Ionization Detection Using a Single Mode High Energy Capacitor Discharge Ignition System

Aravind Srinivasan and Karthikeyan Ramanathan

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Abstract

A system and method for a high power single mode ignition system with a built-in mechanism for detection of ionization levels inside a combustion chamber using the spark plug as electrodes is disclosed. A single capacitor energy source is used to generate both the initial high-voltage to break down the spark gap, ie,. the high voltage spark, and also supply the follow-on current to sustain a high current plasma arc. Furthermore, a simple current detection circuit senses the leakage current due to the ions across the spark gap flowing from the same capacitor, thus allowing the inference of various conditions and events in the immediate environment of the spark gap such as engine misfire, combustion duration, engine knocking, approximate air/fuel ratio, indications of spark plug fouling, and preignition. This method of plasma ignition with ionization detection is a significant improvement over the state of the art as it utilizes only one capacitor to generate the high voltage energy spark required to ignite the fuel as well as supplying the voltage necessary to generate an ionization current, which allows for miniaturization so the entire circuit can be mounted as a coil on plug ignition system for todays automobiles in a cost effective manner.

Claims

1. A high energy single mode plasma ignition system with ionization detection comprising:
   (a) a step-up transformer having a primary and secondary winding;
   (b) a single energy source which is a capacitor that is electrically connected to the primary winding;
   (c) a spark gap electrically connected with the secondary winding in such a way that energy released from the single energy source which is a capacitor into the primary winding creates a spark across the gap;
   (d) a supplemental path that connects the primary discharge side of the capacitor directly to the spark gap which is also connected across the secondary windings of the ignition coil or high voltage transformer through an appropriate blocking element to ensure one way flow of current.

2. An ionization detection circuit which utilizes the single energy source which is a capacitor to apply a voltage across the spark gap, the detection circuit measuring the resulting ionization current through the spark gap and providing an ionization current signal.

3. The system of claim 1, and claim 2 wherein the detection circuit comprises a resistor electrically connected in series after the blocking element with the single energy source which is a capacitor, along the supplemental path, whereby the voltage drop across the resistor provides the ionization signal.

4. The system of claim 3 further including a high-pass filter to eliminate DC bias from the ionization signal and a low-pass filter to eliminate high frequency noise from the ionization signal.

5. The system of claim 4 wherein the detection circuit further comprises an amplifier to boost the ionization signal.

6. The system of claim 3 wherein the detection circuit further comprises a zener diode electrically connected in parallel with the resistor along the supplemental path, whereby the sustained arc substantially bypasses the resistor.

7. The system of claim 1 and claim 2 further including a processor which performs an analysis of the ionization signal to determine occurrence of a misfire.

8. The system of claim 1 and claim 2 further including a processor which performs an analysis of the ionization signal to determine occurrence of engine knocking.

9. The system of claim 1 and claim 2 further including a processor which performs an analysis of the ionization signal to determine approximate air/fuel ratio.

10. The system of claim 1 and claim 2 further including a processor which performs an analysis of the ionization signal to determine indications of spark plug fouling.

11. The system of claim 1 and claim 2 further including a processor which performs an analysis of the ionization signal to determine occurrence of preignition.

12. The system of claim 1 and 2 further including a processor which performs an analysis of the ionization signal to determine combustion duration.

13. The system of claim 7, 8, 9, 10, 11 or 12 further including a memory unit which stores processor analyses for future use.

14. The system of claim 7, 8, 9, 10, 11 or 12 further including a measuring device which determines engine angular position, the processor analyzing the angular position with respect to the ionization signal, and a memory unit which stores the processor analyses for future use.

15. The system of claim 1 and 2 further including a measuring device which determines engine angular position.

16. The system of claim 14 further including a memory unit which stores the engine angular position for future use.

17. The system of claim 15 further including a processor which performs an analysis of the ionization signal and the engine angular position to determine the position of peak pressure.

18. The system of claim 17 further including a memory unit which stores the position of peak pressure for future use.

19. The system of claim 1 and 2 further including a memory unit which stores the ionization signal for future use.

Background of the Invention

Field of the Invention

This invention relates to a single mode high energy ignition system and means for ionization current detection to detect an ionization current which flows across the spark plug gap situated within cylinders of a spark ignited internal combustion engine and which is indicative of the combustion states within the cylinders.

Prior Art

The relationship between spark plug gap ionization and engine misfire is well understood in the automotive industry (See S. Miyata, et al., "Flame Ion Density Measurement Using Spark Plug Voltage Analysis," SAE Technical Paper 930462). When the plug sparks, the gases around the plug are ionized. It is known that the electrical conductivity within a spark plug gap increases following successful ignition due to the ionization of hot combustion gases. Thus, voltage applied across the gap following ignition results in a current, specifically an ionization current. Measuring and analyzing the ionization current provides information about the combustion process. The existence of a sizeable ionization current is known to indicate combustion. Low or zero current is likewise known to indicate a misfire. The occurrence of engine knock, approximate air/fuel ratios, spark plug fouling, and other combustion characteristics can also be derived from measurements and analysis of the ionization current.

