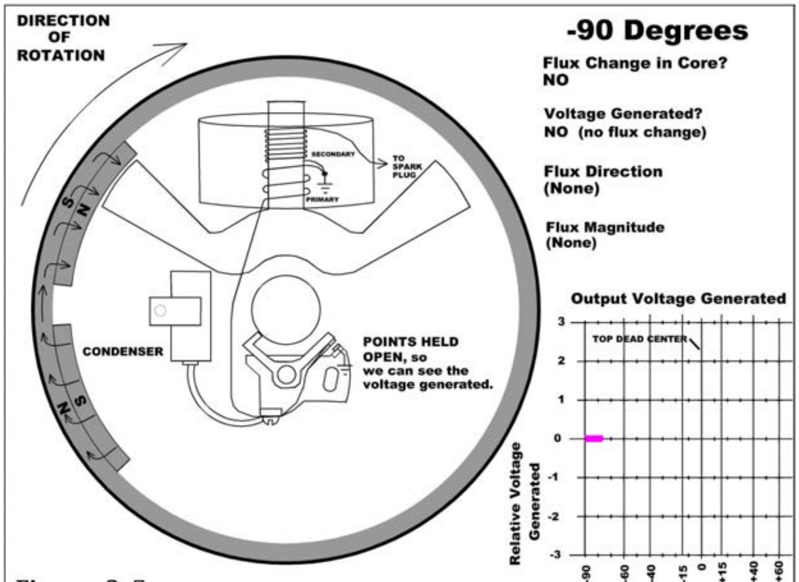


Figure 3-5

In figure 3-5, the flywheel is at -90 degrees before the piston reaches TDC. The North flywheel magnet pole is aligned with the Left armature pole. While the North pole would like to direct magnetic flux into the armature, there isn't any return path for the flux to get back to the South pole so no output voltage is generated, as indicated by the short mark at the left end of the "0" voltage line on our Output Voltage Generated graph. This "lack of flux through the core" condition will continue from -90 to about -40 degrees, so no voltage is generated over all this time.

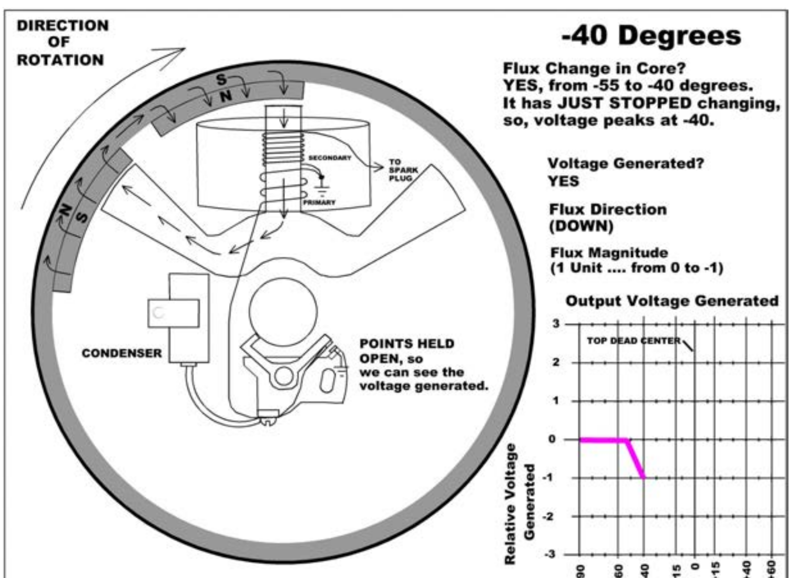


Figure 3-6

At –40 degrees before TDC (figure 3-6), the flywheel has rotated a bit. The North magnet pole is now aligned with the Center pole of the armature, while the South magnet pole is now aligned with the Left armature pole. Magnetic flux is now traveling DOWN the center pole of the armature and out the Left pole**.** This represents a change in magnetic flux in the armature of 1 "relative unit" from 0 to maximum. (As with voltage, I am using "relative units" because we don't know the strength of the magnets, so I can't indicate a specific magnetic field strength in terms of gauss per square inch. The actual field strength doesn't matter for this discussion of basic principles.)

The key point is that we now have a change in the magnetic flux going through the armature core, so an output voltage will be generated and will have a maximum value of 1 relative unit of voltage at -40 degrees. (Right now, we are only interested in the relative magnitude of the magnetic flux changes. It's not possible to tell exactly how many volts will be generated, as that is a function of the strength of the magnets, the number of turns in the windings in the primary coil, and the speed the flywheel is turning. Since we don't know those details, we will only describe things in terms of "relative units." Not to worry, this will make sense very soon!) Let's keep turning the flywheel.

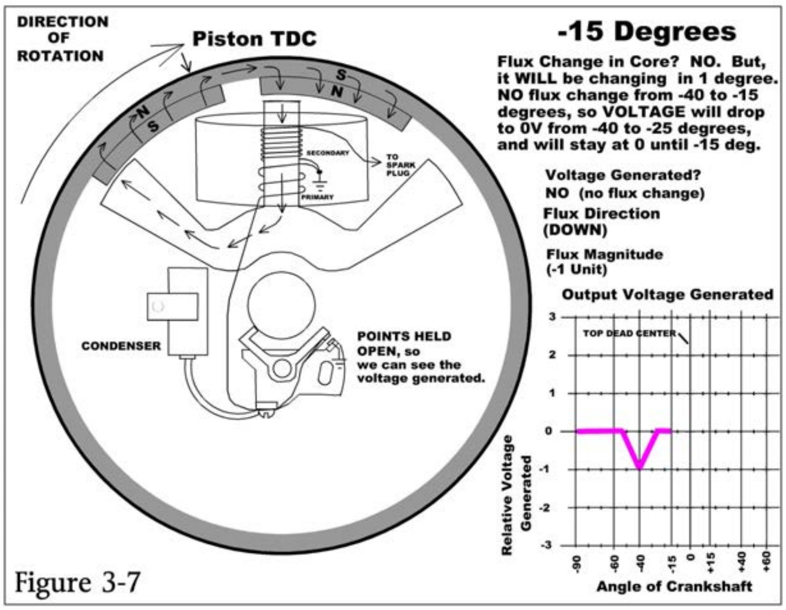


Figure 3-7

At about -15 degrees before TDC (figure 3-7), the flywheel has moved a bit, but the North magnet pole is still aligned with the Center armature pole and the South magnet pole is still aligned with the Left armature pole. Nothing has changed, so there is NO CHANGE in the magnetic flux. Remember that if there is no change in the flux, then NO voltage will be generated and our output voltage will now drop back to 0 volts. (See the voltage diagram for details.)

