FUEL INJECTOR WAVEFORMS SLICED EXTRA THIN

By Bernie Thompson

We took a slice out of an injector to remind you that injector waveforms are nothing more than snapshots of thin slices of time.

Language is the key to understanding what's happening around you. Imagine being in a foreign country and not being able to speak the language. Now, imagine being given the task of gathering information and making an informed decision based on that information. This is what many of us do every day when we attempt to diagnose vehicle malfunctions, lacking a clear understanding of the language spoken by the vehicles we're attempting to service.

The basic unit of the electrical language of the automobile is impulses, or changes in voltage (amplitude) over time. In a written language, letters join together to convey useful information. In this electrical language, changes in voltage convey the information. These changes are the letters or symbols of the electrical language. Individually, the letters can't tell you very much. But when they're linked together, they have a story to tell.

The oscilloscope is a powerful tool that can help you interpret and understand the electrical language. It displays voltage amplitude over time, thus creating a visual display or graph that's commonly referred to as a *waveform*. These electrical waveforms carry information that's needed to diagnose a vehicle. Each of these waveforms contains unique information about the electrical circuits that affect the operation of the vehicle's systems.

Our purpose here is not to teach you how to use a specific scope model; that's what instruction manuals and training videos are for. Rather, we'll explain how certain vehicle electrical components work, show you what their waveforms typically look like and explain how to diagnose component faults based on the information those waveforms provide.

The first waveform we'll examine belongs to the very common saturation-style fuel injector. The cutaway drawing in Fig. 1 on page 36 illustrates the internal components of this type of injector. At first glance, the waveform produced by this injector looks like a very simple signal. However, an in-depth analysis is required to understand what's actually occurring.

Each part of the waveform (a record of voltage over time) has a story to tell. Let's look at waveform segment A in Fig. 2. This is the *open circuit* or *source voltage*. It's referred to as open circuit voltage because the injector circuit has not been completed and there's no current flowing at this point. The voltage drops abruptly in waveform segment B when the powertrain control module (PCM) driver turns on, thus completing the injector circuit to ground. A magnified view of the waveform can be seen in the lower screen of Fig. 2.

The voltage should come very close to ground at this point. 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 to 1 volt. This is due to the resistance across the transistor's output. MOSFETs have less resistance across their output, causing a lower voltage drop of .2 to .3 volt.

The voltage drop is the voltage that remains in the circuit to push the current across the resistance of the PCM driver or gate (waveform segment C). Once the PCM commands the injector driver closed, current starts to

