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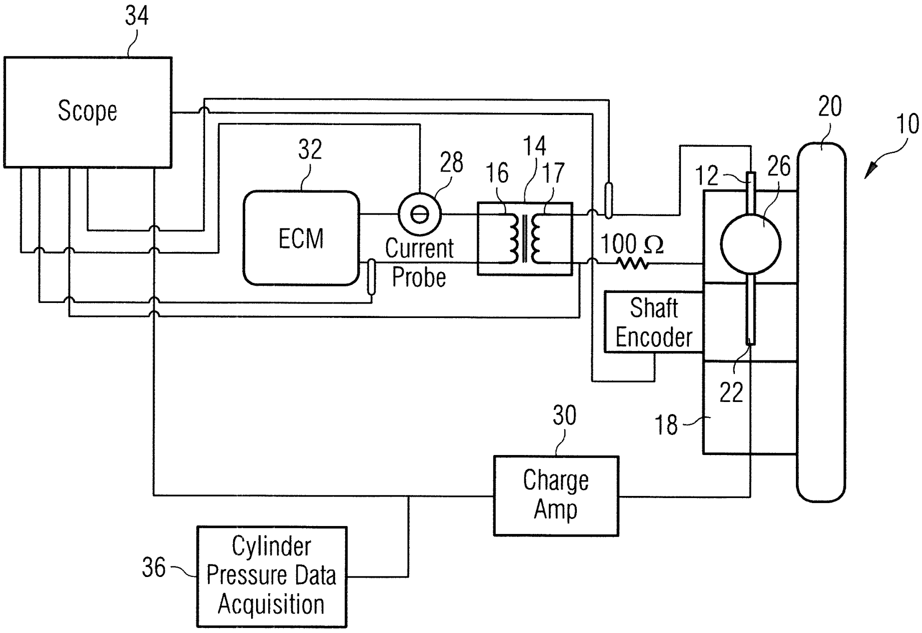
(54) METHOD FOR DETERMINING A DEFECT IN A SPARK PLUG OF AN INTERNAL COMBUSTION ENGINE

(57) In a method for determining a defect in a spark plug (12) associated with a cylinder (26) of a spark-ignited internal combustion engine (10), an ignition delay from starting a supply of current to a primary winding (16) of an ignition coil (14) associated with the spark plug (12) to reaching a maximum value of the supplied current is determined. When the ignition delay is above a threshold defined in advance for the spark plug (12), it is determined that the spark plug (12) is defective or approaches the end of its service life and should be replaced. A corresponding indication is output to an operator of the internal combustion engine (10) to allow for scheduling a downtime of the engine for exchanging the spark plug (12).

FIG 1



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Description

Technical Field

[0001] The present disclosure generally relates to an internal combustion engine and a method of operating the same, in particular, to a method for determining a defect in a spark plug associated with a cylinder of a spark-ignited internal combustion engine.

Background

[0002] Generally, the combustion of a mixture of fuel and air in a cylinder of a spark-ignited internal combustion engine, e.g., an Otto engine, is initiated using an ignition device including a spark plug. For example, the ignition device may include an ignition coil comprising a primary winding and a secondary winding. The secondary winding is connected to the spark plug, and a current is selectively supplied to the primary winding to induce a magnetic field in the secondary winding. This results in an increase in the voltage across the spark plug, and eventually the spark plug is discharged. Upon discharge, the mixture of fuel and air in the combustion chamber of the cylinder is ignited and the combustion energy pushes down the piston to rotate the internal combustion engine. The rotation speed is varied by controlling the frequency of reciprocation of the piston, for example, by varying the fuel content while the torque is constant. As a consequence, the discharge frequency of the spark plug has to be changed.

[0003] In spark-ignited internal combustion engines, the spark plugs are members that are subject to considerable wear, resulting in a reduced service life and high failure rates. As a result of such failures, an emergency stop of the internal combustion engine may have to be initiated, which may result in further thermal stress on the spark plugs of the engine and potential further damage to the same. This may negatively affect the operation and/or productivity of the facilities including the internal combustion engine, for example, power plants, construction machines, etc.

[0004] The present disclosure is directed, at least in part, to improving or overcoming one or more aspects of prior systems.

Summary of the Disclosure

[0005] According to one aspect of the disclosure, a method for determining a defect in a spark plug associated with a cylinder of a spark-ignited internal combustion engine comprises starting a supply of current to a primary winding of an ignition coil associated with the spark plug, measuring the current flowing through the primary winding, determining that the current flowing through the primary winding has reached a predetermined current value, determining a time interval based on a timing of starting the supply of current and a timing of reaching the predetermined current value, and determining whether the spark plug is defective based on the determined time interval.

[0006] According to another aspect of the present disclosure, a spark-ignited internal combustion engine comprises an engine block defining at least in part a cylinder, a spark plug associated with the cylinder, and a control unit. The control unit is configured to start a supply of current to a primary winding of an ignition coil associated with the spark plug, measure the current flowing through the primary winding, determine that the current flowing through the primary winding has reached a predetermined current value, determine a time interval based on a timing of starting the supply of current and a timing of reaching the predetermined current value, and determine whether the spark plug is defective based on the determined time interval.

[0007] In yet another aspect of the present disclosure, a computer program comprises computer-executable instructions which, when run on a computer, cause the computer to perform the steps of starting a supply of current to a primary winding of an ignition coil associated with a spark plug associated with a cylinder of a spark-ignited internal combustion engine, measuring the current flowing through the primary winding, determining that the current flowing through the primary winding has reached a predetermined current value, determining a time interval based on a timing of starting the supply of current and a timing of reaching the predetermined current value, and determining whether the spark plug is defective based on the determined time interval.

[0008] Other features and aspects of the present disclosure will become apparent from the following description and the accompanying drawings.

Brief Description of the Drawings

[0009]

Fig. 1 is a schematic overview of a spark-ignited internal combustion engine in accordance with the present disclosure;

Fig. 2 is a graph showing a current in a primary winding of an ignition coil and a current and a voltage in a secondary winding of the ignition coil in accordance with the present disclosure;

Fig. 3 is a graph showing ignition delays for cylinders of a spark-ignited internal combustion engine and a cylinder pressure of the associated cylinders; and

Fig. 4 is a graph illustrating upper and lower thresholds for detecting a defect in a spark plug based on ignition delays.

