Advanced Plasma and Variable Spark Ignition System
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Abstract: Stable ignition in internal combustion engines under lean or high EGR (exhaust gas recycling) is difficult to achieve with current spark ignition systems. North-West University has developed a novel ignition system to improve ignition by generating a high energy plasma over a larger volume. The plasma is either generated by a corona discharge only, called the Advanced Plasma Ignition (API), or with both a corona and spark discharge, called Variable Spark Ignition (VSI). Although corona ignition systems are not new, API and VSI make use of several novel, patented components to achieve a compact, inexpensive and reliable system.

The system consists of three main components, a novel corona plug, a compact high voltage transformer and a robust drive circuit. It is designed to have a similar size, weight and material cost as conventional pencil coils.

The high voltage transformer is driven at its resonance frequency to generate a high output voltage (up to 40 kV) of several MHz. The output voltage first generates a corona inside a ceramic cavity. Thereafter the corona plasma is further heated and ejected into the combustion chamber away from the corona plug. Depending on the configuration of the ground electrode, the corona will either continue to grow away from the corona-plug (API) or towards the ground electrode forming a spark (VSI). The corona plug has no sharp metal points exposed in the combustion chamber and no electrodes that obstruct the flame front. The system actively controls the amount of power that is delivered to the plasma depending on the plasma resistance within less than a micro second. For corona ignition (API), sparking is undesired and the system is configured to temporarily suspend power transfer the moment a spark is formed and then resumes again when the conduction channel disappears.

To operate the system, 200 V DC power and a digital enabled signal has to be supplied. The system is able to generate several short (<100us) corona or spark discharges per ignition cycle or to grow and sustain one or several corona discharges or sparks for several milliseconds, as determined by the enabled signal.

To minimise costs, the high-voltage transformer has only a few metres of copper wire wound on a non-magnetic core and relatively inexpensive components are used in the drive circuit. For reliability, a simple, analogue, self-oscillating drive circuit is used, which make use of a novel, patented technique to protect the semiconductors.

The complete system has a diameter of 20 mm, length of 24 cm and can deliver up to 1 J into a 100 kΩ plasma, with more than 50% efficiency.

1. System Description

The Advanced Plasma Ignition (API) consists of a corona plug, transformer and drive circuit PCB, as shown in Figure 1.

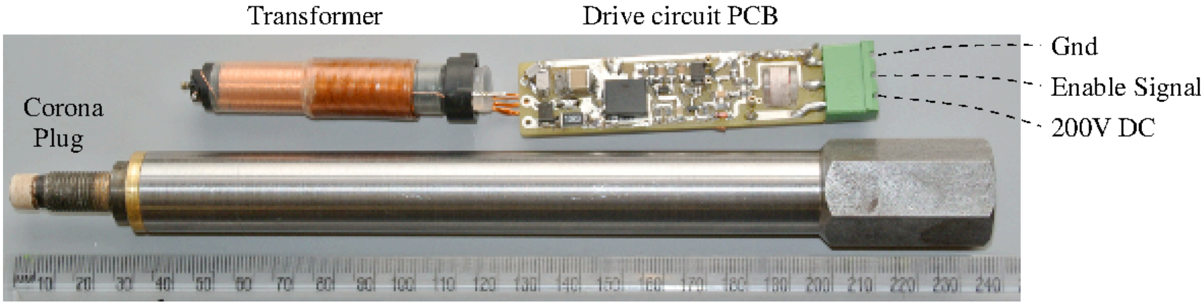

Figure 1: Photo of API prototype and its main components.

200 V DC power is supplied on the power input and a digital signal on the Enabled input switch the system on and off. When in the on state, the drive circuit drives the primary winding of the transformer at a resonance frequency. A high voltage of several MHz is generated on the secondary side which is connected to the inner electrode of the corona plug. The corona plug is configured such that a high electric field is generated at the tip of the inner electrode. A corona discharge from the inner electrode into the combustion chamber then takes place. The corona is sustained for the duration of the enable pulse, which may range from a few microseconds to several milliseconds. Multiple corona discharges can also be performed in a single ignition cycle by giving more than one enable pulse.

