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Training

UNDERSTANDING FUEL INJECTOR WAVEFORMS

by Bernie C. Thompson

FUEL injectors – Chapter 1

Language is the key to understanding what is happening around you. Imagine being in a foreign country but not knowing how to speak the language of that land. Now, imagine being given your task in this land, to gather data and then make an informed decision based on this information. Not very many of us are that adventurous, and would cringe at the thought of this situation. However, this is what many of us do everyday. Many modern automotive technicians approach a vehicle not understanding the language, or data, that the vehicle is communicating with. After checking systems and gathering data, the modern technician is going to make a decision on what is wrong with the vehicle. But if the information was not understood or misinterpreted altogether, then this decision might be incorrect. Now, imagine you are working on a modern vehicle and could understand the language that it is speaking. This language is electrical impulses, changing amplitude (voltage) over time. Just like learning to read a written language, letters join together to convey useful information. In this electrical language, changes in voltage will convey useful information. The question at hand is how does one obtain this information or analyze this information? The key to unlocking this electrical language is the oscilloscope.

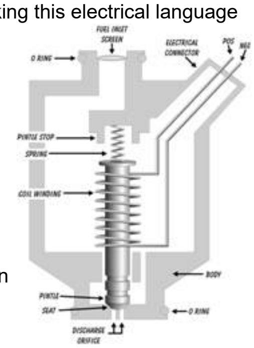
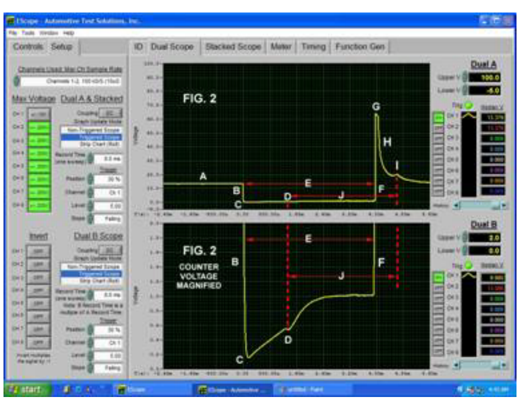


Figure 1

An oscilloscope is a device that displays voltage amplitude over time, thus creating a visual display or graph that is commonly referred to as a wave-form. These electrical waveforms carry information or data that is needed in diagnosing a vehicle. Each of these waveforms contains unique information about the electrical circuits which affect the operation of the vehicle's systems. But what do these electrical impulses have to communicate or tell you?

Let us examine a very common saturation style injector (Figure 1).

At first glance the wave form this injector makes looks like a very simple signal. However, an in depth analysis is required to understand what is actually occurring.



For each part of the electrical change; voltage over time, will have a story to tell you. Let's look at Figure 2 Part A on page 27. This is the open circuit voltage or source voltage. The reason this is referred to as an open circuit voltage is the circuit has not been completed. There is no current flowing through the injector circuit at this point. In Figure 2 Part B, the voltage drops abruptly when the PCM driver turns on, thus completing the injector circuit to ground. This voltage drop should come very close to ground. The initial voltage drop will depend on whether the electrical device used is a transistor or a MOSFET. If a transistor is used, the drop will be .7 volts to 1 volt. This is due to the resistance across the transistor's gate. MOSFETs have less resistance across their gate causing less voltage drop, usually about .2 volt to .3 volt drop. The voltage drop is the voltage that is remaining in the circuit to push the current across the resistance of the PCM driver or gate (Figure 2 Part C). Once the power train control module (PCM) commands the injector driver closed, current starts to flow through the injector coil circuit. When current flows through a coil winding all of the current is used to create a magnetic field around the winding (Figure 3). This magnetic field build up is inductance.

The magnetic field is proportional to the inductance and the current, in other words, the larger the current the larger the magnetic inductance. As the magnetic field is building, the inductance offers resistance to the current flowing through the injector circuit. This is due to the magnetic field building, as the field builds it moves across the coil winding which induces voltage into the coil winding. This induced voltage frees electrons which gives resistance to current flowing through the coil. This resistance is called counter voltage. Anytime there is resistance in a circuit there will be a voltage drop proportional to the resistance. This voltage drop can be seen at the bottom of the injector waveform. This is what causes the slight rise at the bottom of the injector waveform.