Detailed Description

[0010] The following is a detailed description of exemplary embodiments of the present disclosure. The exemplary embodiments described herein are intended to teach the principles of the present disclosure, enabling those of ordinary skill in the art to implement and use the present disclosure in many different environments and for many different applications. Therefore, the exemplary embodiments are not intended to be, and should not be, considered as a limiting description of the scope of protection. Instead, the scope of protection shall be defined by the appended claims.

[0011] The present disclosure may be based in part on the realization that, although it may be conceivable to determine whether a spark plug is defective or reaches the end of its service life (i.e., becomes defective due to wear) based on a secondary voltage of an ignition coil, it may be very difficult to continuously measure the secondary voltage during operation of the internal combustion engine. Therefore, according to the present disclosure, it is determined from the primary current flowing through the primary winding of the ignition coil whether a spark plug becomes defective, i.e., has been damaged or reaches the end of its service life due to wear. Accordingly, as used herein, the term "defect" also includes wear of the spark plug due to operation of the same over extended periods of time. In this respect, the present disclosure may be based in part on the realization that a rise time of the primary current, i.e., a time from starting supply of the primary current to reaching a first global maximum of the primary current, may be used as an indicator for the secondary voltage and therefore the condition of the spark plug. This rise time (also referred to as pull-in time or ignition delay) may be compared to a reference time in order to predict the remaining service life of the spark plug.

[0012] The present disclosure may also be based, at least in part, on the realization that the reference time may be empirically determined for a given type of spark plug and/or depending on the current supply, for example, the maximum value for the primary current or the power supply voltage.

[0013] In addition, the present disclosure may be based in part on the realization that, when it is detected that a spark plug becomes defective, an emergency stop of the engine may be avoided by reducing the load of the engine. In this manner, the engine can be shut down in a controlled manner before the spark plug fails. This may allow continuing operation of the internal combustion engine for several days or even weeks before exchanging the defective spark plug. For example, as the rise time is load-dependent, the engine load may be limited by the associated control unit outputting a derate pulse in response to the detection of the defect in the spark plug.

[0014] Further, the present disclosure may be based in part on the realization that, while generally a defective spark plug will lead to increased rise times, there may also be defects that result in a significantly lower rise time. For example, when a mechanical defect results in a reduced distance between the parts of the spark plug where the discharge occurs, this may lead to a significant decrease of the rise time. According to the present disclosure, a rise time window may be defined in order to detect different types of defects in a spark plug by checking whether the determined rise time is within said window.

[0015] Referring now to the drawings, an exemplary embodiment of an internal combustion engine 10 is illustrated in Fig. 1. Internal combustion engine 10 may include features not shown, such a fuel systems, air systems, cooling systems, drive train components, etc. For the purpose of the present disclosure, internal combustion engine 10 is a gas engine. One skilled in the art will recognize, however, that internal combustion engine 10 may be any type of spark-ignited internal combustion engine, for example, a dual fuel engine or any other Otto engine that utilizes a spark plug for igniting a mixture of gaseous fuel and air for combustion.

[0016] Internal combustion engine 10 may be of any size, with any number of cylinders and in any configuration ("V", "in-line", etc.). Internal combustion engine 10 may be used to power any machine or other device, including ships or other marine applications, locomotive applications, on-highway trucks or vehicles, off-highway machines, earth-moving equipment, generators, pumps, stationary equipment such as power plants, or other engine-powered applications.

[0017] Still referring to Fig. 1, internal combustion engine 10 comprises an engine block 18 including a bank of cylinders. In Fig. 1, only a single exemplary cylinder 26 is shown. A piston (not shown) may reciprocate in cylinder 26 to rotate a crank shaft (not shown) of internal combustion engine 10. The crank shaft may in turn drive a flywheel 20 of internal combustion engine 10.

[0018] A spark plug 12 is associated with cylinder 26 and configured to ignite the mixture of gaseous fuel and air within the combustion chamber of cylinder 26 at a desired timing. A cylinder pressure sensor 22 may be provided for cylinder 26 and configured for detecting a cylinder pressure of cylinder 26, for example, for detecting knock or the like. Cylinder pressure sensor 22 is operatively connected to a charge amplifier 30 for amplifying the associated measurement signal. Charge amplifier 30 is connected to a cylinder pressure data acquisition unit 36 configured to determine the cylinder pressure based on the measurement signal output by cylinder pressure sensor 22. As shown in Fig. 1, for example, during testing of the internal combustion engine and the associated systems, charge amplifier 30 may also be connected to an oscilloscope 34 for displaying the detected cylinder pressure signals.

[0019] A shaft encoder 24 may be associated with the crank shaft of internal combustion engine 10 and configured to detect the rotational position of the crank shaft, i.e., the position of the piston reciprocating in cylinder 26. An output of shaft encoder 24 may also be connected to oscilloscope 34, for example, during testing of engine 10.

[0020] Spark plug 12 is connected to an ignition coil 14 associated with the same. A control unit 32 is also connected to ignition coil 14 and configured to operate the same in order to generate a spark at spark plug 12 with a desired ignition timing for igniting the mixture of gaseous fuel and air in cylinder 26. Control unit 32 may include a single microprocessor or plural microprocessors that include means for controlling, among others, an operation of various components of internal combustion engine 10. In the present embodiment, control unit 32 is a general engine control module (ECM) capable of controlling internal combustion engine 10 and/or its associated components. Control unit 32 may include all components required to run an application, such as, for example, a memory, a secondary storage device, and a processor such as a central processing unit or any other means known in the art for controlling internal combustion engine 10 and its components. Various other known circuits may be associated with control unit 32, including power supply circuitry, signal conditioning circuitry, communication circuitry and other appropriate circuitry. Control unit 32 may analyze and compare received and stored data, and, based on instructions and data stored in memory or input by a user, determine whether action is required. For example, control unit 32 may compare received values with target values stored in memory and transmit signals to one or more components based on the results of the comparison to alter the operation status of the same.