The system makes use of five novel concepts:

- A *corona plug* (patent pending) which generate the corona inside a ceramic cavity and then ejects the warm plasma into the combustion chamber
- A *resonant drive* [1] that drive the primary winding at a resonance frequency of the secondary winding in order to achieve a high voltage using a weakly coupled transformer.
- A *push-pull drive circuit* [2] where inexpensive transistors can be driven reliably at high frequencies.
- A *spark quenching mechanism* (patent pending) where power transfer is immediately suspended when a spark occurs.
- A *segmented-core transformer* [3] to achieve a low-loss, compact coil with a large energy density when the system is adapted for a conventional sparkplug.

1.1 Corona plug

The corona plug consists of a cylindrical symmetric ceramic body with a high-voltage (HV) electrode in the centre and a grounded metal body on the outside. The tip of the HV electrode is inside a small ceramic bore, as shown in Figure 2.

The plug operates by firstly generating a corona discharge at the tip of the HV electrode. The plasma then grows towards the opening of the cavity from which it is then ejected into the combustion chamber. Depending on the shape of the ceramic and the position of the ground electrode, the corona will either grow away from the corona plug (API – Figure 2 left side), or grow towards the ground electrode forming a spark discharge (VSI – Figure 2 right side).

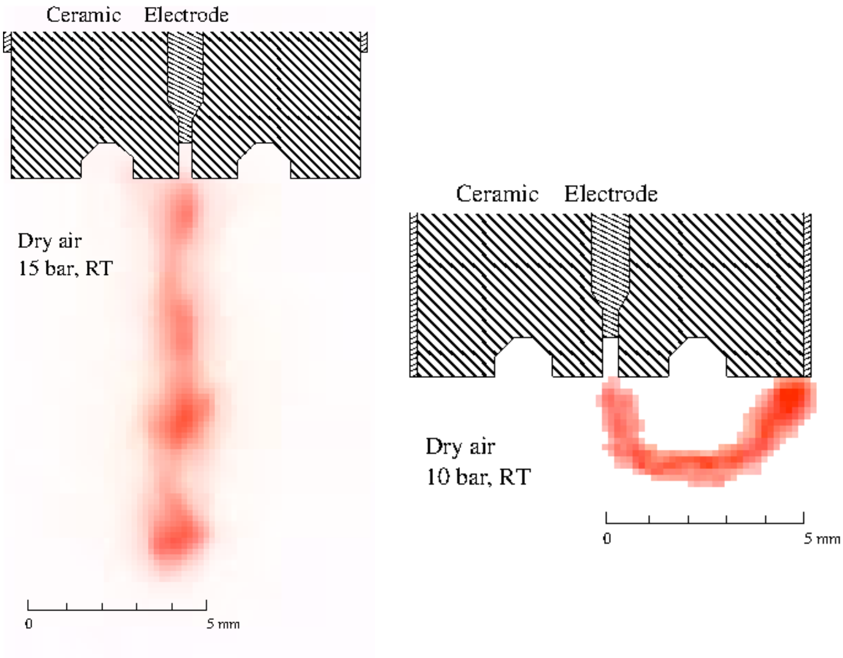

Figure 2: Cross-section of two different corona plug configurations to either generate a spark (left) or corona (right). A false colour photo of a spark and corona in compressed air at room temperature is also shown.

Initiation of Corona discharge
Corona ignition system requires a very high electric field to generate a corona discharge a high pressures. However, the maximum voltage that can be supplied is limited by the small size of the engine port and the dielectric strength of the ceramic isolator. In order to achieve a high electric field using a voltage of 30-40 kV on the inner electrode, the tip of the electrode is surrounded by a dielectric material with a high dielectric constant. Figure 3 shows the effect of the dielectric material on the electric field compared to an electrode in air and a normal spark plug. For the electrode at 30 kV, the spark plug has a peak field of 60 kV/mm (for a gap length of 1 mm). The thin electrode (0.3mm diameter) in air (ε_r=1) has a field of 120 kV/mm at its tip. The same thickness electrode in a dielectric medium (ε_r=10) gives rise to a peak electric field of 200 kV/mm.

Growth and ejection of corona in cavity
When a corona discharge forms a plasma at the tip of the HV electrode, the conducting plasma will have the same potential as the HV electrode. The plasma therefore in effect extends the electrode as shown in Figure 4. The corona discharge continues at the edge of the plasma, so that the plasma grows in the direction of the opening of the cavity.