However, notice that the alignment of the poles is about to shift, and rather dramatically! Let's turn the flywheel a bit more, and see what happens.

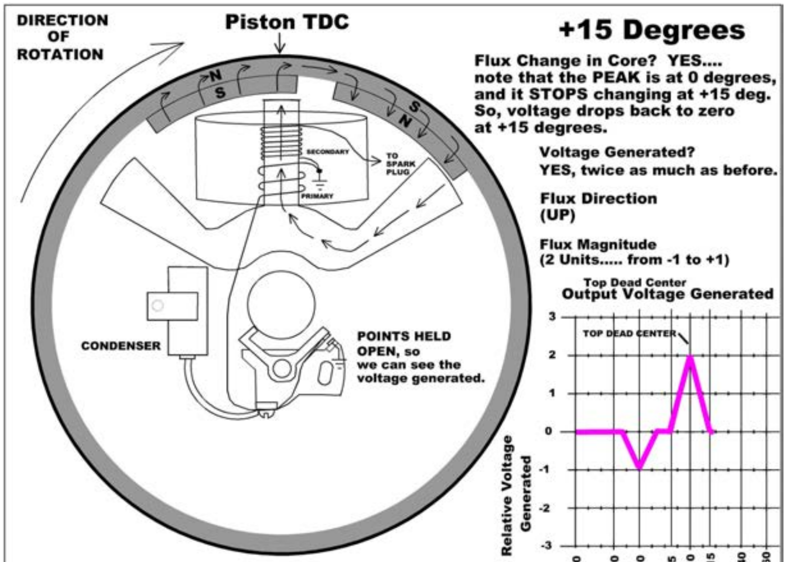


Figure 3-8

Here (figure 3-8) is where some of the magic happens! As we swing from -15 degrees before TDC to +15 degrees, the alignment of the poles completely changes. The North magnet pole is now aligned with the Right armature pole and the South magnet pole is now aligned with the Center armature pole. The magnetic flux that was going DOWN the Center armature pole has completely reversed direction, and is now going UP the Center armature pole. This is a rapid, 180 degree shift in direction from DOWN 1 unit to UP 1 unit, a relative magnitude change of +2 units so we WILL have voltage developed here, but it's going to be twice as large as the negative spike generated earlier because the **relative change** in the flux is twice as large as before. This voltage spike will be centered right at TDC (between -15 degrees and +15 degrees.)

Note that piston TDC happens either right at the peak of this voltage spike or just a few degrees later. This is when we want the spark to be generated!

Let's keep turning the flywheel and see what happens.

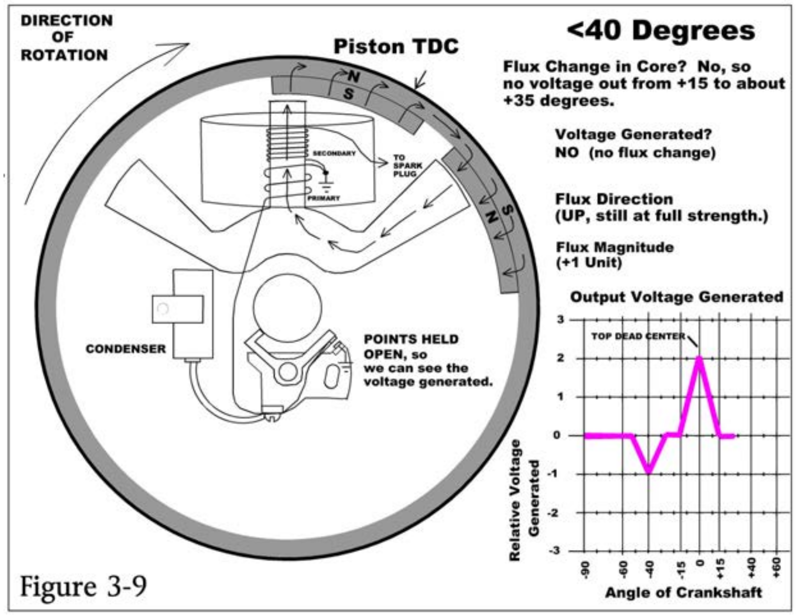


Figure 3-9

From +15 degrees to about +40 degrees (figure 3-9), the magnet and armature poles still have the same alignment. There’s no change in flux**,** so the output voltage stays at zero.