[0021] Control unit 32 may include any memory device known in the art for storing data relating to operation of internal combustion engine 10 and its components. The data may be stored in the form of one or more maps that describe and/or relate, for example, the detection results from associated sensors to reference values stored in the memory of the same. Each of the maps may be in the form of tables, graphs and/or equations, and may include a compilation of data collected from lab and/or field operation of internal combustion engine 10. The maps may be generated by performing instrumented tests on internal combustion engine 10 under various operating conditions via varying parameters associated therewith or performing various measurements. Control unit 32 may reference these maps and control one component in response to the desired operation of another component. For example, the maps may contain data on the normal rise times of the primary current of ignition coil 14 for different engine loads and/or different types of spark plugs when spark plug 12 is operating normally.

[0022] Ignition coil 14 includes a primary winding 16 and a secondary winding 17. Primary winding 16 is connected to control unit 32 and configured to receive current supplied by control unit 32, for example, by actuating a switch disposed in the current path between control unit 32 and primary winding 16. A current detector 28 is provided in the current path between control unit 32 or a power supply (not shown) and primary winding 16 to detect the current flowing through primary winding 16. Current detector 28 is connected to control unit 32, which may receive the output form current detector 28 to determine the instantaneous value of the current flowing through primary winding 16. In the exemplary embodiment, the output of current detector 28 is also connected to oscilloscope 34. In addition, further probes are connected to respective power supply lines connected to both primary winding 16 and secondary winding 17 to detect the voltage across primary winding 16 and across secondary winding 17, which probes are also connected to oscilloscope 34. In this manner, during testing of internal combustion engine 10, the instantaneous values of the primary current, the primary voltage and the secondary voltage may be detected and displayed on oscilloscope 34.

[0023] Fig. 2 shows a graphical illustration of the primary current I_P, the secondary current Is and the secondary voltage Us measured during an ignition event for a spark plug that is defective. In Fig. 2, the dashed line shows the primary current I_P, the dotted line shows the secondary current Is, and the dot-dashed line shows the secondary voltage Us.

[0024] As shown in Fig. 2, when an ignition event is initiated, control unit 32 initiates a supply of current to primary winding 16 at a timing t_1. Accordingly, the primary current in primary winding 16 increases. Ideally, the primary current I_P increases in a linear manner, with the slope of the increase being defined by the ratio of the power supply voltage U divided by the inductance L of primary winding 16. This is illustrated by the solid line I_{ref} in Fig. 2.

[0025] As shown in Fig. 2, however, when spark plug 12 is defective, the primary current I_P increases in a non-linear manner, i.e., slower than in the ideal case I_{ref}. Simultaneously, the secondary voltage Us also increases more slowly due to the magnetic field induced by the primary current I_P. At a certain point, when the secondary voltage Us reaches a given value (in the example, about 22 kV), a discharge occurs at spark plug 12, and the mixture of gaseous fuel and air in cylinder 26 is ignited. The secondary voltage Us breaks down, and the primary current I_P continues to increase linearly, in accordance with the ideal behavior I_{ref}. At the same time, the secondary current Is increases. When the primary current I_P reaches a predetermined maximum value, for example, about -23 A, this is detected by control unit 32 via current detector 28, and the supply of current to primary winding 16 is stopped. Subsequently, in order to assure that ignition occurs, additional current pulses are output by control unit 32, resulting in the behaviour of the primary current, the secondary current and the secondary voltage shown in Fig. 2.

[0026] As shown in Fig. 2, a time interval T_D lapses between the timing t_1 of starting the supply of current to primary winding 16 and a timing t_2 of reaching the predetermined current value. It can be seen from Fig. 2 that the time interval T_D, which is also referred to as pull-in time or ignition delay, is longer than the corresponding time interval (t_2-t_3) in case of a strictly linear increase as shown by I_{ref}. Accordingly, control unit 32 may detect the time interval T_D and compare the same to a predetermined reference interval for a normal spark plug 12 that may be stored in the memory of the same, for example, as a map relating the reference interval to the engine load. When the detected time interval T_D is significantly larger than the reference interval, control unit 32 may determine that spark plug 12 is defective.

[0027] Alternatively, control unit 32 may determine an ignition delay difference ΔT_D, for example, based on the slope I_{ref} and the timing of reaching the maximum of the primary current at time t_2. For example, the slope I_{ref} may be calculated in advance based on the voltage applied to primary winding 16 and the inductance of the same. Based on the maximum value of the primary current, the timing t_3 may be calculated, at which the supply of the primary current would have to be started in case of an ideal, i.e., non-defective behavior of spark plug 12 to reach the maximum value of the primary current at time t_2. The reference timing t_3 obtained in this manner may then be subtracted from the ignition delay T_D to obtain ΔT_D for spark plug 12. Similar to the above, when ΔT_D is substantially larger than a reference value for the same, control unit 32 may determine that spark plug 12 is defective.

[0028] Fig. 3 shows the behavior of the determined ignition delay for three cylinders, where one of the cylinders has a defective spark plug. The upper half of Fig. 3 shows the ignition delays of the three cylinders as a function of time, with the engine load increasing over time and the engine speed increasing to a desired engine speed. As shown by the dotted line $T_{D2,3}$ for the two cylinders having normally functioning spark plugs, the ignition delay is substantially constant with varying engine load and engine speed. On the other hand, the solid line indicating the ignition delay T_{D1} for the cylinder having a defective spark plug shows that the ignition delay increases with increasing engine load. In particular, as the ignition delay T_{D1} increases past a threshold Th1 with increasing engine load, misfiring may occur in the associated cylinder. This can be seen from the measured cylinder pressure ICPM for the associated cylinder, which is shown in the lower half of Fig. 3 (indicated by the region A in Fig. 3). Control unit 32 may therefore determine the ignition delay for each cylinder, and may determine that one of the spark plugs is defective when the ignition delay associated with the same increases beyond the threshold Th1. In this case, control unit 32 may further be configured to operate internal combustion engine 10 under limited load conditions. For example, control unit 32 may be configured to activate a derate pulse to hold mode in order to prevent any power increase and operate the engine under stable conditions for a predetermined amount of time. The derate pulse is a signal output by the ECM and indicating that maximum power has been reached and no further increase in power is possible. At the same time, a warning can be output to an operator of internal combustion engine 10 to notify the same that an exchange of a spark plug should be scheduled. In some embodiments, internal combustion engine 10 may be operated under the limited load conditions for several days or weeks before the spark plug has to be exchanged.