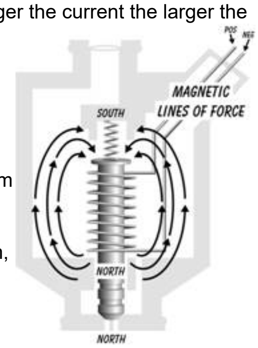
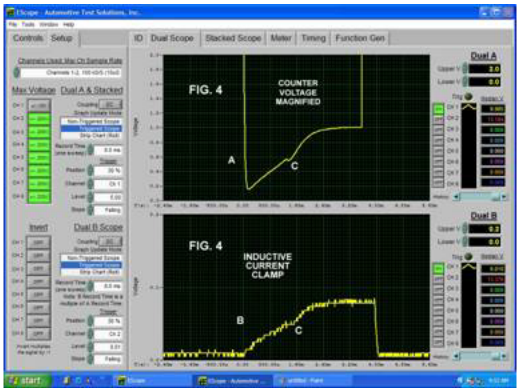


Figure 3

If the oscilloscope voltage setting is lowered to magnify the bottom of the injector waveform, the voltage drop of the waveform can be seen more clearly (Figure 4 Part A). Since the current flowing through the winding makes the resistance for the voltage drop it mirrors the injector waveform made with an inductive amperage clamp (Figure 4 Part B).



Once the PCM driver closes, current starts to flow through the circuit. The magnetic field builds until it becomes strong enough to overcome the mechanical spring pressure holding the injector pintle in the seated position. At this point the injector pintle starts to move away from the seat through the magnetic field (Figure 5).

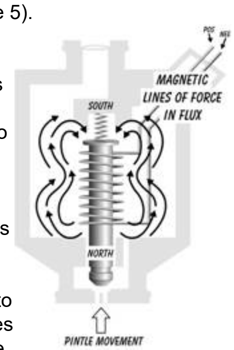


Figure 5

When a ferrous metal moves through a magnetic field it causes the magnetic field to flex or change, thus inducing voltage into the coil winding. This induction releases free electrons which impedes the flow of current in the injector winding circuit, in turn, this causes the current to diminish slightly, creating the hump in the waveform (Figure 4 Part C). This hump shows when the injector pintle opens and allows fuel to flow through the injector. Note: Not all injectors will show this hump. The current then continues to build until the waveform reaches its maximum current. This is set by source voltage and the resistance in the circuit.

The PCM then calculates the correct time and turns the injector driver off, opening the circuit (Figure 2 Part F). This creates an abrupt voltage rise. The voltage level will then pass the open circuit voltage until it is clipped at a critical point. Note: Some injectors do not clip the flyback voltage. The voltage rise is caused by the magnetic field that has been built around the injector coil winding. Once the circuit is opened and current stops flowing, the stored energy in the magnetic field falls across the winding causing voltage to be induced into the injector coil (Figure 2 Part G).

This induced voltage is called the fly back voltage. The flyback voltage is then clipped (Figure 2 Part G). This voltage level changes between manufactures and systems. The flyback voltage is adjusted for the injector design being used in the circuit. The flyback voltage is set for the electromagnetic coupling of the injector and the mechanical spring rate. The magnetic field around the injector winding is stored energy which is used to control the speed that the pintle is closing with. If the pintle is allowed to close too fast the pintle and seat will become pounded out and will begin to leak fuel. With a fast closing rate the pintle can also bounce causing extra fuel to be delivered to the engine. This extra fuel cannot be controlled accurately so the engineer must adjust the energy held within the flyback voltage to accurately control the closing rate of the injector.

This is done by using a zener diode across the PCM driver (transistor or MOSFET). See Figure 6.

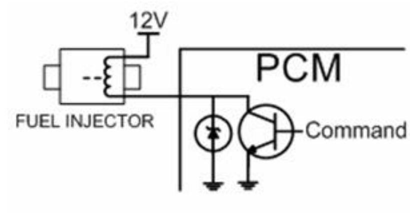


Figure 6

As the magnetic field falls back into the injector winding the energy is allowed to loop through the circuit. This allows the current to diminish at a set rate. The lower the voltage is set by the zener diode, the more energy is allowed to loop through the circuit. If a diode were used rather than a zener diode, this would let the most energy allowed loop through the circuit.

A diode will allow the stored energy to loop until it reaches source voltage, in this case 12 volts. This would allow the injector the longest period of time to close. The higher the zener diode voltage, the shorter the period of time allowed for the injector to close. This is due to the energy looping through the circuit being cut off early by the voltage rating of the zener diode.