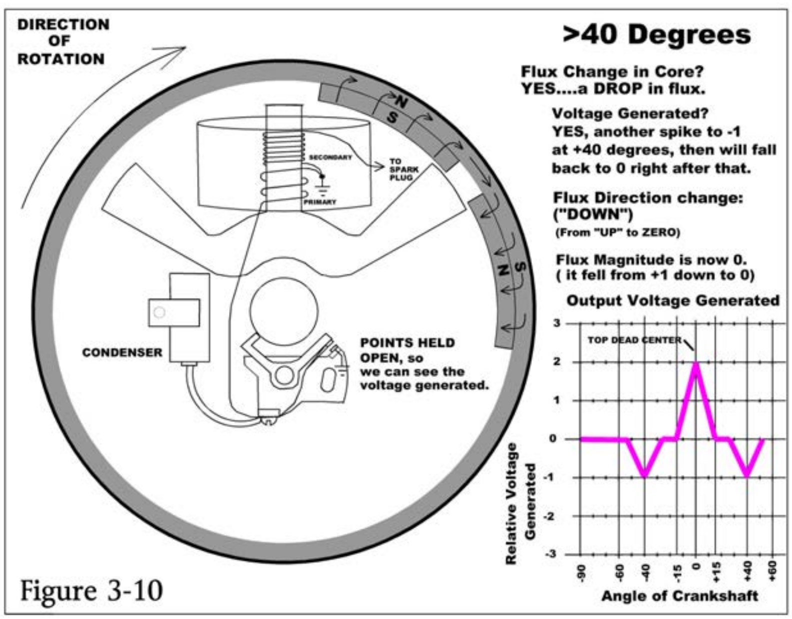


Figure 3-10

At about +40 degrees (figure 3-10), the magnet and armature pole alignment changes again. The North magnet pole is now not aligned with anything, while the South magnet pole is aligned with the Right armature pole. Just like before, the South magnet pole would like to force magnetic flux through the armature, but because there’s no way to get back to the North magnet pole, the flux in the armature drops back to zero. This is a change of flux in the armature core, from 1 in the UP direction down to zero, which is a relative change of –1. This will create a negative voltage spike again, centered at +40 degrees after TDC, at a relative level of –1.

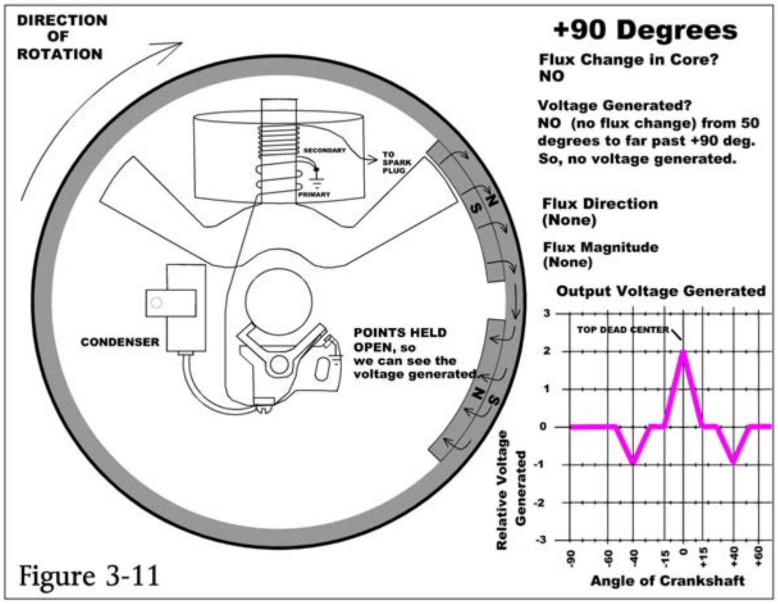


Figure 3-11

From +40 degrees to +90 degrees after TDC (figure 3-11), there is still no flux change, so the output voltage stays at zero. This pattern repeats every 360 degrees! Compare the final voltage waveform in figure 3-12 with the actual voltage waveform from a magneto, shown at the bottom of figure 3-2. Look familiar? It should!

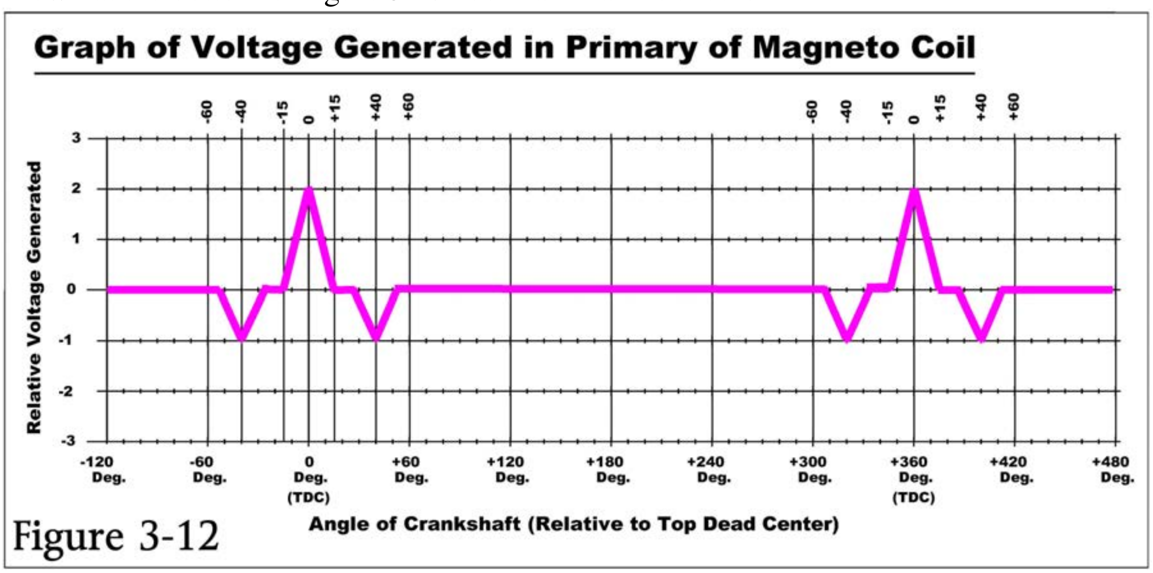


Figure 3-12

So we now have a big positive voltage spike available, right when the spark needs to be generated. What we now have to do is insert a set of points to connect this positive voltage spike to the spark coil primary at the correct time. Just like in the newer battery, coil, and points systems, this is done with a cam on the crankshaft. The shape of this cam closes the points at the correct time to turn the positive voltage into current, and then opens the points to interrupt the current flow, creating the inductive kick that produces about 50 to 100 volts across the primary winding of the magneto's spark coil. Due to the turns ratio of 200 to 1, this produces about 10,000 to 20,000 volts across the secondary winding of the spark coil, creating the spark for our spark plug.

Cam Shape

The experienced reader will likely be aware that there are two completely different cam shapes used in outboard motors. One looks like a letter D, and the other looks more egg shaped (see figure 3-13).