[0029] As previously mentioned, control unit 32 may also use the ignition delay difference ΔT_D in order to determine that a spark plug is defective. ΔT_D can be determined in the above-described manner, and an appropriate threshold may be defined for determining whether a spark plug is defective. For example, in the embodiment, ΔT_D may be between around 7 and around 20 μs, depending on the power output by internal combustion engine 10. For example, at 90% power, ΔT_D may be around 20 μs, with the secondary voltage reaching about 20 kV prior to the discharge in spark plug 12.

[0030] In some embodiments, a second threshold Th2 may be defined to determine whether the ignition delay T_{D1} is below a lower time limit determined in advance for spark plug 12. This is shown in Fig. 4. Accordingly, control unit 32 may determine ignition delay T_{D1} in the above-described manner, and determine that spark plug 12 is defective when ignition delay T_{D1} is higher than first threshold Th1 and/or lower than second threshold Th2. The behavior of the ignition delays with three cylinders shown in Fig. 4 is the same as that in Fig. 3.

[0031] It will be readily appreciated that control unit 32 may determine whether spark plug 12 is defective or nearing the end of its service life based on the ignition delay determined for the same in various manners. Generally, control unit 32 is configured to determine a time interval based on a timing of starting a supply of current and a timing of reaching a predetermined current value for a given spark plug. As described above, the time interval may be the ignition delay T_D, i.e., the difference between the timing of reaching the predetermined current value t_2 and the timing of starting the supply of current t_1. In other embodiments, the time interval may be the ignition delay difference ΔT_D, which is defined by the difference between the reference timing t_3 determined based on the known behavior for a non-defective spark plug and the timing of starting the supply of current t_1.

[0032] Further, as outlined above, in case of a defective spark plug, the determined ignition delay varies with varying engine load. Accordingly, in other embodiments, it may be determined that a spark plug is defective when the time interval or ignition delay determined for the same varies by more than a predetermined amount with varying engine loads. For example, control unit 32 may be configured to monitor the ignition delay of each spark plug as the engine load increases, and determine that the spark plug is defective when the ignition delay increases or decreases by more than the predetermined amount, for example, 5 or 10 %, 10 to 20 %, 20 to 30 %, 30 to 40 %, or 40 % to 50% with varying engine load. In other embodiments, control unit 32 may determine a rate of change of the ignition delay, and determine whether the spark plug is defective based on said rate of change being greater than a predetermined reference rate. It will be readily appreciated that there are many other possibilities for determining whether a spark plug is defective based on a variation of the measured ignition delay with varying engine load.

[0033] In other embodiments, control unit 32 may be configured to continuously monitor the ignition delay of each spark plug during operation of internal combustion engine 10. As outlined above, as the ignition delay will generally increase or decrease when a defect occurs, control unit 32 may also be configured to determine that a spark plug has become defective when the associated ignition delay changes significantly during operation of internal combustion engine 10. For example, control unit 32 may determine that a spark plug has become defective when an absolute value of the variation of the ignition delay from an initial value is greater than a threshold value as internal combustion engine 10 is operated, or when a change is greater than, for example, 5 or 10 %, or up to 40 % to 50 %. It should be noted that the normal end of the lifetime of a spark plug can also be detected using this method.

[0034] In some embodiments, control unit 32 may further be configured to estimate a remaining service life of a defective spark plug 12 based on the duration of the determined time interval or ignition delay, for example, for a given engine load. In other words, a corresponding map may be stored in the memory of control unit 32, said map establishing a relationship between the duration of the time interval and the expected remaining service life before spark plug 12 fails. The time stored in the map may be based on experiments and/or knowledge obtained during operation or testing of internal combustion engine 10. Further, the map may also include a relationship between the estimated remaining service life and the engine load at which internal combustion engine 10 is operated. This may allow control unit 32 to determine the power limit for internal combustion engine 10 that will likely allow reaching a desired remaining operating time before spark plug 12 has to be exchanged. Of course, an operator may also be able to specify the engine load at which internal combustion engine 10 is to be operated, depending on the determined ignition delay and/or the desired time for which the engine is to be operated before the spark plug is to be exchanged.

[0035] As shown in Figs. 3 and 4, the ignition delay is different for a defective spark plug when compared to the ignition delay for non-defective spark plugs. Accordingly, in some embodiments, control unit 32 may be configured to determine the ignition delay for a plurality of cylinders, compare the ignition delay for the plurality of cylinders, and determine that a spark plug associated with one cylinder has become defective when the ignition delay of the same differs by more than a predetermined amount from the ignition delay determined for the other spark plugs. Again, it will be appreciated that there are many possibilities for defining appropriate thresholds for determining that one of the plurality of spark plugs is defective due to the ignition delay of the same being significantly different from the ignition delays of the other spark plugs. In some embodiments, control unit 32 may also be configured to determine an average of the ignition delays for the spark plugs, and to determine that one or more of the spark plugs are defective when the ignition delays determined for the same differ from the average by more than a predetermined amount.

[0036] As also shown in Figs. 3 and 4, in case a spark plug is defective and the engine load increases towards maximum load, misfires occur in the associated cylinder, as shown by the region A in Fig. 3. Therefore, in order to improve the reliability of the determination of a defective a spark plug, control unit 32 may also be configured to receive the cylinder pressures measured for the cylinders of internal combustion engine 10 as inputs, and determine that the spark plug, for which an increased or decreased ignition delay has been determined, is defective when, in addition, a measured cylinder pressure of the associated cylinder shows irregularities, i.e., differs from the measured cylinder pressures of the other cylinders or is above or below respective thresholds and indicates misfiring.