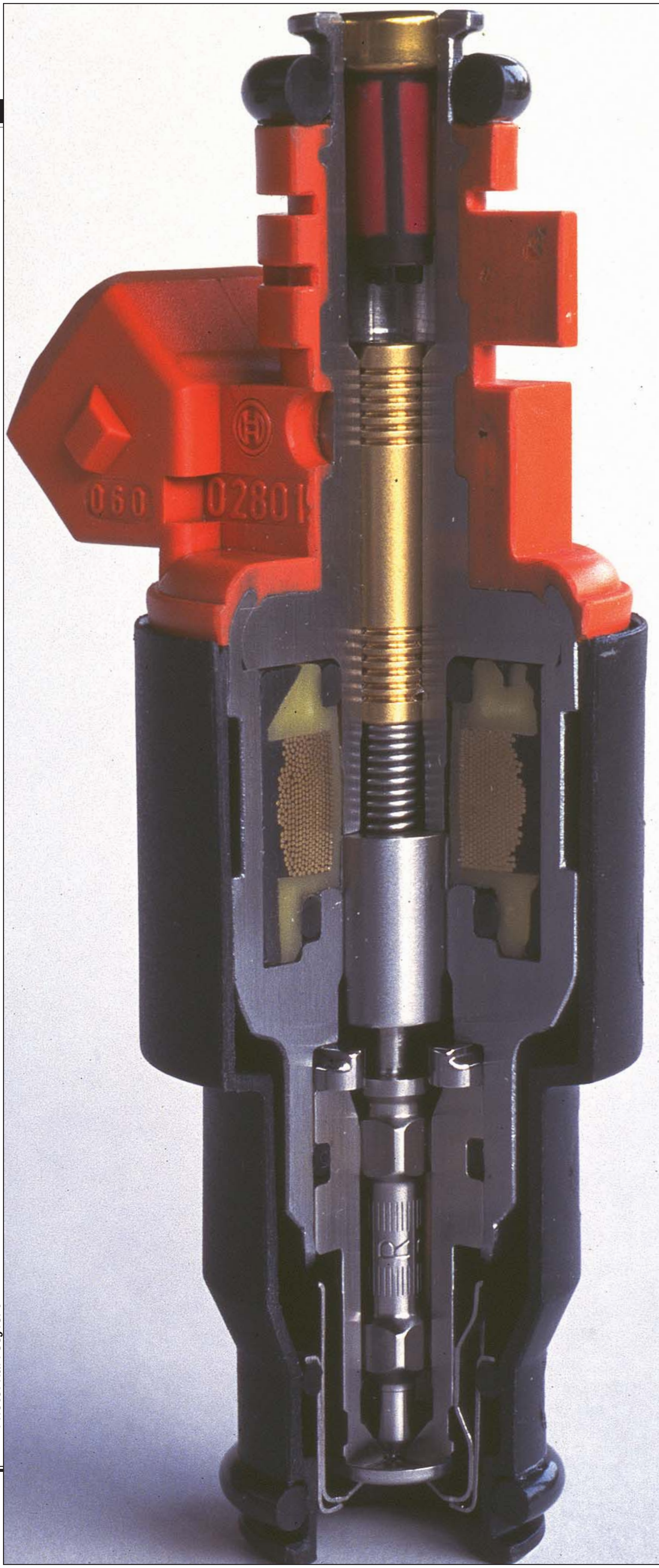

Photo: Karl Seyfert

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 (Fig. 3, page 38).

The magnetic field is proportional to the current and the number of turns in the coil. In other words, the larger the current, the larger the magnetic field. As the magnetic field is building, the inductance offers resistance to the change in current flowing through the injector circuit. As the field builds, it moves across the coil winding and induces voltage into the coil winding. This induced voltage frees electrons, offering resistance to the change in current flowing through the coil.

Imagine a school hallway packed shoulder to shoulder with children running as fast as they can. Now imagine children entering the hallway from classrooms located along this hallway. The children leaving the classrooms can't change the flow of children already running down the hallway without increasing the pressure. Just like the children entering the hallway, the induced voltage (pressure) in the injector winding creates resistance to the change in current flowing through the injector circuit. This resistance is called *counter electromotive force* (*emf* for short), or *counter voltage*.

Whenever there's inductance in a circuit, a counter emf will be produced by a change in current in such a way as to resist the change in current. And whenever there's resistance in a circuit, there will be a voltage drop proportional to the resistance. This voltage drop can be seen as the slight rise at the bottom of the injector waveform.

If the oscilloscope voltage setting is lowered to magnify the bottom of the injector waveform, the waveform voltage drop can be seen more clearly (waveform segment A in the upper screen of Fig. 4). Since the current flowing through the winding produces the resistance for the voltage drop, it mirrors the injector waveform made with an inductive current clamp (waveform segment B in the lower screen of Fig. 4).

Once the PCM driver has closed, 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 and through the magnetic field (Fig. 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 impede the flow of current in the injector winding circuit. In turn, this causes the current to diminish slightly and create the hump in the waveform (waveform segment C in the upper screen of Fig. 4). This hump shows when the injector pintle opens and allows fuel to flow through the injector. 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. *Note*: Not all injector designs will exhibit this characteristic hump.