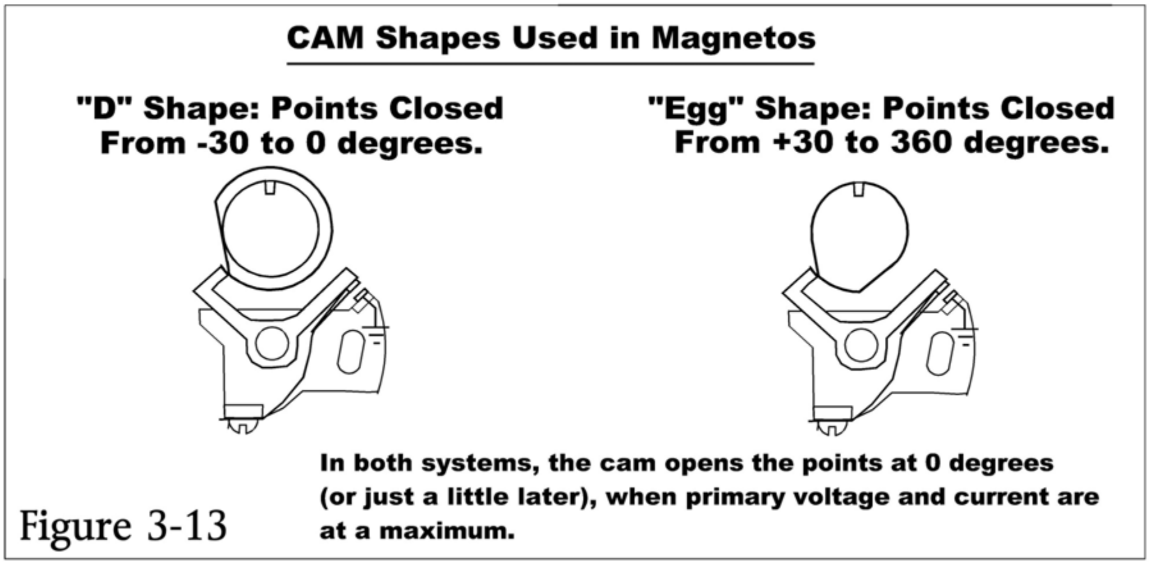


Figure 3-13

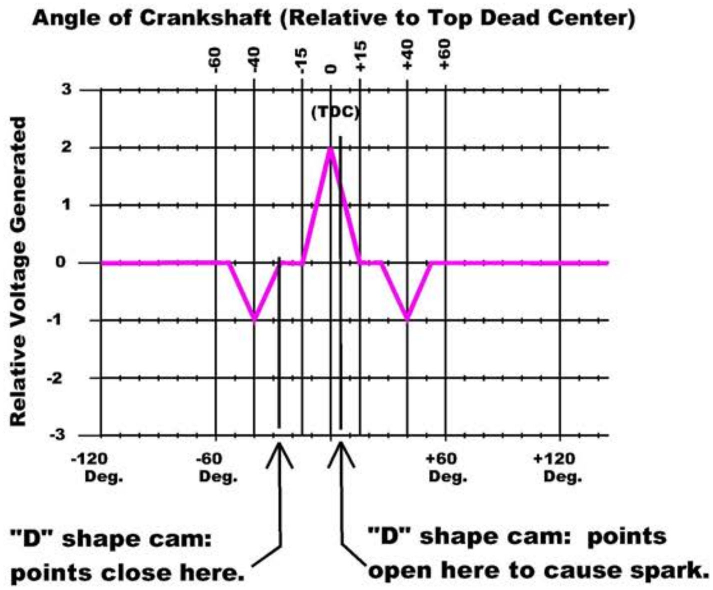
These systems seem to be completely opposite! However, note that in both arrangements, the points open up right at top dead center of the piston, or just a few degrees later, right when the voltage and current in the magneto's primary coil are at maximum.

Let's look at the voltage graphs in figure 3-14 to see the complete, functioning magneto in action!

Graph of Voltage Generated in Primary of Magneto Coil: POINTS FUNCTIONING

If the points are held OPEN, we can see the voltage being generated in the primary winding by the magnets spinning past the spark coil armature poles.

This graph is not showing specific voltages, because the actual voltage generated will depend on the speed that the flywheel is moving. The faster the flywheel magnets are turning, the more voltage you will get. At idle, you might only see the positive spike reach 4 to 5 volts. At 1000 RPM, you might see the positive spike reach 10 volts (very close to what you see in battery-points based systems.)



With the points FUNCTIONING, the voltages get a lot larger! (Note the change in the scale on the graph; it's displaying 10 times more relative voltage per grid line than before.)

1. **Points are OPEN here, so you will see the negative voltage spike.**
2. **The points close just before the positive voltage spike.**
3. **Because the points are closed here, the primary windings are connected. This converts the positive voltage spike into HIGH CURRENT in the primary winding.**
4. **When the primary current is at absolute maximum, the points open. The inductive kick then converts this into a 50 to 100 volt spike (just like in battery-based ignition systems).**
5. **With the points now open, you will again be able to see this small negative voltage spike as well.**

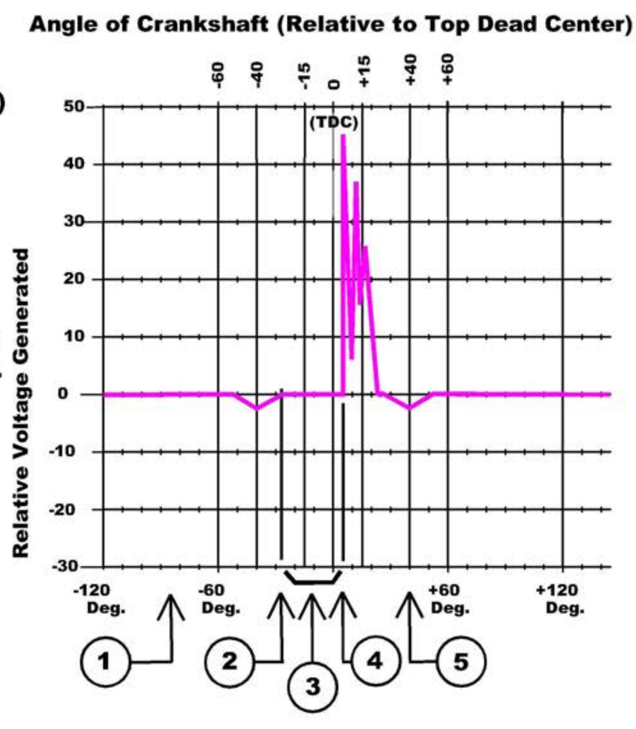


Figure 3-14

A note about figure 3-14: Please remember that these graphs are showing relative voltage, not actual voltage. This is because all of these voltages will depend on how fast your motor (and flywheel) are turning. At idle, you might only see a few volts across the primary winding. At 1,000 RPM, you might see 10 volts (just like with a battery-points based ignition system). At 5,000 RPM, you'll see much higher voltages. (Remember, the faster an engine runs, the stronger the spark generated by a magneto. This is why many racing engines today still use magnetos.)