The cavity has a capacitance of about 0.2 pF due to the large dielectric constant of the ceramic. During each half cycle of the AC voltage signal, this capacitance is charged and discharged (with a RMS current of about 0.1 mA). This currents passes through the plasma, heating the plasma. Due to the small volume of gas inside the cavity, very little energy is needed to heat the gas to a high temperature. For example, at 10 bar pressure, 1 mJ of energy is enough to heat all the gas in the cavity by about 1000 ^{o}C. The fast rise in temperature will result in a rise in pressure inside the cavity which will eject the plasma out of the cavity into the combustion chamber. Additionally, the alternating electric field also accelerates the plasma out of the cavity, similar to a dielectric barrier discharge plasma actuator.

Growth of corona in combustion chamber

Once the plasma is ejected from the cavity, the plasma is still electrically connected to the HV electrode so that a corona discharge still takes place at the edge of the plasma. Once in the combustion chamber, the plasma is therefore still heated and extended.

Better ignition is achieved when the plasma grows away from the ceramic body than when it grows on the surface of the ceramic. The ceramic is therefore designed so that the electric field parallel to the surface of the ceramic is smaller than the perpendicular field, as can be seen on the right in Figure 4. This is achieved by having a small dent in the ceramic around the opening (see Figure 2).

However, for the VSI, the ground electrode comes to the end of the ceramic as shown in Figure 2b. After the plasma has grown away from the ceramic, it will grow towards the ground electrode, resulting in a conducting path between the two electrodes and a spark discharge takes place as shown in Figure 2.

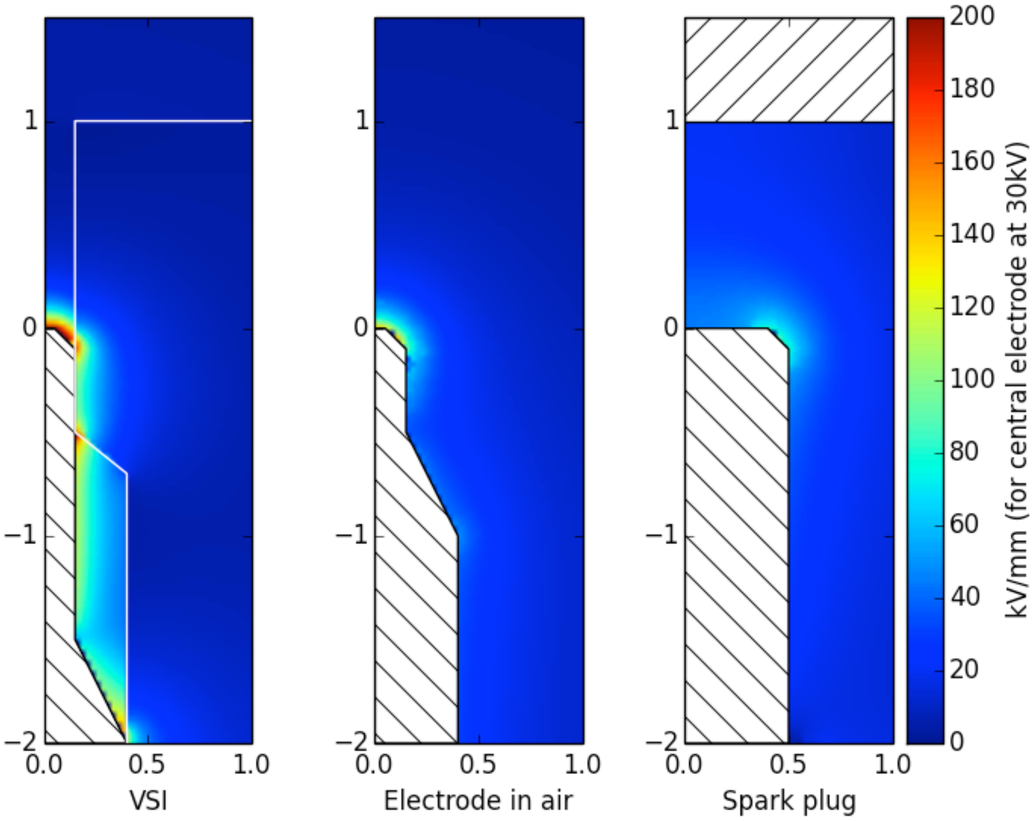

Figure 3: *Electrostatic simulation (using the software Poisson Superfish [6]) showing the effect of a dielectric material (white outline) on the electric field of a wire at 30 kV. Cylindrical symmetry is assumed.*