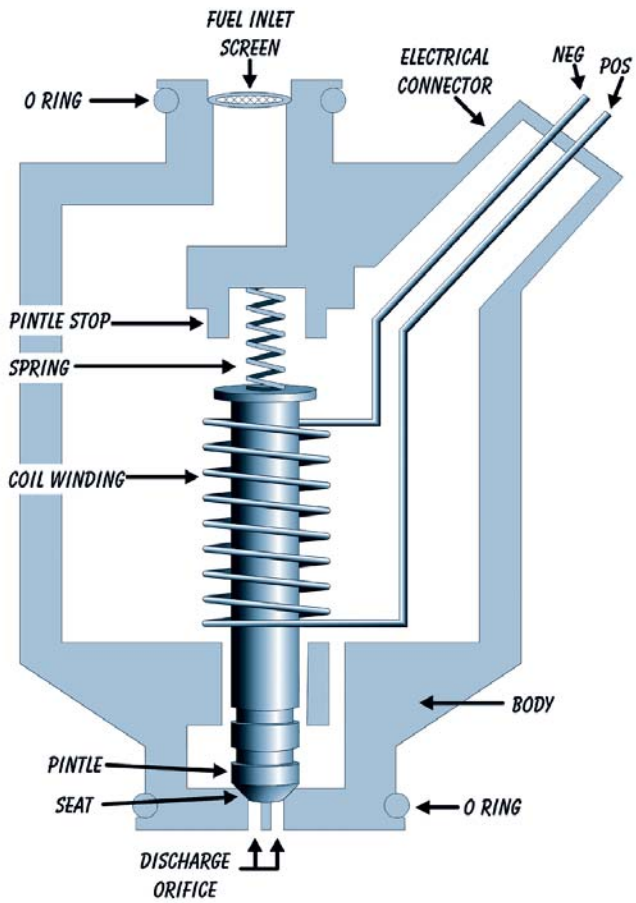

Fig. 1

The PCM has calculated the proper injector ON time and turns the injector driver off, opening the circuit (waveform segment F in Fig. 2 below). This creates an abrupt voltage rise, as the counter emf resists the change in current. The voltage level will continue to rise, passing the open circuit voltage, until it's clipped at a critical point.

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 tries to stabilize the current in the injector circuit. As this energy falls back into the injector winding, it falls across the turns of the winding, thus causing induction at the injector coil (waveform segment G in Fig. 2). The induced (flyback) voltage is clipped at a voltage level specified by the fuel injection manufacturer, based on the particular injector design in the circuit (waveform segment G in Fig. 2). The flyback voltage clipping point is set based on the injector's electromagnetic coupling and mechanical spring rate.

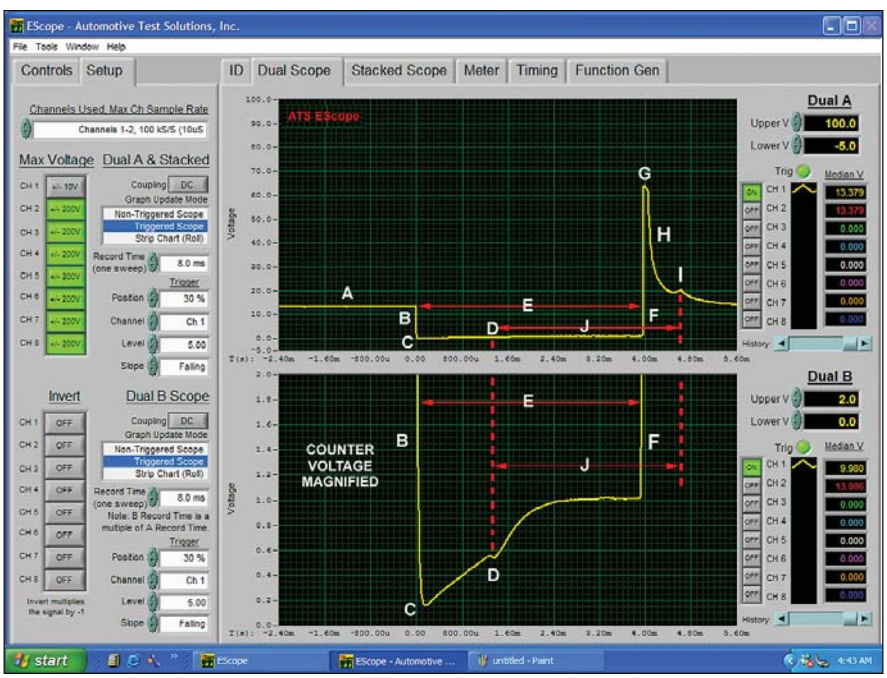

Fig. 2

Illustrations: Automotive Test Solutions

The stored energy of the magnetic field around the injector winding is used to control the pintle closing speed. If the pintle is allowed to close too fast, the pintle and seat will soon become pounded out and begin to leak fuel. A fast closing rate will also cause the pintle to bounce, allowing extra fuel to be delivered to the engine. This extra fuel can't be accurately controlled, so the engineer must adjust the energy held within the flyback voltage to control the closing rate of the injector. This is accomplished by placing a zener diode across the PCM driver (transistor or MOSFET), as illustrated in Fig. 6. *Note*: Some fuel injection systems do not clip the flyback voltage.