The key to understanding magnetos is to remember that it is the **reversing of the direction of the magnetic field in the spark coil armature core that creates the large positive voltage spike.** This positive spike produces the highest current peak in the primary winding. The points opening up at ④ (figure 3-14) converts that current to a 50 to 100 volt spike in the primary winding and the turns ratio between the primary and the secondary magnifies this by another factor of 200 to 1, creating the 10,000 to 20,000 volts needed to jump your spark plug gap.

Figure 3-15 illustrates the exact moment when the points open, with a "D" type cam. If you understand what is going on in this picture, then you understand magnetos!

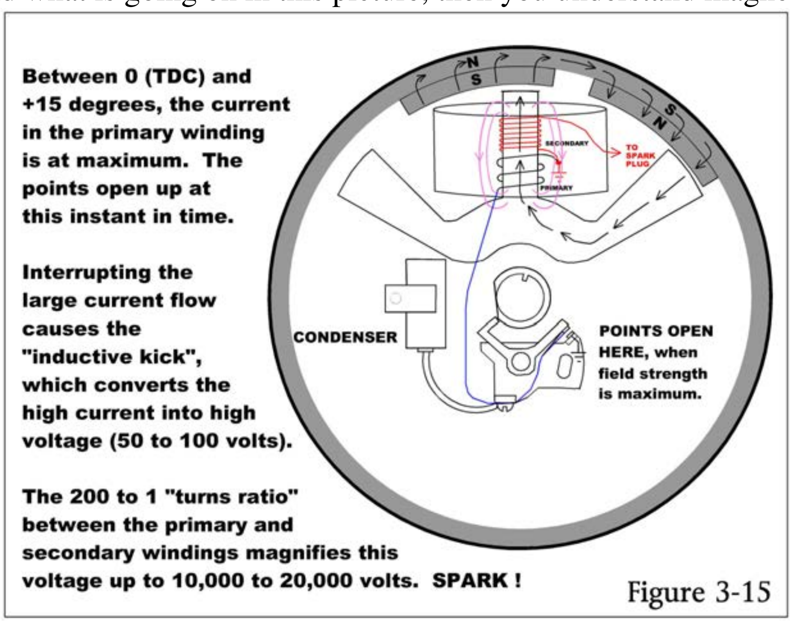


Figure 3-15

Now, you are probably wondering if the voltages you would see in a real outboard motor with a magneto will look as I have described here. Not to worry! Domenic Durda, Gary Orloff and I did a little experiment with a real outboard motor, to prove that theory and reality actually do match up. For our test case, we chose to look at the magneto on Domenic's Wizard WA3.

REAL WORLD TEST CASE

The Wizard WA3 was chosen because it was simple to work on, and because it has the three-pole armature that's typically also seen in Johnson and Evinrude outboards. The three-pole system is a bit easier to understand than the two-pole armature system, so we'll look at that system first.

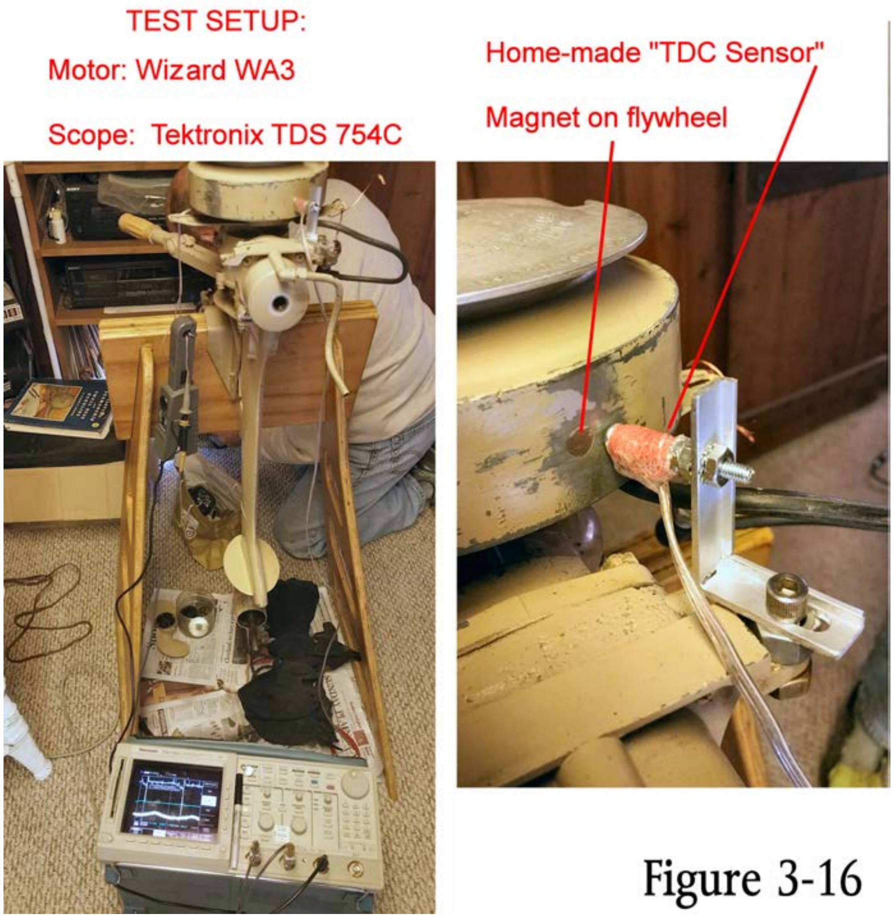


Figure 3-16

We planned to measure voltages and currents in the magneto in this outboard motor, but we also wanted to know **when** these voltages happened with respect to the position of the magnets in the flywheel relative to the position of the piston. To do this, we needed to be able to "take pictures" with the oscilloscope, with some indication of crankshaft position included. We decided to build our own magnetic pickup, made out of a screw and a few turns of wire, and position it so it would give us a pulse every time the piston was at Top Dead Center. This would allow us to see when the points open and close and when the magneto generates the spark with respect to the position of the piston and flywheel.