Industrial Applicability

[0037] The industrial applicability of the systems and methods disclosed herein will be readily appreciated from the foregoing discussion. An exemplary machine suited to the disclosure is a large internal combustion engine such as the engines of the series M46DF, GCM46, GCM34, M32DF, M34DF, M3x manufactured by Caterpillar Motoren GmbH & Co. KG, Kiel, Germany. Similarly, the systems and methods described herein can be adapted to a large variety of internal combustion engines used for various different tasks. With the system and method disclosed herein, it is possible to determine an impending failure of a spark plug of an internal combustion engine by determining the ignition delay for the respective spark plugs of the engine. In this manner, a timely warning can be output for an operator of internal combustion engine 10 to warn the same that one or more spark plugs 12 are defective and should be replaced. In this manner, the operator of internal combustion engine 10 may schedule an exchange of the one or more spark plugs, while emergency stops of internal combustion engine 10 due to a failed spark plug can be avoided. As such, the reliability and productivity of internal combustion engine 10 can be increased. An exemplary control in accordance with the present disclosure is described in the following.

[0038] Internal combustion engine 10 may be operated by control unit 32 at a desired engine load or engine speed. While internal combustion 10 is operating at the desired engine speed, control unit 32 determines the ignition timing for each spark plug 12 of internal combustion engine 10 in the above-described manner. For example, control unit 32 determines the timing of starting a supply of current to primary winding 16 of each spark plug 12, and determines a timing of reaching a predetermined maximum value of the primary current. From the two timings t_1 and t_2 (see Fig. 2), control unit 32 may then determine ignition delay T_D for each spark plug. Next, control unit 32 compares the determined ignition delay T_D to threshold Th1 (see Fig. 3). If it is determined that the ignition delay T_D is greater than threshold Th1 in Fig. 3 (or less than threshold Th2 in Fig. 4), control unit 32 determines that the associated spark plug 12 may be defective.

[0039] Accordingly, control unit 32 activates the derate pulse to limit the engine power. Further, control unit 32 outputs a warning to an operator on internal combustion engine 10 to indicate that spark plug 12 is defective. As a consequence, the operator of internal combustion engine 10 may schedule a downtime for internal combustion engine 10 to allow for replacement of spark plug 12.

[0040] It will be appreciated that the foregoing description provides examples of the disclosed systems and methods. However, it is contemplated that other implementations of the disclosure may differ in detail from the foregoing examples. All references to the disclosure or examples thereof are intended to reference the particular example being discussed at that point and are not intended to imply any limitation as to the general disclosure.

[0041] Recitations of ranges of values herein are merely intended to serve as a shorthand method for referring individually to each separate value falling within the range, unless otherwise indicated, and each separate value is incorporated into the specification as if it were individually recited herein. All method steps described herein can be performed in any suitable order, unless otherwise indicated or clearly contradicted by the context.

[0042] Although the preferred embodiments of the present disclosure have been described herein, improvements and modifications may be incorporated without departing from the scope of the following claims.

Claims

1. A method for determining a defect in a spark plug (12) associated with a cylinder (26) of a spark-ignited internal combustion engine (10), the method comprising:

   starting a supply of current to a primary winding (16) of an ignition coil (14) associated with the spark plug (12);
   measuring the current flowing through the primary winding (16);
   determining that the current flowing through the primary winding (16) has reached a predetermined current value;
   determining a time interval (T_D, ΔT_D) based on a timing of starting the supply of current (t_1) and a timing of reaching the predetermined current value (t_2); and
   determining whether the spark plug (12) is defective based on the determined time interval (T_D, ΔT_D).

2. The method of claim 1, further comprising determining the time interval (T_D) from a time difference between the timing of reaching the predetermined current value (t_2) and the timing of starting the supply of current (t_1).

3. The method of claim 1, further comprising:

   determining a slope (I_{ref}) of the measured current signal when the predetermined current value is reached;
   determining a reference timing (t_3) based on the determined slope (I_{ref}); and
   determining the time interval (ΔT_D) from a time difference between the reference timing (t_3) and the timing of starting the supply of current (t_1).

4. The method of any one of claims 1 to 3, further comprising determining that the spark plug (12) is defective when the time interval (T_D, ΔT_D) is longer than an upper limit time interval (Th1) determined in advance for the spark plug (12).

5. The method of any one of claims 1 to 4, further comprising determining that the spark plug (12) is defective when the time interval (T_D, ΔT_D) is shorter than a lower limit time interval (Th2) determined in advance for the spark plug (12).

6. The method of any one of claims 1 to 5, further comprising:

   varying a load of the internal combustion engine (10);
   determining the time interval (T_D, ΔT_D) for different engine loads; and
   determining that the spark plug (12) is defective when the time interval (T_D, ΔT_D) varies by more than a predetermined first amount with varying engine loads.

7. The method of any one of claims 1 to 6, further comprising:

   determining a temporal variation of the time interval (T_D, ΔT_D) during operation of the internal combustion engine (10), for example, for a given engine load; and
   determining that the spark plug (12) is defective when an absolute value of the variation is greater than a first threshold.

8. The method of any one of claims 1 to 7, further comprising estimating a remaining service life of the spark plug (12) based on the duration of the time interval (T_D, ΔT_D), for example, for a given engine load.

9. The method of any one of claims 1 to 8, further comprising operating the internal combustion engine (10) under a limited load condition when it is determined that the spark plug (12) is defective.

10. The method of claim 9, wherein a load limit of the internal combustion engine (10) is determined based on the duration of the time interval (T_D, ΔT_D), for example, at a given engine load.

11. The method of any one of claims 1 to 10, wherein the internal combustion engine (10) includes a plurality of cylinders (26), each being associated with a spark plug (12), the method further comprising:

determining the time interval (T_D, ΔT_D) for each of the plurality of cylinders (26);
comparing the time intervals for the plurality of cylinders (26); and
determining that the spark plug (12) associated with a cylinder (26) is defective when the time interval (T_D, ΔT_D) determined for the same differs by more than a predetermined second amount from the time interval determined for at least one other spark plug.