There exists several types of ionization current detection systems for detecting combustion through the use of ionization current sensing across the spark gap inside the combustion chamber of an internal combustion engine. Virtually all of these systems typically employ two substantially decoupled energy sources where the function of a first energy source is to generate a spark across a spark plug gap and the function of a second energy source includes delivering current to the plug gap and providing a voltage across the plug gap such that an ionization current results and can be detected and measured by a detection circuit. U.S. Pat. No. 5,321,978 by Brandt et al. discloses an additional power source to create a voltage and generate an ionization current. Brandt et al. has the limitation that the only function of the additional power supply is to provide voltage for generating ionization current. The Dual Energy Ignition System (disclosed in U.S. Pat. No. 5,197,448 to Porreca et al.) and Ignition system with ionization detection (disclosed in U.S. Pat. No. 5777216 to Van Duyne et al) separates the ignition process into two phenomena, the spark and the arc. This system includes a first and second energy source to create the two phenomena. The first energy source is electrically connected to a spark gap in such a way that energy released from the first energy source provides high voltage to the spark gap for creating the spark. The second energy source is electrically connected with the spark gap in such a way that coupling between the second energy source and the first energy source is minimized, but also in such a way that energy released from the second energy source provides high current to the spark gap via a low impedance path, the energy being of sufficient strength to sustain an arc across the spark gap. In other words, the second energy source in addition to providing a voltage across the plug gap for ionization current sensing also increases the energy of the low current high voltage spark of a standard ignition by acting as secondary current source that discharges across the low impedance path provided by the spark.

The use of two energy sources requires two high voltage diodes to decouple the ionization circuit from the primary ignition circuit in addition to two DC-DC converters to energize the two decoupled energy sources which are capacitors. Such dual capacitor charging circuits are costly given the high expense of the high voltage diodes, DC-DC converters, long lasting metallized film capacitors and additional components that make up the charging circuit for each power source. Furthermore if one of the diodes breaks down, there will be no ignition in the corresponding cylinder. If any of the components that comprise the charging circuit to energize the second energy source were to fail then ionization sensing and the plasma arc can no longer take place.

Therefore, it would be desirable in the art of motor vehicle ignition systems to have an ionization current sensing circuit that is inexpensive to produce, has relatively few components, and produce a smooth current ionization output signal using a single energy source.

Summary of the Invention

It is a general object of the present invention to provide a simple method and circuit to detect ionization and measure ionization current. Efficiency and economy are achieved over the prior art by utilizing a single energy source for two distinct functions. The present invention is a single mode plasma ignition system with an ionization detection mechanism which utilizes a single energy source. Coupling between the ionization current sensing circuit and the high voltage spark circuit is minimized by providing a supplemental path that connects the primary discharge side of the capacitor directly to the spark gap which is connected across the secondary windings of the ignition coil or high voltage transformer through a blocking element to ensure one way flow of current. The single energy source provides energy for a spark across the spark plug gap as it discharges across the primary windings of the transformer. Owing to the high impedance of the primary windings of the ignition coil, the energy source which is a capacitor discharges the remainder of its energy across the high voltage spark through the supplemental path that connects the primary discharge side of the single energy source directly to the spark gap through a blocking element, thus causing a high current plasma arc. Subsequent to providing the spark and secondary source of current to the arc, the single energy source is immediately recharged to apply a voltage across the spark gap. This applied voltage results in an ionization current through the spark plug gap. Detection, measurement and analysis of the ionization current along side data such as ignition trigger time and the cycle the cylinder is in, provides information about the combustion process such as occurrence of partial ignition or misfire, engine knocking, approximate air/fuel ratio, and spark plug performance.

In accordance with the present invention, the Single Mode High Energy Ignition System, having a single capacitor as the energy source, is adapted to include a detection circuit for measuring ionization in a spark plug gap along the supplemental path placed after the blocking element. Adaptation of the Single Mode High Energy Ignition System according to the present invention provides efficient and economical ionization measurement, while maintaining all of the advantages inherent in a Dual Energy Ignition System. In the preferred embodiment, the detection circuit includes a resistor through which the ionization current flows at times when the fuel has not been ignited by triggering a high voltage spark. The resulting voltage drop provides an ionization signal, indicative of the degree of ionization of the gases in the cylinder, which is filtered, digitized and analyzed by a processor and combustion characteristics are thereby derived. The processor analyses may be stored for future use. The circuit further includes a zener diode which allows the arc current to bypass the resistor in the event of a successful ignition event and also allows for greater measurement accuracy and ignition efficiency. Few additional parts are required and accurate measurement is inherent.