The Wizard WA3's magneto structure looks just like figure 3-15, so the voltages should match the theoretical relative voltages we have been discussing so far.

To begin the experiment, we put some paper in between the points, so the points could not close. This, of course, turned the magneto into a simple AC voltage generator. We were curious as to what voltages were generated, and at which crankshaft angle, with respect to TDC. Our results can be seen in figure 3-17. Note the high positive voltage pulse, just before the piston reaches TDC. It is this large pulse of energy that creates the initial primary current and the field in the core.

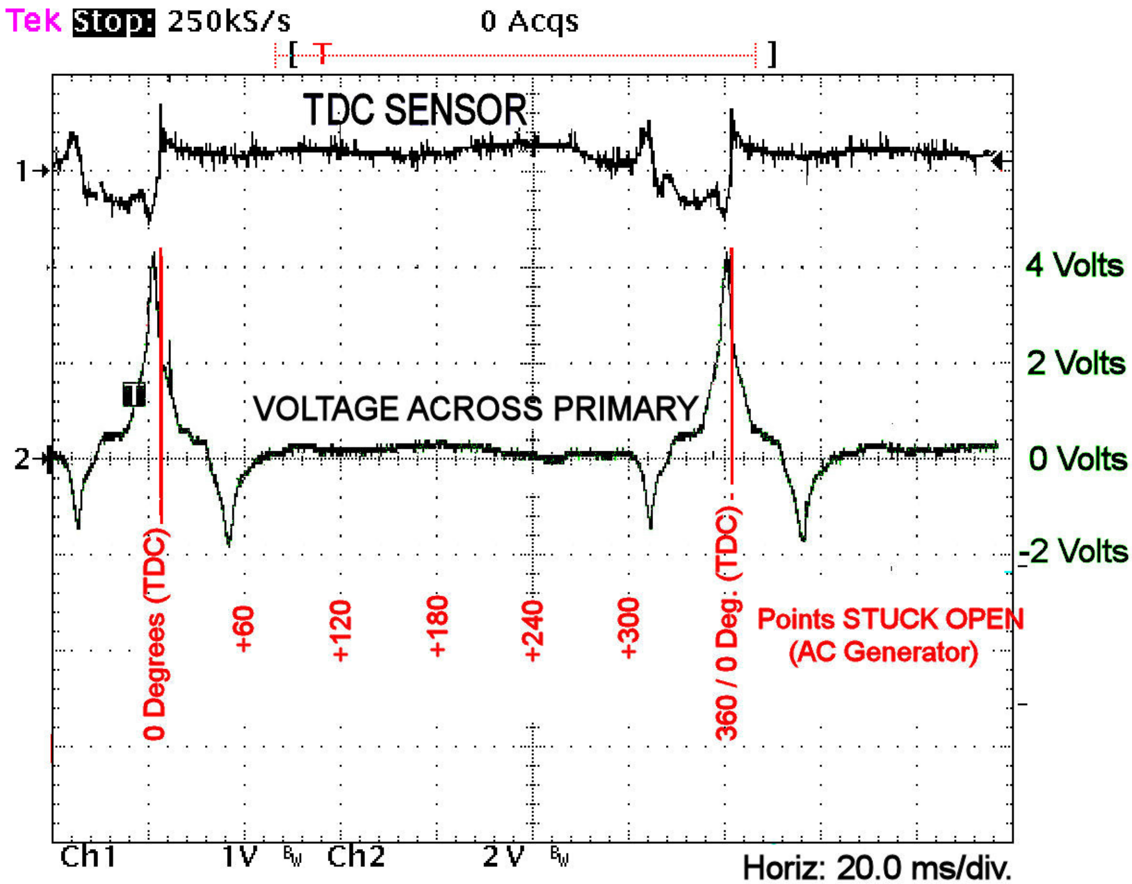


Figure 3-17

Again, this is just a test case with the points disabled. Initially, we were surprised that we were only generating about 4 volts here, not 12 volts like battery-powered systems. However, this is because we were turning the flywheel fairly slowly, so the output voltage was low. Spinning the flywheel faster generated higher output voltages.

Removing the piece of paper from the points allows the magneto to function normally. See figure 3-18.

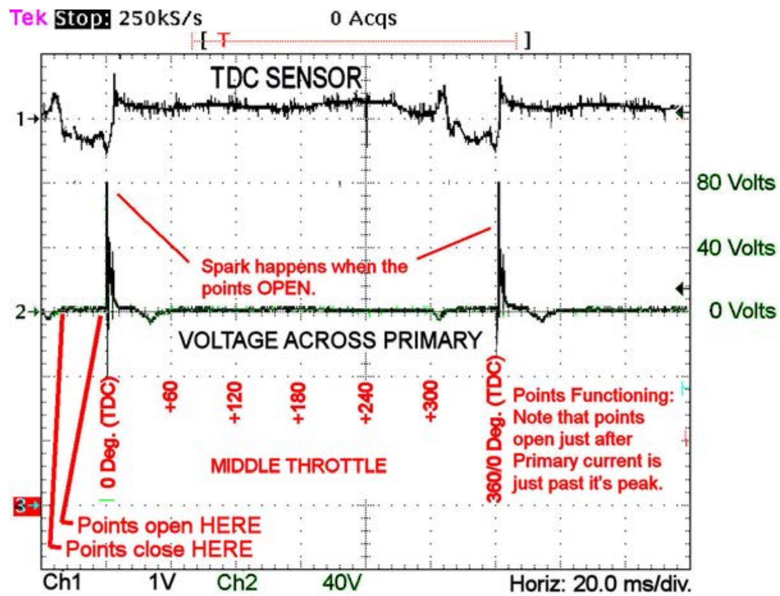


Figure 3-18

(Note that on this Wizard motor, at mid-throttle the spark fires exactly when the piston is at TDC.)