As the magnetic field falls back into

the injector winding, the energy loops through the clipping circuit. This allows the current to diminish at a set rate. The lower the voltage level set by the zener diode, the more energy that will be allowed to loop through the circuit. If an ordinary diode were used instead of a zener diode, it would allow the largest amount of stored energy to 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.

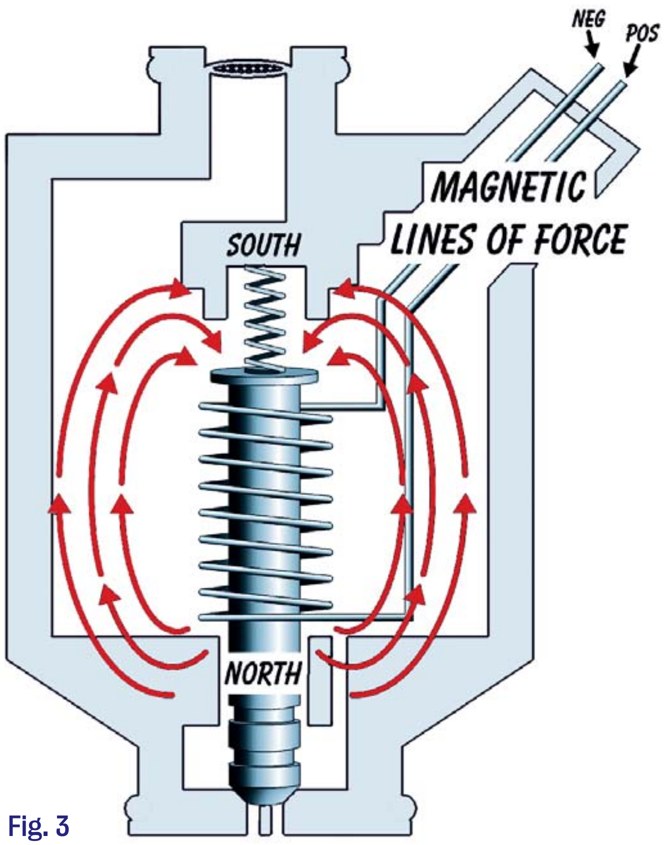

Fig. 3

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

When the pintle starts to fall through the magnetic field, the field is distorted and a voltage is induced (Fig. 7). The delay in closing voltage can be seen in waveform segment H in Fig. 2. The delay is the source of 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 (waveform segment I in Fig. 2). *Note*: Some injector waveforms will not exhibit this bump.

The PCM-commanded ON time is the time between segments B and F in Fig. 2. However, this is not the true injector opening time. The true injector opening time is from hump D to the closing bump I (indicated by measurement J). In a good circuit, the time to get from D to I will equal the PCM's command time from segments B to F (indicated by measurement E).

Now that we understand the data contained in a saturation injector waveform, we can use it to see what may have failed within the circuit. Let's begin by analyzing two injector waveforms (Fig. 8 on page 40). At first glance, both of these waveforms look good. However, one has a problem. Can you see it?

Look at segment A in both waveforms. The PCM has commanded the injector driver ON. The voltage exhibits an abrupt change and falls near ground on both patterns (segment B in both waveforms). Current begins to flow through the injector winding and counter voltage begins to rise off