12. The method of claim 11, further comprising:

determining an average of the time intervals for the spark plugs (12); and
determining that one or more of the spark plugs (12) are defective when the time intervals determined for the same differ from the average by more than a predetermined third amount.

13. The method of any one of claims 1 to 12, further comprising:

measuring a cylinder pressure (ICPM) of the cylinder (26); and
determining that the spark plug (12) is defective based on the measured cylinder pressure (ICPM) in addition to the determined time interval (T_D, ΔT_D).

14. A spark-ignited internal combustion engine (10), comprising:

an engine block (18) defining at least in part a cylinder (26);
a spark plug (12) associated with the cylinder (26); and
a control unit (32) configured to:

start a supply of current to a primary winding (16) of an ignition coil (14) associated with the spark plug (12);
measure the current flowing through the primary winding (16);
determine that the current flowing through the primary winding (16) has reached a predetermined current value;
determine a time interval (T_D, ΔT_D) based on a timing of starting the supply of current (t_1) and a timing of reaching the predetermined current value (t_2); and
determine whether the spark plug (12) is defective based on the determined time interval (T_D, ΔT_D).

15. A computer program comprising computer-executable instructions which, when run on a computer, cause the computer to perform the steps of the method of any one of claims 1 to 14.

FIG 1

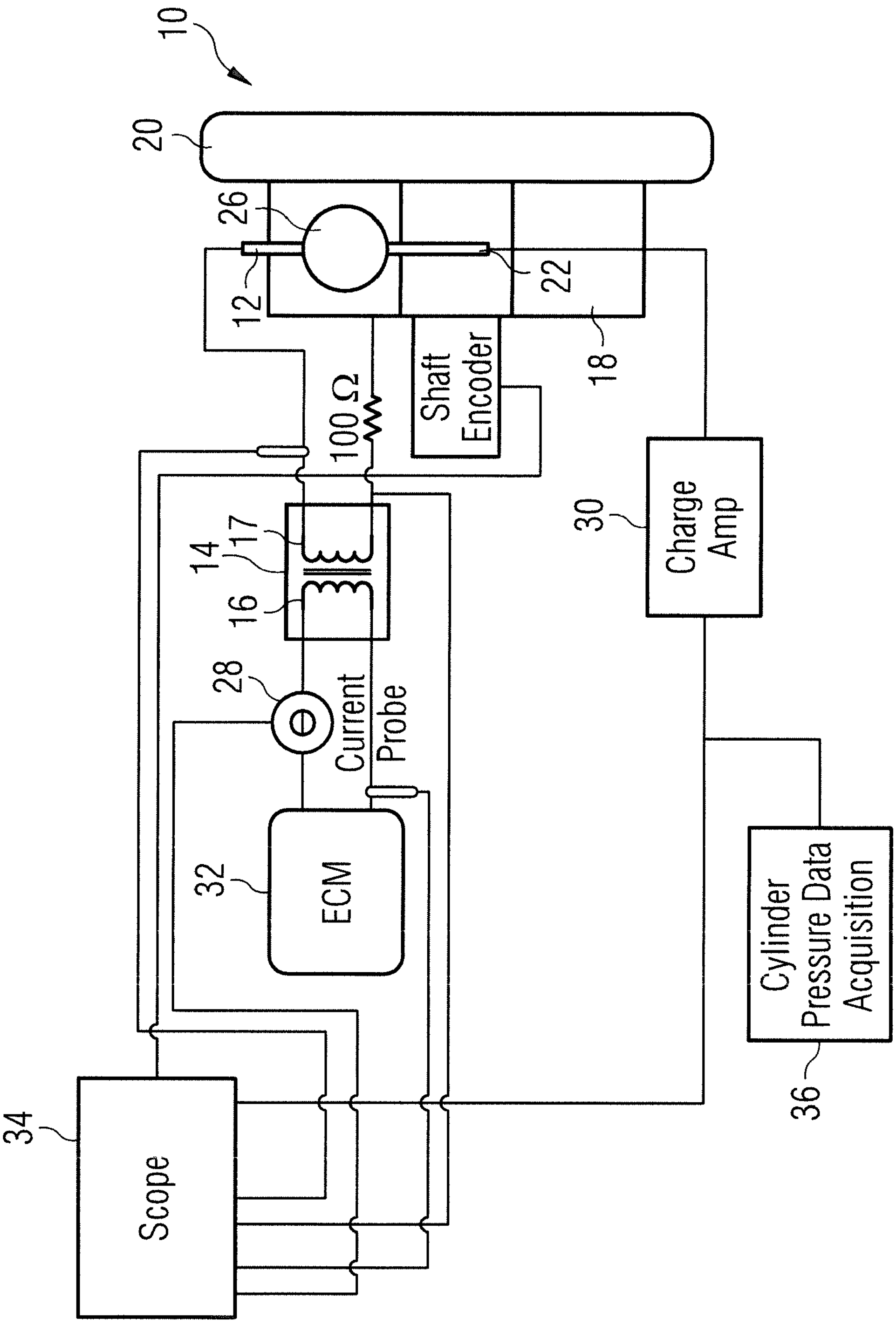

10
20
26
12
22
18
Shaft Encoder
100 Ω
14
17
16
28
Current Probe
32
ECM
30
Charge Amp
Cylinder Pressure Data Acquisition
36
34
Scope