If a 65 volt zener diode is used, the energy that is looping through the circuit is stopped at 65 volts which is 53 volts sooner than a diode, that allows the energy to continue to loop through the circuit until it reaches 12 volts. So the energy from a higher rated zener diode will shut off the energy looping through the circuit sooner which allows a faster pintle closing rate. Likewise, the energy from a lower rated zener diode will allow the energy to loop longer which will cause a slower pintle closing rate. This rate is set by the zener diode voltage which is matched to the injector design.

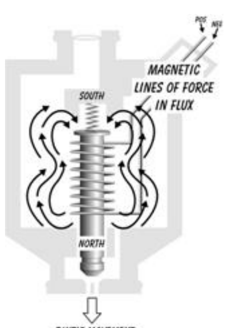


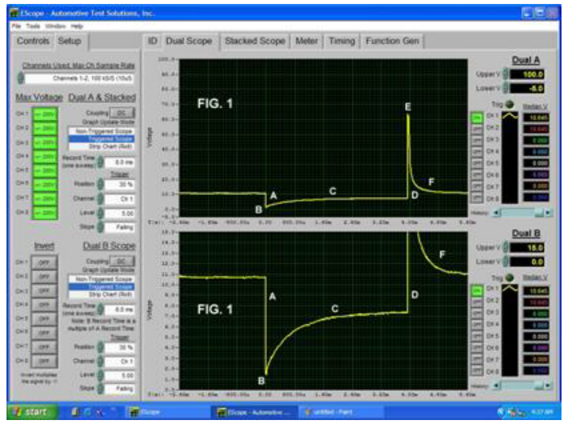
Figure 7

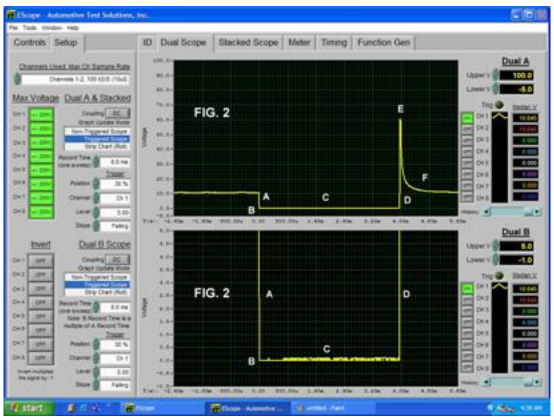
The delay in closing voltage can be seen in Figure 2 Part H on page 27. Once the Pintle starts to fall through the magnetic field, the pintle distorts the magnetic field causing voltage to be induced (Figure 7). This is what causes the injector closing bump in the waveform. Notice that when current is not flowing through the injector circuit the pintle movement induces a positive voltage (Figure 2 Part I). Note: Not all injectors will show this bump. The PCM commanded time is the time from “B” to “F”; however this is not the true injector opening time. The true injector opening time is from hump “D” to the closing bump “I” (Figure 2 Part J). In a good circuit this time from “D” to “I” will equal the PCM command time from “B” to “F” (Figure 2 Part E).

The first thing in understanding a language is to understand the characters that make up the language. Once you can understand what data is being transferred, you can use this to make diagnostic decisions. Now that we understand the data contained in a saturation injector waveform we can use this data to see what has failed within the circuit. What story will a bad injector waveform have to tell you?

FUEL injectors - Chapter 2

In the last chapter we explained a language made up of electrical impulses changing amplitude (voltage) over time. Each electrical change makes up the letters or symbols of this language. Individually the letters can not tell you very much, but when the letters are linked together they have a story to tell you. Just like evaluating an ancient language each character or symbol plays a very important roll in telling the whole story. If any character is missing or cannot be understood, a portion of the story is missing. This could change the story considerably depending on which part may be missing. It will be very important when evaluating waveforms that each letter or character is understood. This will enable you to have the complete story. When diagnosing a modern vehicle, one must have the complete story to arrive at the correct conclusion. Now let us check the letters of this language and link them together so they may tell you a story. We will analyze several saturation style injector waveforms that are bad (Figure 1 Part A). When the power train control module (PCM) turns on the injector driver, the voltage drops abruptly. Notice the initial voltage drop through the driver is elevated to 1.8 volts. (Figure 1 Part B). This is high and shows there is resistance in the ground circuit. As current flows, the voltage drop across the resistance rises to 7 volts. Notice the injector pintle opening hump is missing (Figure 1 Part C). The PCM then calculates the on-time of the injection pulse. At this time the PCM commands the injector driver off (Figure 1 Part D). The voltage has an abrupt rise which goes above the open circuit voltage and reaches 65 volts (Figure 1 Part E).