Figure 3-19 shows a greatly magnified view of the primary voltage, when the spark occurs.

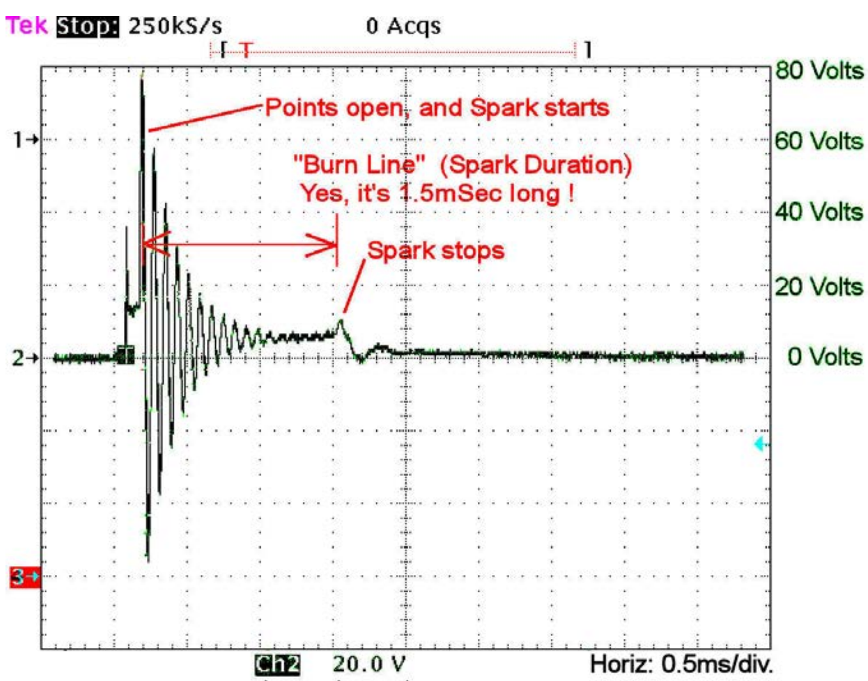


Figure 3-19

The oscilloscope is measuring 20 volts per division (10x probe), so the primary voltage is jumping from 4 volts to about 80, when the points open. With a turns ratio of 60:1, this means the Wizard's spark plug is firing at about 4,800 volts. The spark voltage instantly drops to about 600 volts (still jumping across the ionized gas in the spark plug gap) and this continues for 1.5 milliseconds. While these voltages seem low, it's because we had the spark plug firing in open air. (The engine is a lot easier to spin when the spark plugs are not in the cylinders!) When the spark plugs are installed in the engine, the denser air/fuel mixture is harder to penetrate, requiring higher voltages to jump the gap. In all ignition systems, the inductive kick will cause the spark coil voltage to rise as high as necessary, until the voltage jumps across the spark gap.

Note in figure 3-19 that the arc continues for a duration of 1.5 milliseconds. That is what makes this a really hot spark!

Out of curiosity, we moved the spark advance/throttle setting from middle to full throttle, and then to idle, to see the spark advance and retard produced by this system (see figures 3-20 and 3-21). Our goal was to see how much the spark timing would change, based on the throttle setting.

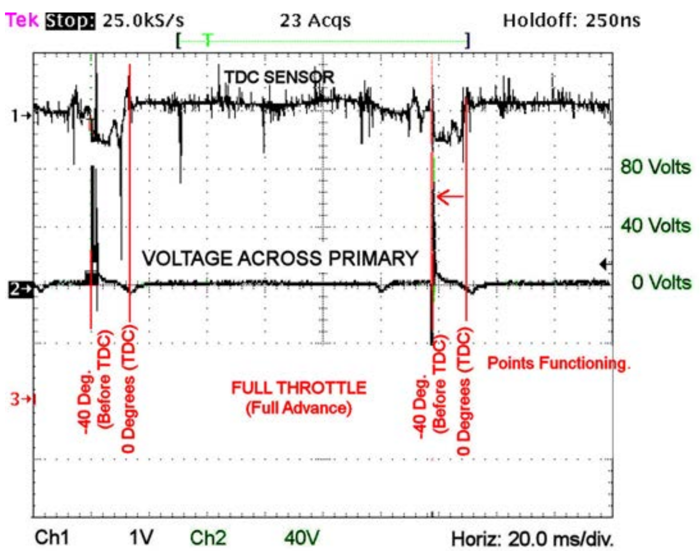


Figure 3-20

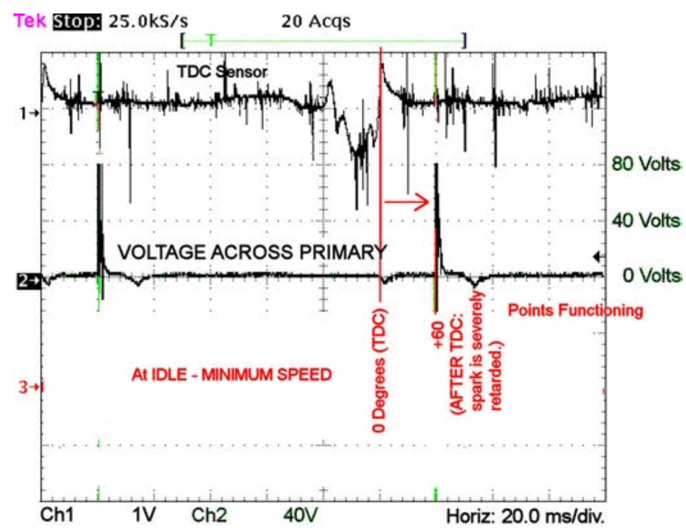


Figure 3-21

Analysis: At full throttle, we saw the spark advance to about 40 degrees before TDC. At idle, the spark was retarded to about 60 degrees after TDC. This seems excessive, but in our test case the mechanical linkage between the carburetor throttle arm and the magneto baseplate was not connected; it's likely that the carburetor linkage would limit the advance and retard to some angles smaller than this.