FIG 2

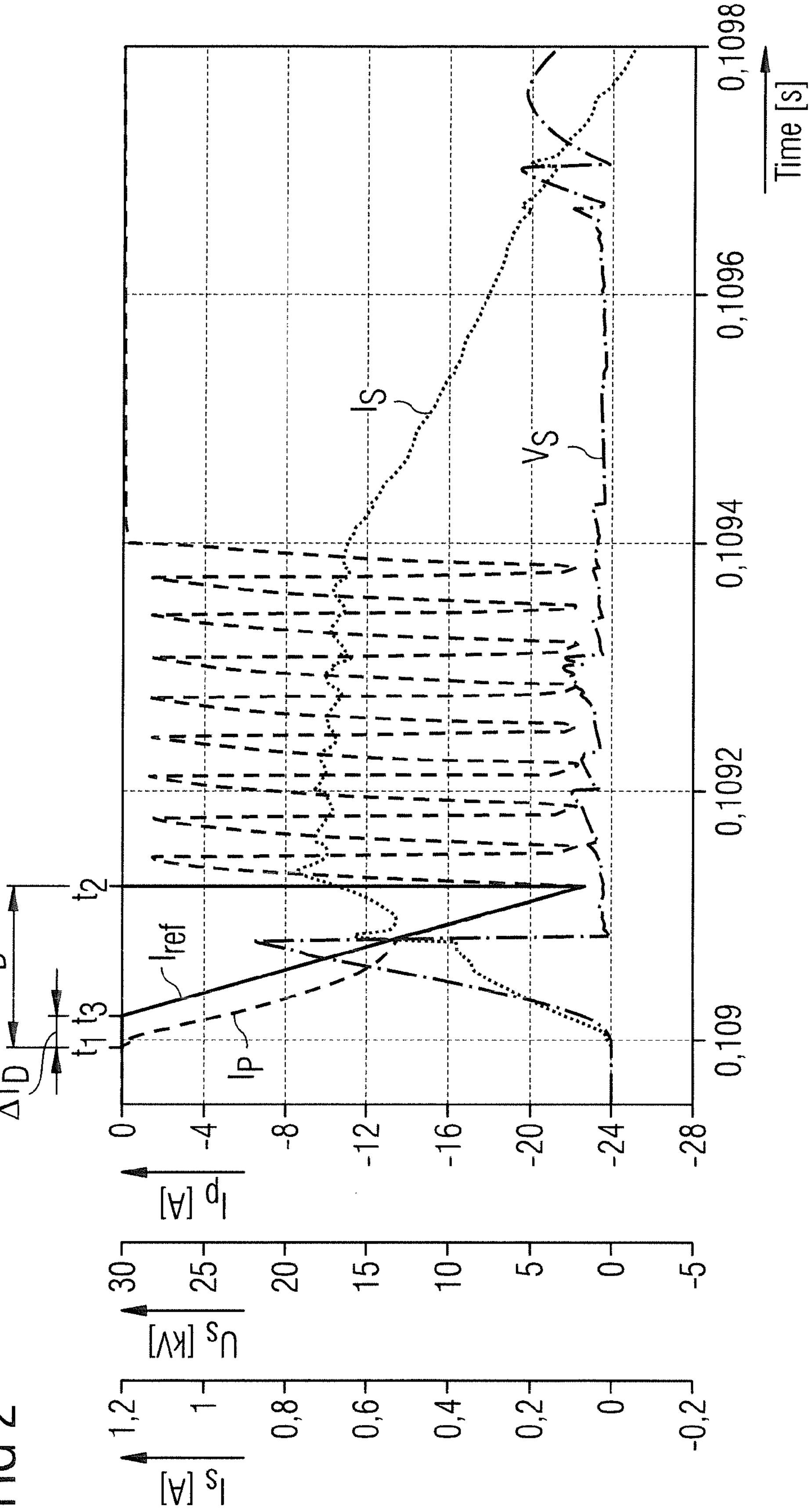
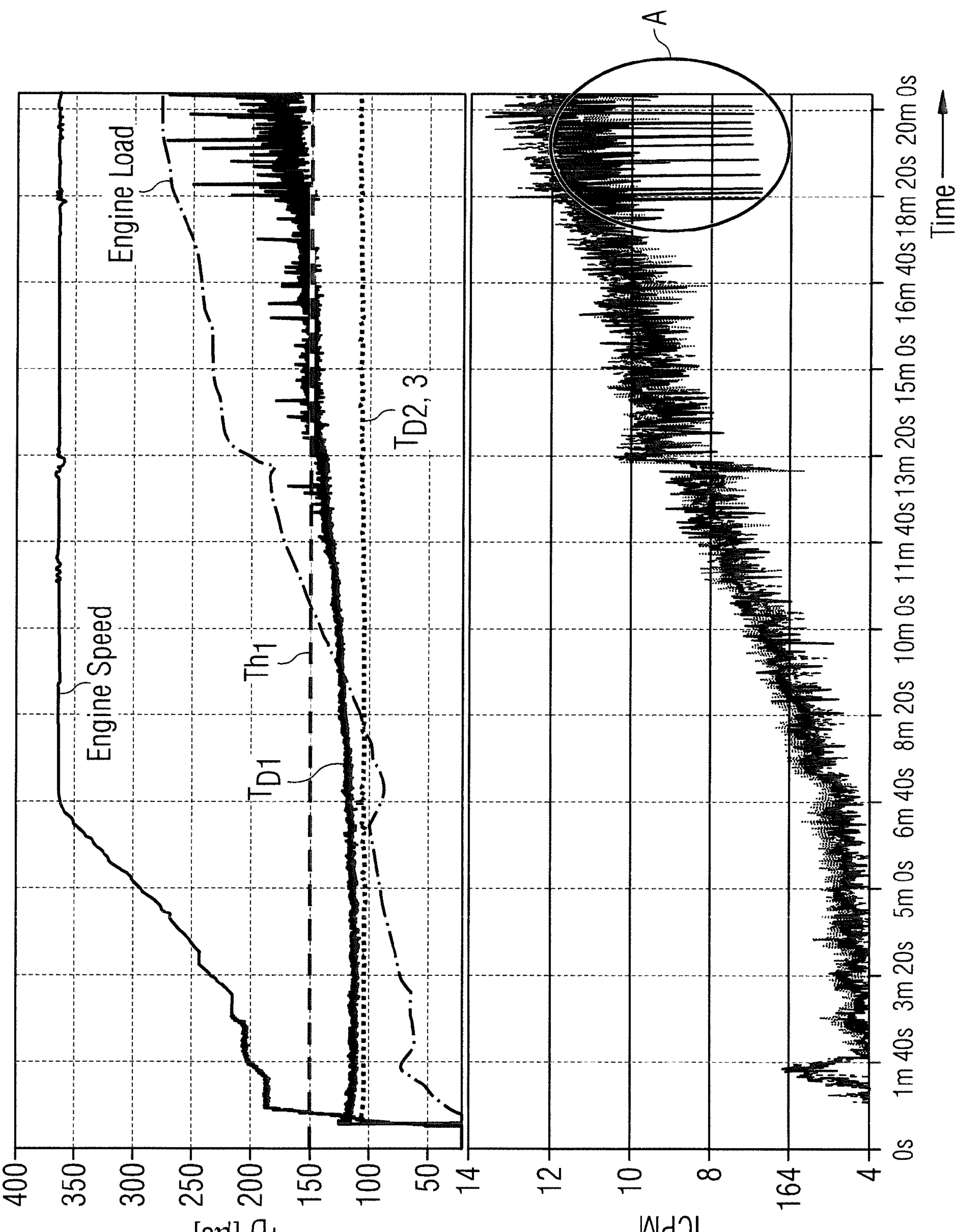
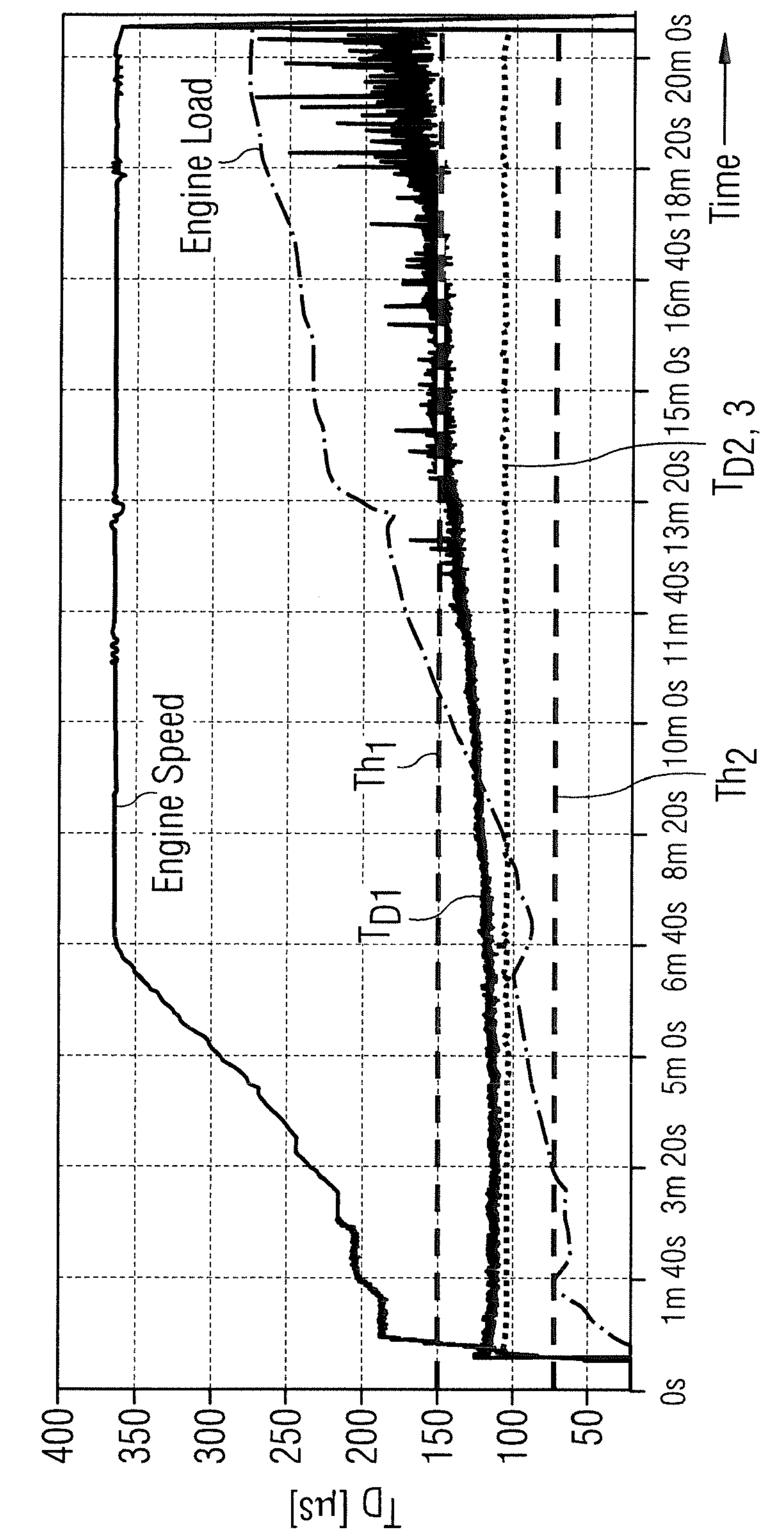