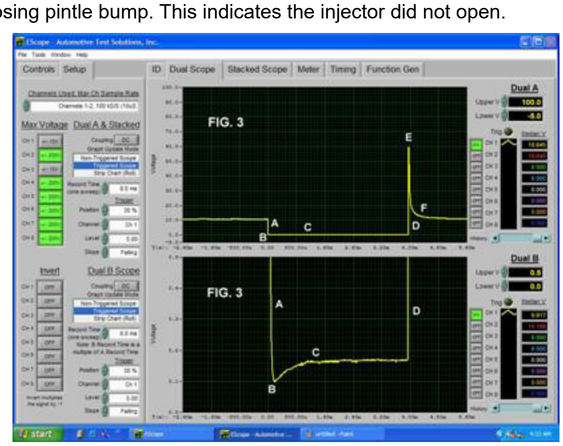
The flyback voltage from rise to fall is very close together. This is unlike a clipped flyback voltage where there is space between the rising and falling edge of the voltage. Since this injector waveform is a clipped signal at 65 volts, this shows there was not enough energy stored in the magnetic field. Since the current flowing through the injector winding makes the magnetic field, this indicates the current through the circuit is diminished.

As the voltage falls back to open circuit voltage there is no injector pintle closing bump (Figure 1 Part F). This injector never opened due to resistance on the ground side of the circuit.

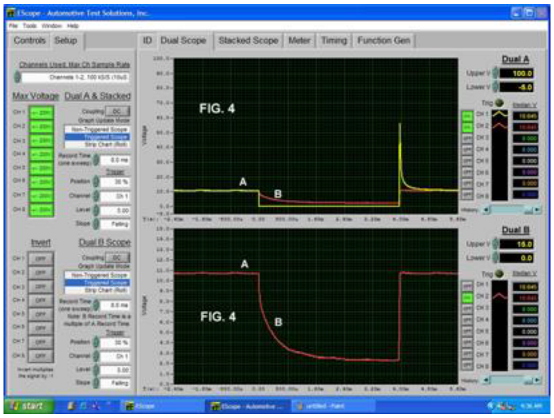
To locate where the resistance is within the ground circuit, one must move the scope probe from the injector connector to the PCM connector. In Figure 2 this is the same circuit, but the probe has been moved to the PCM connector. This waveform shows that we are past the resistance, indicating the problem would be with the signal wire or a connection between the injector and PCM.

Let’s take a closer look at this injection waveform. The PCM commands the injector driver to close (Figure 2 Part A). Notice the initial voltage drop through the driver is 0 volts which indicates there is very low current flowing through the driver (Figure 2 Part B). The higher the current flow through the driver is, the higher the initial voltage drop occurs across the driver or gate. Once the current starts to flow through the circuit there is no counter voltage (Figure 2 Part C). In other words, across the injector on-time the voltage has no rise and stays at 0 volts. Since current flowing through the winding makes the counter voltage, this shows there is very low current flowing through the injector winding. Once the PCM calculates the on-time it commands the driver off. At this point the voltage has an abrupt rise (Figure 2 Part D). The voltage rises above open circuit to 65 volts. Again, notice how close together the rising and falling edges of the flyback voltage are. This indicates low current flow through the injector winding. As the voltage falls back into the open circuit voltage there is no injector closing pintle bump. This indicates the injector did not open.

Now let us look at another injector waveform that has some of the same traits as the injector waveform that we have just covered. In Figure 3 Part A the PCM commands the injector driver on. The initial voltage drop through the driver is 0 volts (Figure 3 Part B). This indicates there is very low current flowing through the circuit. As current starts flowing through the injector winding there is no counter voltage rise (Figure 3 Part C). This indicates very low current flow.