Detailed Description

The present invention generates a high energy plasma and subsequently detects, measures and samples ionization current across a spark plug gap inside the cylinder of a typical spark ignited combustion engine. Ignition efficiency, combustion emissions levels, and thermal efficiency are improved by providing a supplemental path directly to the spark plug gap that allows the complete discharge of the single energy source through a blocking element once a high voltage spark is established across the spark gap. The blocking element causes the discharge current to flow in one direction only, and protects the primary side electronics from the high voltages developed in the secondary side of the transformer. According to the present invention, the energy source that discharges into the primary coil of the transformer (thus causing the spark at the spark plug gap) is the same source that also discharges the remainder of its stored energy across said spark to sustain and increase the energy of the arc. Furthermore, it is the same energy source that also causes an ionization current to flow across the spark plug gap during the period of time when the spark is absent across the spark gap. This ionization current is measurable and is duly sampled and analyzed and characteristics of the combustion process can be determined on a per cylinder basis.

Figure **??** depicts a conceptual illustration of the prior art Dual Energy Ignition and Ionization detection System, as disclosed in U.S. Pat. No 5777216 to Edward Van Duyne et al and incorporated in full herein by reference. An ignition spark generation device, including a voltage amplifying transformer 10, has the sole purpose of creating a spark in a spark gap 11. A second energy source which is a capacitor 18, that is charged by a DC-DC converter 21 is responsible for creating a high current arc in the spark gap 11 in addition to providing a voltage across the spark gap 11 in order to measure ionization current. Importantly, the second energy source 18 has a discharge path to the spark gap 11 which is decoupled from the primary side of the transformer 10 by a high-voltage diode 17. The High voltage diode 17 protects the secondary energy source 22 from receiving the high voltage discharge generated across the secondary side of the high voltage transformer 10. It is important that the energy released from the secondary energy source is coupled to the spark gap 11 via a low impedance path while the high voltage blocking element 17 ensures one way flow of current from the second energy source to the spark plug gap. A trigger circuit including a high voltage, high peak current switching device such as a silicone controlled rectifier 5 is preferably used to trigger the discharge of the capacitor 4 through the transformer 10. This rapid discharge induces a very high voltage on the secondary winding of the transformer 8. This voltage ionizes the matter surrounding the spark gap 11 and creates the spark.

On the secondary side of the transformer 10 is a second power source 22 which charges a capacitor 18. The energy stored in capacitor 18 will discharge and result in an arc through the spark gap 11 after a spark has been formed. The secondary energy source causes an ionization current to flow across the spark plug gap during the period of time when the spark is absent across the spark gap. This ionization current is measured, sampled and analyzed and characteristics of the combustion process can be determined on a per cylinder basis by analytics circuitry.

Figure **??** depicts a conceptual illustration of a high power plasma ignition system with ionization current sensing according to the present invention. The spark generation circuit includes the primary charging circuit 12 which charges the sole capacitor energy source 4, the coil driver circuit 13, the SCR 5 and voltage amplifying transformer 10, and has the sole purpose of creating a spark in spark gap 11. An ionization detection circuit 23 utilizes energy source 4 to create and detect the ionization current in the spark gap 11. The ionization detection circuit 23 of the present invention is illustrated in Figure **??**. The detection circuit 23 utilizes the energy stored in capacitor 4 as the voltage source for the ionization current which in turn travels via resistor 15 thus making this current measurable. The detection circuit 23 comprises a resistor 15, the spark gap 11, the high-voltage diode 6, and the capacitor 4. After the spark and the arc occur, the capacitor 4 is quickly re-charged by the primary charging circuit 12. The energy stored in the re-biased capacitor 4 provides a voltage across the spark gap 11. Any current which results is termed the ionization current, and it is a function of the ionization levels present around the spark gap 11 which is indicative of the ionization levels in the cylinder. If the current exceeds certain threshold, then combustion occurred. If the threshold is not reached, then partial combustion or a misfire occurred. The ionization current is measured via the voltage across the resistor 15. This voltage drop provides an ionization signal 25. Problems occur when trying to analyze ionization signal 25 because of noise during charging capacitor 4 and DC bias across resistor 15 during discharging capacitor 4. Being selective as to when to "pay attention" to the voltage across resistor 15 is a solution to both problems. An analog multiplexer 26 can supply the proper DC bias to a high pass filter 27 most of the time. The analog multiplexer 26 then supplies the ionization signal 25 to the high pass filter 27 during the combustion process. Therefore, the noise and the DC bias are removed from the ionization signal 25 before entering an amplifier 28. Another method of eliminating the noise is to use a low pass filter 26 in addition to or in place of the multiplexer 26. Once amplified by amplifier 28, a signal processor 29 analyzes the ionization signal 25 to determine various characteristics of the combustion process, including detection of misfire. A memory unit 30 stores the analysis data from the processor 29 for future use.