I_S [A]
U_S [kV]
I_P [A]
T_D
ΔT_D
t_1 t_3
t_2
I_{ref}
I_P
I_S
V_S
Time [s]
1,2 1 0,8 0,6 0,4 0,2 0 -0,2
30 25 20 15 10 5 0 -5
0 -4 -8 -12 -16 -20 -24 -28
0,109 0,1092 0,1094 0,1096 0,1098

FIG 3



Engine Speed
Engine Load
Th1
TD1
TD2, 3
A
TD [µs]
400
350
300
250
200
150
100
50
14
12
10
8
164
4
ICPM
0s
1m 40s
3m 20s
5m 0s
6m 40s
8m 20s
10m 0s
11m 40s
13m 20s
15m 0s
16m 40s
18m 20s
20m 0s
Time

FIG 4



TD [µs]
400
350
300
250
200
150
100
50
0s
1m 40s
3m 20s
5m 0s
6m 40s
8m 20s
10m 0s
11m 40s
13m 20s
15m 0s
16m 40s
18m 20s
20m 0s
Time
Engine Speed
Engine Load
Th1
TD1
Th2
TD2, 3

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EUROPEAN SEARCH REPORT

Application Number
EP 16 18 1892

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The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
Munich	24 January 2017	Ulivieri, Enrico

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X : particularly relevant if taken alone
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