The PCM then commands the injector driver off, creating an abrupt voltage rise which rises above open circuit voltage (Figure 3 Part D). The flyback voltage only reaches 60 volts which is 5 volts below the zener diode voltage for this circuit (Figure 3 Part E). This shows the magnetic field is very weak. It does not even have enough energy to reach the zener voltage at 65 volts. As the flyback voltage falls back to open circuit voltage there is no injector pintle closing bump. This shows the magnetic field never built strong enough to overcome the pintle spring, so, the injector never opened. The scope probe was located at the injector connector and there is not a voltage drop indicated on the control side of the circuit. The problem would be up stream of the probe connection which would indicate the connection, injector winding, or power to the injector would have a resistance problem. Before disturbing the injector connector by unplugging it, move the scope probe to the power (voltage) side of the injector connector. Figure 4 shows the power side (CH2) and control side (CH1) of this injector circuit. Now you can see the problem more clearly. Ch2, the red trace, is the 12 volt feed circuit to the injector. Notice the open circuit voltage on both power and control is equal. When a circuit is open no current is flowing, thus, no voltage drop can occur (Figure 4

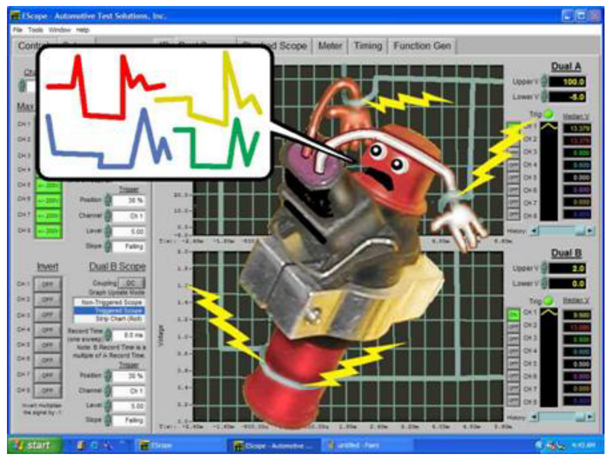


Part A). Once the PCM commands the injector driver to close, the current starts to flow. Now the power side shows the voltage drop clearly (Figure 4 Part B).

To find where the resistance would be within the power circuit one would move the scope probe up stream until there was no voltage drop. Once the scope probe has moved past the resistance, it will no longer show the voltage drop. This would indicate the resistance would lie between the injector connector and the point at which the voltage drop stopped. Note: On some systems a voltage drop on the power side is normal. If a dropping resistor is engineered in the injector circuit this would be normal (Check the correct wiring diagram for the vehicle). However, if the injector is not opening there is still a current problem within the circuit.

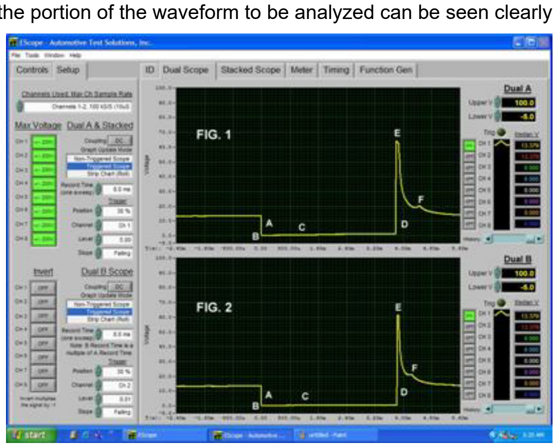
Now check how large the voltage drop is. If the dropping resistor has too much resistance or a connector is dropping voltage, the current to the injector will not be enough to properly work the injector. As you can see, when the letters of the language are linked together and can be understood, they are able to tell a story about what has gone wrong within a circuit.

FUEL injectors - Chapter 3



In the last chapter we looked at an electrical language where changes in voltage over time show you how to trouble shoot a circuit. When you can understand the secret unseen language of the computer you can tell a great deal about the circuit. In the days of old, to acquire information from a person who was unwilling to talk, kings would put the individual on the rack and then tighten the screw. At this point the unwilling individual could be persuaded to talk. The question at hand is “how can a technician persuade electrical waveforms to talk and give you the information that you need to repair modern vehicles”?