Further included in the detection circuit 23 is a zener diode 16. The zener diode 16, in parallel with the resistor 15, is important for two reasons. First, because the arc current is relatively large, accurate measurement of the small ionization bleed current can be difficult. The zener diode 16 serves to limit the voltage drop across the resistor 15. This protects the amplifier circuit and also allows a higher/more sensitive resistor 15 to be used, thereby providing for better measurement of the ionization signal 25. Secondly, and more importantly, the zener diode 16 avalanches in reverse mode and provides a low impedance path, bypassing resistor 15, for the arc current discharged from the capacitor 4. This is necessary for efficient operation of the ignition system. Without the zener diode 16 the arc current would face a significant impedance caused by the resistor 15. It is highly desirable to minimize the circuit impedance, so as to maximize the peak current and the arc intensity across the spark gap 11. Referring to Figure **??**, circuit component values will be provided for an illustrative embodiment. In this embodiment, the 4.7μF capacitor 4 is charged to 650 volts by the power source 1 which includes a 12 volt to 600 volt DC-DC convertor. The trigger circuit includes a 1000 volt 35 amp SCR. The step-up transformer 10 has a winds ratio of 1:100. A supplemental path is provided directly connecting the primary discharge side of capacitor 4 to the spark plug gap 11, through the high-voltage diode 6 rated at 50,000 volts and 1 amp with a 50 amp surge. The 3.3 volt zener diode 16 in parallel with the 1 kΩ resistor 15 serves to limit voltage drop across the resistor 15 to 3.3 volts.

For the purpose of electromagnetic interference (EMI), shielding is preferably utilized. Also, components are preferably placed close to the spark plug to shorten the high current, EMI generating discharge path (antenna). Characteristics of the combustion process can be determined from the ionization signal 25. One simple example is the duration of combustion, which is simply how long the ionization signal 25 exceeds a certain threshold. Another example is engine knock. Engine knock occurs when combustion exceeds the speed of sound. Engine knock is a sound wave in the 5-8 KHz range and it can be detected in the ionization signal 25. The processor 29 can be used to isolate and analyze ionization signal waves in the 5-8 KHz range. Presence of such waves indicate that engine knock has occurred. This processor analysis data may also be stored in the memory unit 30. Another example of a combustion process characteristic that can be derived from the ionization signal 25 is the air/fuel ratio. There is a correlation between ionization and air/fuel ratios (see S. Miyata, et al., Flame Ion Density Measurement Using Spark Plug Voltage Analysis, SAE Technical Paper 930462. The duration of the ionization measurement and the rate of ionization signal 25 decay provide an indication of air/fuel ratio. Therefore, ignition system testing yields a reference curve correlating ionization levels to various air/fuel ratios for particular engine designs. By providing the processor 29 with these correlation data, the processor 29 can analyze the ionization signal 25 and derive an approximate air/fuel ratio. Again, this may be stored for future use in memory unit 30. Two additional examples of characteristics of combustion determinable from the ionization signal 25 are spark plug fouling and preignition. These characteristics are indicated by the presence of ionization currents during certain engine cycles where combustion is not supposed to occur. In particular, spark plug fouling is indicated when the ionization signal 25 persists for too long. The other characteristic, preignition, occurs when combustion begins before the ignition has fired. Thus, if the ionization signal 25 indicates combustion before sparking has occurred, preignition is indicated. Once again, the manifestation of these characteristics may be stored for future use in memory unit 30. Another useful measurement is engine angular position. Means for providing this data is well-known to those skilled in the internal combustion engine art. Engine angular position provides a reference point for processor data derived from the ionization signal 25. For example, when engine knock is detected (via the analyzed ionization signal 25) there is a corresponding engine angular position. If the corresponding engine angular position is also stored in the memory unit 30 along with the engine knock analysis, a technician can later utilize this information for engine repair, adjustment and the like. Similar angular position information corresponding to misfire, combustion duration, engine knocking, air/fuel ratio, and preignition is likewise a useful diagnostic tool. Furthermore, once the engine angular position is determined, the angular position of peak pressure can be approximated because it closely corresponds to the peak of the ionization signal 25. An approximation of the position of peak pressure is very useful for optimizing two engine efficiency parameters. First, in order to generate the optimal (greatest) torque from a given amount of fuel, the peak pressure in the combustion chamber should occur approximately between 10 and 15 degrees after top dead center (TDC). Second, to lower the temperature of combustion and to lower NO_x emissions, the peak pressure should occur after 15 degrees TDC. This allows for the possibility of emissions control using the ionization signal 25.