For one last test, we deliberately mis-adjusted the points, to see what effect that would have on the ignition timing. We wanted to know if an outboard motor's points are slightly mis-adjusted, would it have serious effects on the ignition timing or not? To find out, we set the points at 0.015", 0.020" (nominal), and 0.030" to see how much of an effect each would have. Results are shown in figure 3-22.

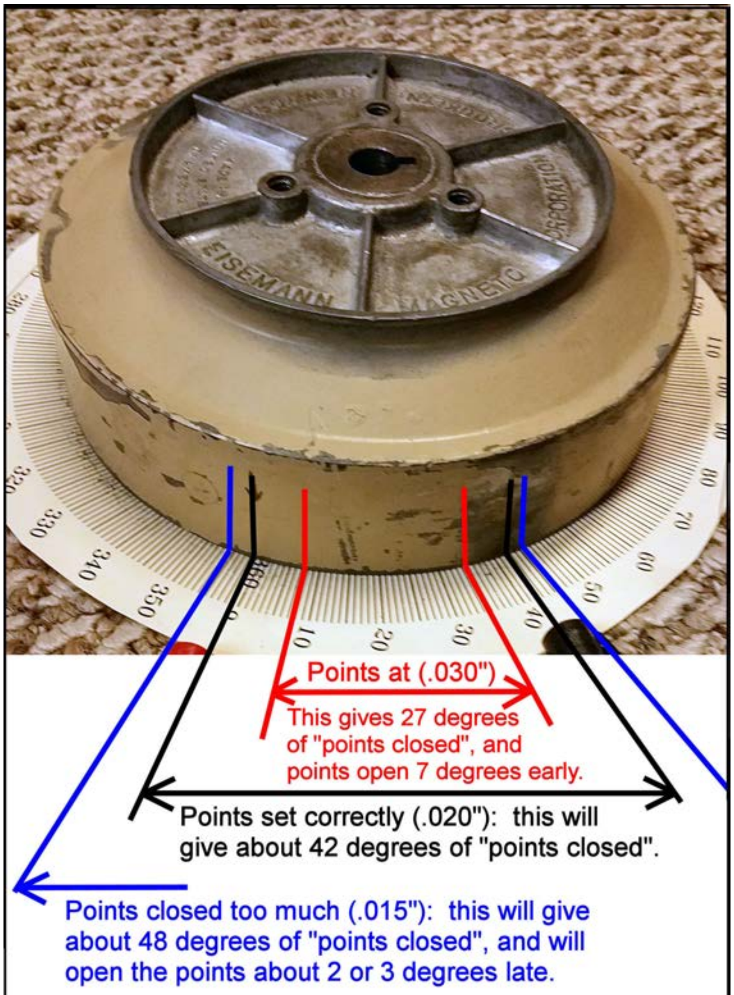


Figure 3-22

Analysis: With the points set correctly at about .020", the spark will fire at the correct angle with respect to TDC. At a gap of .030", the dwell angle will decrease a bit, but the plug will fire 7 degrees early. Seven degrees of extra advance will cause the fuel to be ignited early, causing stress on the engine, reducing horsepower, and possibly making the engine hard to start. If the points are closed too much (.015"), then the spark will fire 2 to 3 degrees late. This isn't terribly serious, which is why an outboard motor will run even with the points misadjusted rather badly in either direction. The result will be hard starting and poor power, along with bad fuel economy. So, keeping your points adjusted is important, but not so much that you have to check the timing every few weeks. (Unless you are racing, of course!)

Two related topics of interest:

1) MAGNETS. Modern magnets (Alnico, Samarium Cobalt and Neodymium) hold their magnetic strength for many years. Typically, they lose less than 10% of their strength over 100 years – but this is not true of the magnets used in antique outboards. Back in the 1930s and 1940s, most outboards were built with steel magnets. These magnets lose about 1% of their strength every year. After 50 years or more, their strength can be very low, often not enough for the magneto to work properly. Your coils and points may be fine, but you won't get any spark if the magnets in your flywheel are too weak.

There are magnetizers available that can re-magnetize the weak magnets in an old flywheel and get them back up to full strength. Some old repair shops and some members of the Antique Outboard Motor Club still own some of these old magnetizers.

2) THE DIFFERENT TYPES OF CAMS. This article discussed D-shaped cams in detail. They are only closed for about 30 out of 360 degrees of the flywheel rotation. The points are open when the negative voltage pulses occur, so these pulses can be seen with an oscilloscope if you look for them. (Think of this as a "mechanical rectifier," if you wish, because that's exactly what it is doing!)

In contrast, egg-shaped cams are closed for 330 out of the 360 degrees. Notice that they are closed during the negative voltage spikes, so they send these negative voltage pulses to the spark coil primary along with the desired positive pulses. When the points controlled by an egg-shaped cam are closed during the negative voltage pulses**,** they get current going in the wrong direction in the spark coil's primary windings. The higher positive voltage pulse then has to stop, then reverse the direction of the current flow in the primary winding before the spark can be generated. This wastes a bit of energy, which isn't the most efficient way to create spark with a magneto.

From an electrical point of view, D shaped cams allow the magneto to create a hotter spark with weaker magnets, while running the coil cooler. Egg-shaped cams are less efficient, electrically speaking, but they experience less wear at the point of contact between the points and the cam. There are strengths and weaknesses with each of the different cam systems, but both of these cams open the points at the exact same time, when the positive voltage is at its peak value, or just a few degrees later.

And a final note:

This article only discussed the three-pole armature system in detail. The three-pole magnet, two-pole armature style of magneto also produces the same odd "W" shaped voltage waveform, but its principle of operation would take another 10 pages to explain. All you need to know is when the direction of the flux in the armature core changes direction, the spark should be generated at that point or just a few degrees later.