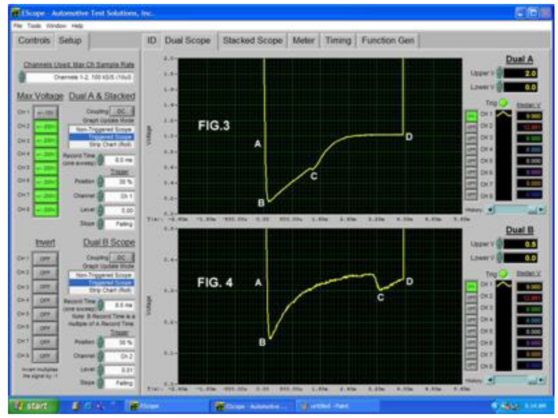
The modern day rack is the oscilloscope. The modern technician will put the wave-forms on the oscilloscope and turn the knobs. Then the un-willing electrical waveforms will not only talk but will tell you a story about the circuit. One must still understand the language of the electron. The oscilloscope is the key to entering the swift silent unseen world of the electron. Once the electrical impulse is put on the oscilloscope and the technician adjusts the voltage and time base so the portion of the waveform to be analyzed can be seen clearly it will be easy to make these waveforms talk.



Now let’s turn the oscilloscope knob on a bad injector wave-form. We will analyze two injector waveforms (Figure 1 and Figure 2). At first glance both of these waveforms look good. However, one of these has a problem. Can you see it? Let’s analyze Figure 1 Part A and Figure 2 Part A. The power train control module (PCM) commands the injector drive on. The voltage has an abrupt change and falls near ground on both patterns (Figure 1 Part B and Figure 2 Part B). Current begins to flow through the injector winding and counter voltage begins to rise off ground (Figure 1 Part C and Figure 2 Part C).

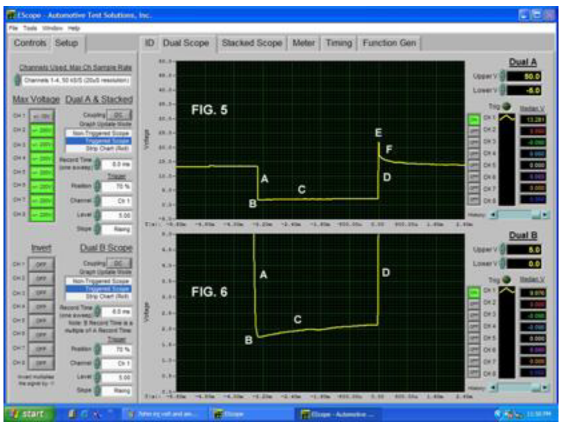
Notice the counter voltage on Figure 1 Part C has more counter voltage rise than in Figure 2 Part C. The PCM then calculates the correct on-time and commands the injector driver off. This causes an abrupt rise in the voltage (Figure 1 Part D and Figure 2 Part D). The voltage rises past the open circuit and peaks out at the point it is clipped at 65 volts (Figure 1 Part E and Figure 2 Part E). Notice that on Figure 1 Part E the flyback voltage between the rising edge and the falling edge has more space between them than Figure 2 Part E. This is an indication that the magnetic field has more energy stored in Figure 1. Since the magnetic field is built by the current flowing through the winding, this shows that Figure 2 has a resistance problem within the injector circuit. As the voltage falls back into the open circuit voltage, you can see the injector pintle closing bump. Notice that Figure 1 Part F has a longer closing rate by 2.5 microseconds than Figure 2 Part F. This is because the magnetic field has more energy and can control the pintle closing rate.
Now let’s magnify the bottom counter voltage and analyze these wave-forms (Figure 3 and Figure 4). At first glance these wave-forms look a lot different. They are not like Figure 1 and Figure 2 where the appearance seems very similar. In Figure 3 Part A and Figure 4 Part A, the PCM commands the injector driver closed. This creates an abrupt fall in the voltage. The initial voltage drop comes very close to ground (Figure 1 Part B and Figure 2 Part B).

The current starts to flow through the injector winding making counter voltage which causes the voltage drop at the bottom of the waveform. Note: Figure 3 voltage setting is at 2 volts for the chart while Figure 4 voltage setting is at .5 volts for the chart. In Figure 3 Part C we can see the injector pintle open, in Figure 4 Part C we can also see the injector pintle open, however, the opening time is delayed by 1.9ms. The counter voltage difference from Figure 3 to Figure 4 is .65 volts. Since the counter voltage mirrors current flow, Figure 4 has considerably lower current flowing through the