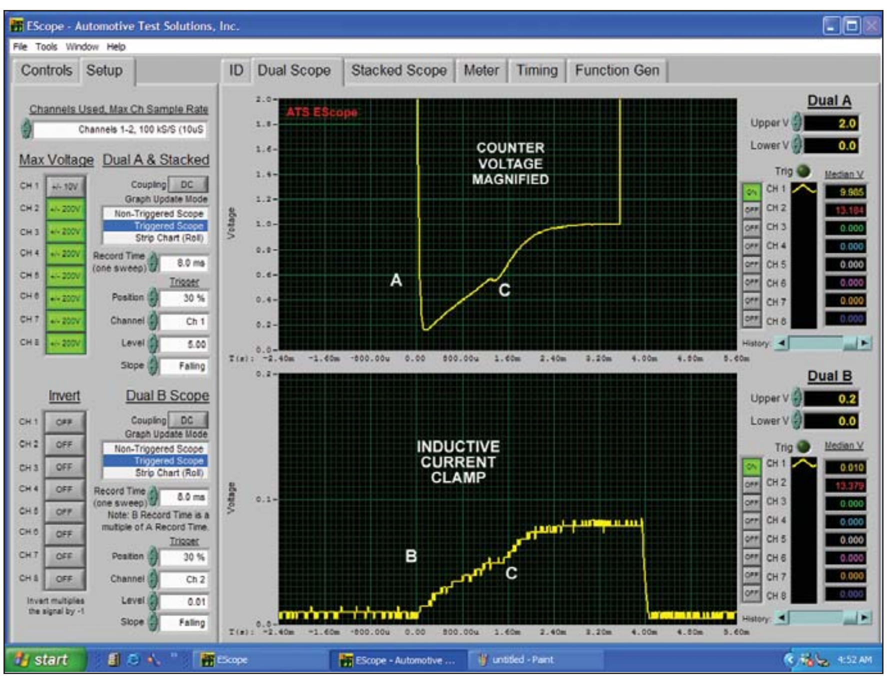

Fig. 4

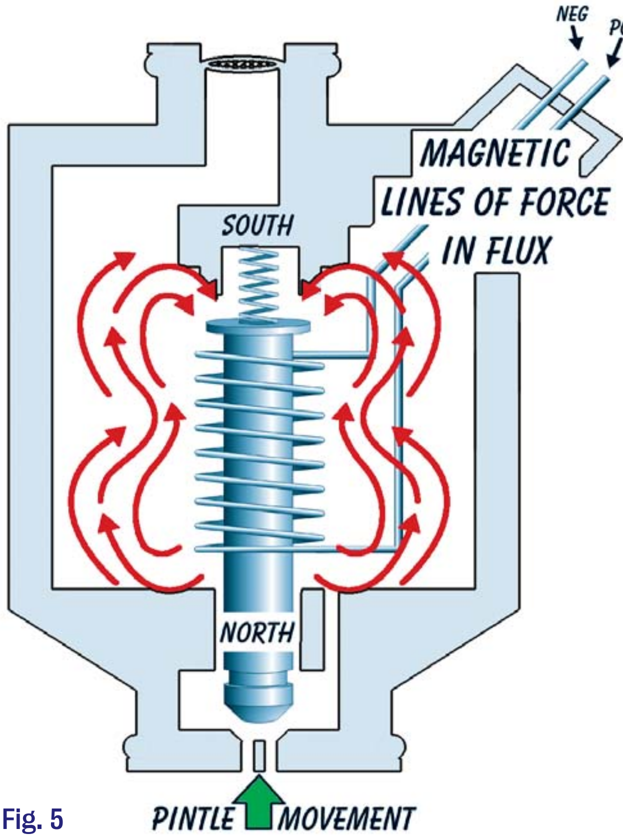

Fig. 5

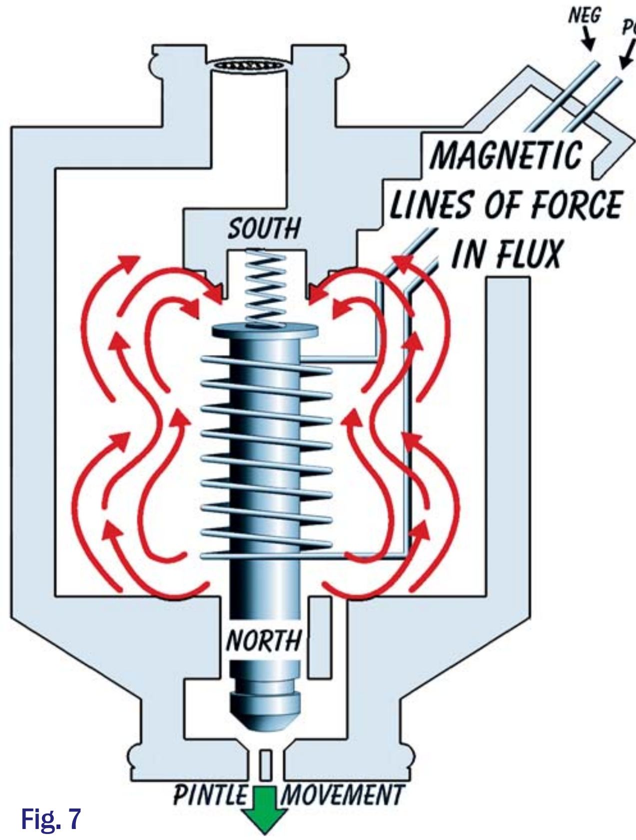

Fig. 7

ground (segment C in both waveforms). Notice there's more rise in the counter voltage on segment C in the upper waveform in Fig. 8 than in segment C in the lower waveform.

Next, the PCM calculates the correct ON time and commands the injector driver OFF. This causes an abrupt rise in the voltage (segment D in both waveforms). The voltage rises past the open circuit level and peaks out at the point where it's clipped at 65 volts (segment E in both waveforms).

Notice that in segment E of the upper waveform in Fig. 8 there's more space between the rising edge and the falling edge of the flyback voltage than in segment E of the lower waveform. This is an indication that the magnetic field of the injector circuit represented by the upper waveform in Fig. 8 has more stored energy. Since the magnetic field is built by the current flowing through the winding, this shows that the other injector circuit (lower waveform) has a resistance problem.

As the voltage falls back to the open circuit voltage, you can see the injector pintle closing bump. Notice that segment F in Fig. 8's upper waveform shows a longer closing time by 2.5 microseconds (μS) than segment E in the lower waveform. This is because the magnetic field has more energy and can correctly control the pintle closing rate.

Now let's magnify the bottom counter voltage in both waveforms in Fig. 8 and further analyze them (Fig. 9). These waveforms look quite different at first glance. They're not like the waveforms in Fig. 8, where the appear-

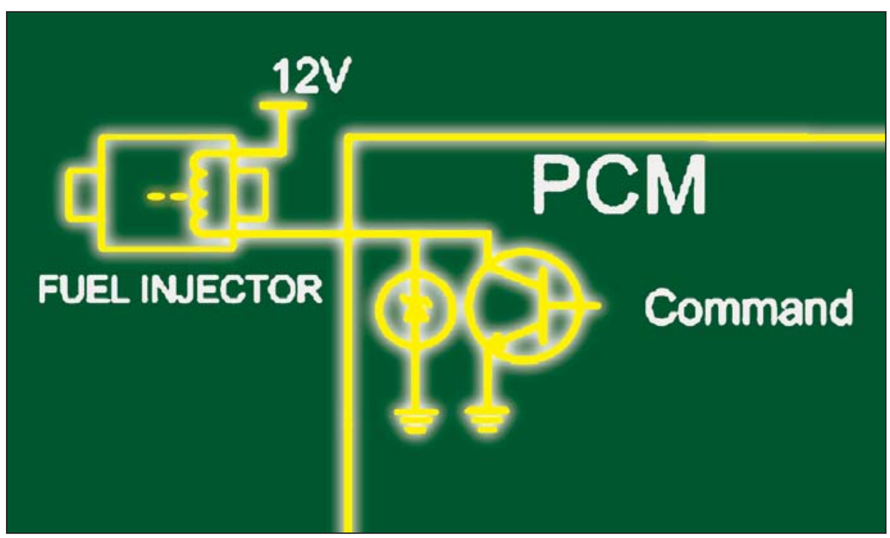

Fig. 6

ance seems very similar. In segment A (both waveforms in Fig. 9), the PCM commands the injector driver closed. This creates an abrupt drop in voltage. The initial voltage drop comes very close to ground (segment B). The current starts to flow through the injector winding, making a counter voltage and causing the voltage drop at the bottom of the waveform. *Note*: The scope was set at 2 volts per division for the upper waveform in Fig. 9 and .5 volt per division for the lower waveform.

We can see the injector pintle open in segment C of both waveforms in Fig. 9. However, the opening time is delayed by 1.9mS in the lower waveform. The counter voltage difference from the upper to the lower waveform is .65 volt. Since the counter voltage mirrors the change of current flow, the lower waveform has considerably less current flowing through the injector circuit.