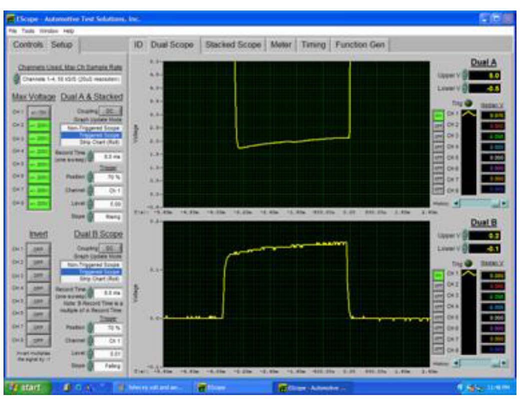
injector circuit. Due to the diminished current flowing through Figure 4 the magnetic field takes longer to build. This delay in the magnetic field causes the pintle spring to keep the pintle seated longer. The magnetic field has to have more energy than the mechanical force of the spring to overcome it and open the injector pintle. The resistance within Figure 4 is not in the control side of the circuit. You can clearly see the voltage drop on the ground side is good. You would need to check the power side of the injector, the injector connector and the injector coil winding to find the problem.

In this example the problem is high resistance in the injector coil winding which causes the opening and closing delay. The problem is very hard to see until you magnify the counter voltage in the injector waveform. At first glance one might not see a difference between Figure 1 and Figure 2, or cylinder 1 and cylinder 2, but upon closer inspection we can see that there is a delay of 2.15ms. In Figure 1 the actual injector opening time is 32us or 3.2ms. In Figure 2 the actual injector opening time is 11us or 1.1ms. This is one third the fuel delivery and would cause a lean misfire and rough idle complaint that can be easily overlooked.



Now let us look at another injector waveform that could give a rough running complaint. In Figure 5 Part A, the PCM commands the injector driver to turn on. The voltage has an abrupt drop towards ground. The initial voltage drop is 1.9 volts (Figure 5 Part B) which is high for a MOSFET style driver. As current starts flowing through the circuit the counter voltage does not have very much change; only about .1 of a volt. This is low and shows the magnetic field is not moving through as many injector coil windings. When we look across the counter voltage the injector pintle opening hump is very small (Figure 5 Part C).

The PCM then calculates the on-time and turns the injector driver off. This creates an abrupt rise in voltage. This rise passes the open circuit voltage and reaches a flyback voltage of 25 volts. This is very low for the circuit that has as a 62 volt zener diode setting the voltage clamp level. Also notice the rising and falling edges of the flyback voltage have no space between them. This indicates there is very low energy stored in the magnetic field. Now the flyback voltage falls back into the open circuit voltage, but there is no sign of the injector pintle closing bump.



Now let us look at the same problem using an inductive amp clamp (Figure 7 Part A). The injector driver turns on and completes the circuit. Current starts to flow through the injector winding. Notice that the transition from 0 volts to 1.4 volts is very abrupt. This shows there is very little counter voltage. This injector is shorted in the coil windings. A good injector will ohm at 16.5 ohms, but this shorted injector ohms at 7.3 ohms which is less than half of the windings that would normally be completed. In Figure 6 Part B the initial drop in the voltage waveform is 1.7 volts, which is quite high. The reason for the elevated voltage is resistance which is in the injector driver. The driver itself is not bad but due to the increased current flowing through the driver, or gate, it will offer more resistance to the current flowing through it. Much like a freeway, as traffic increases on a Monday morning the traffic starts to back up. The more traffic increases the greater the back up will be.

Now let us check the counter voltage which has very little rise. This is due to the decrease in the injector winding count. As the magnetic field builds up there are only one half of the windings that are completed. This cannot offer as much counter electromotive force to impede the current flowing through the circuit. The PCM then commands the driver off. The magnetic field falls back through the injector windings which induces voltage in these windings. Since there are fewer windings to induce voltage in, the flyback voltage is diminished. The injector pintle closing bump is not present due to the reduced magnetic field. Since the magnetic field is weakened it cannot be flexed as much, thus, less induction occurs which in turn creates no closing bump. One thing to notice is that the current flowing through the injector is twice the amount as in a good injector. One might think since there is more current flow the magnetic field will be larger. If we move current through a wire, a magnetic field will surround this wire.

The more current that flows through this wire the larger the magnetic lines of force become. However, in a winding or coil the more turns that are made around a core, the more magnetic amplification will occur. When a coil has fewer turns, this creates less amplification or a weaker magnetic field. It is possible to have an injector shorted with current flowing as high as 9 amps, but the magnetic field is so weak it cannot overcome the mechanical pintle spring to open the injector.

The waveforms are silent and unwilling to talk, but if you put them on you rack and twist the knob, they will tell you a story and what a story they have!

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