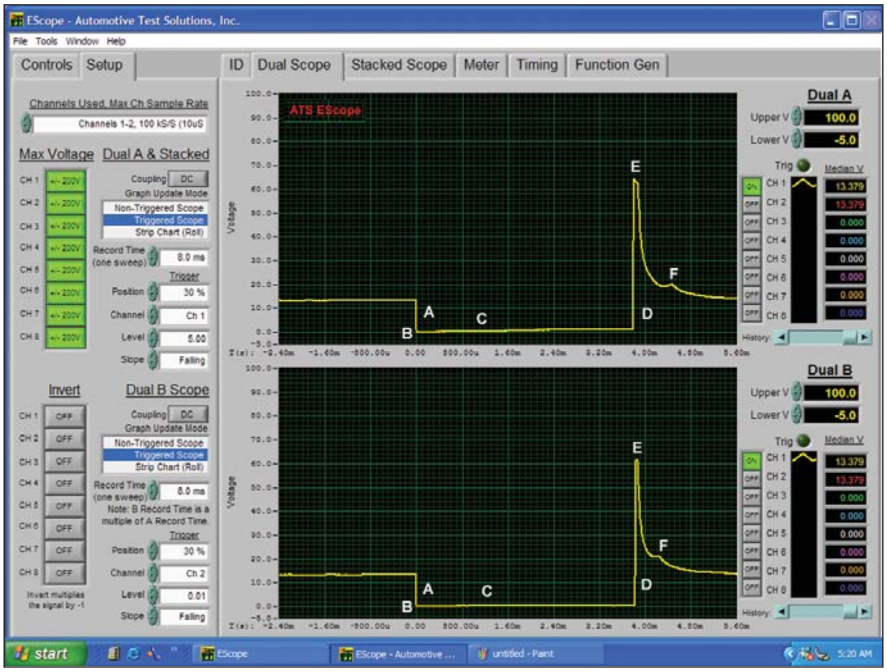

Fig. 8

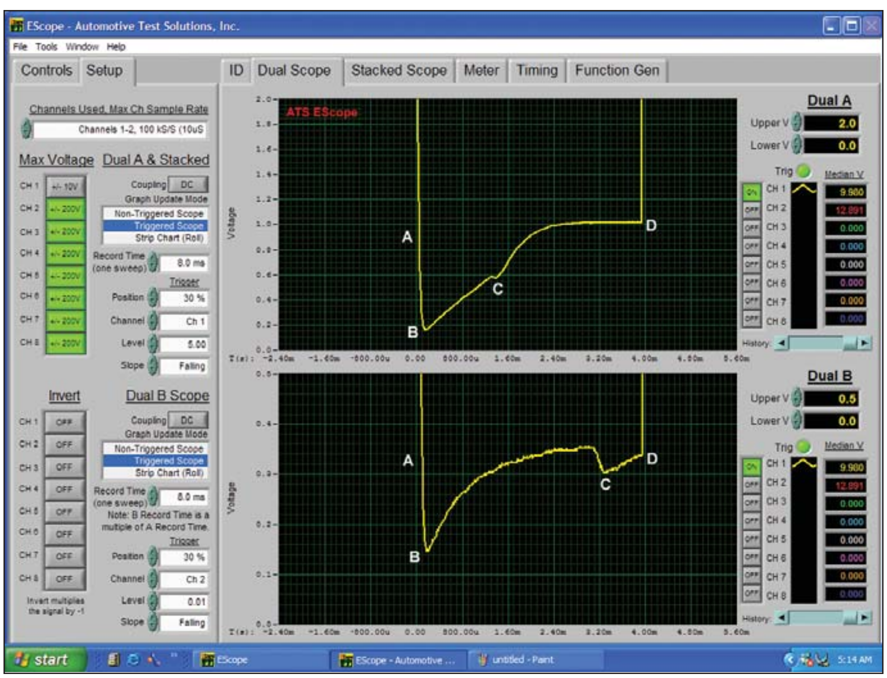

Fig. 9

Due to the diminished rate of change of the current flowing through the lower waveform, 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 must have more energy than the mechanical force of the spring to overcome it and open the injector pintle.

The resistance within the lower waveform in Fig. 9 is not in the control side of the circuit. Since the scope lead is at the injector, you can clearly see the voltage drop on the ground side of the circuit is good. It would be necessary to check the power side of the injector circuit, the injector connector and the injector coil winding to find the problem.

In this example, the problem was due to high resistance in the injector coil winding, which caused the pintle 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 the upper and lower waveforms in Fig. 8, or between cylinder 1 and cylinder 2. But upon closer inspection, we can see that there's a delay of 2.15mS. In the upper waveform, the actual injector opening time is 3200µS, or 3.2mS. In the lower waveform, the actual injector opening time is 1100µS, 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.

As you can see, when the letters of a new electrical language can be linked together and understood, they can tell a story about what has gone wrong within a circuit. M