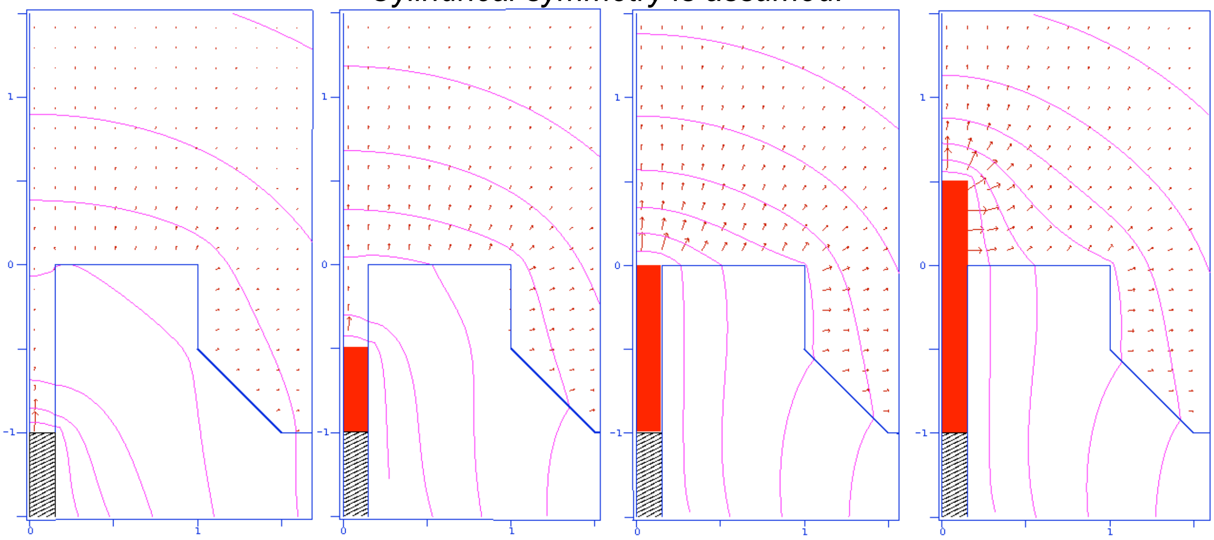

Figure 4: Electric field vectors and equipotential lines (every 3kV) showing the direction in which the plasma grows in an API plug. Electrode at 30 kV and axes in mm.

1.2 Resonant drive

A conventional high voltage transformer cannot be used to generate the high frequency, high voltage signal required for the corona plug. At high frequencies (>1 MHz) most magnetic materials have a low magnetic permeability, resulting in low inductance, and have large energy loss in the magnetic material. This results in weak magnetic coupling between the primary and secondary winding, so that the ratio of output voltage V_s to input voltage V_p, is much lower that the theoretical value of $V_s^2/V_p^2 = L_s/L_p$ where L_s and L_p is the secondary and primary side inductances.

API and VSI make use of resonant, weakly coupled transformers driven at resonance to overcome this problem. The resonant, weakly coupled transformer can be modelled as an ideal transformer combined with a resonator, as illustrated in Figure 5. Firstly, the voltage increase due to the transformer is given by the inductance ratio of the primary and secondary inductances: $V_2^2/V_p^2 = L_{s1}/L_p$. Extra inductance is then added on the secondary, so that the extra inductance L_{s2}, the corona-plug capacitance and the transformer capacitance forms a LC-resonator with a resonance frequency given by $f_r^2 = 2\pi L_{s2} C_s$ where C_s is the effective secondary side capacitance. When driven at resonance, the voltage increase of the resonator is given by its quality factor $V_s/V_2 = Q$. The quality factor is the ratio of the energy loss in the resonator to the energy stored in the resonator.

The inductance L_{s1} and L_{s2} can be combined into a single inductor $L_s = L_{s1} + L_{s2}$ that is weakly coupled to the primary inductor with the coupling coefficient given by $k^2 = L_{s1}/L_s$. This makes it possible to have a weakly coupled transformer, with its output voltage given by $V_s^2 = V_p^2\, Q^2 k^2 L_s/L_p$ at resonance. When $Q^2k^2 > 1$ this is higher than the output voltage given by an ideal transformer with the same inductance ratio.

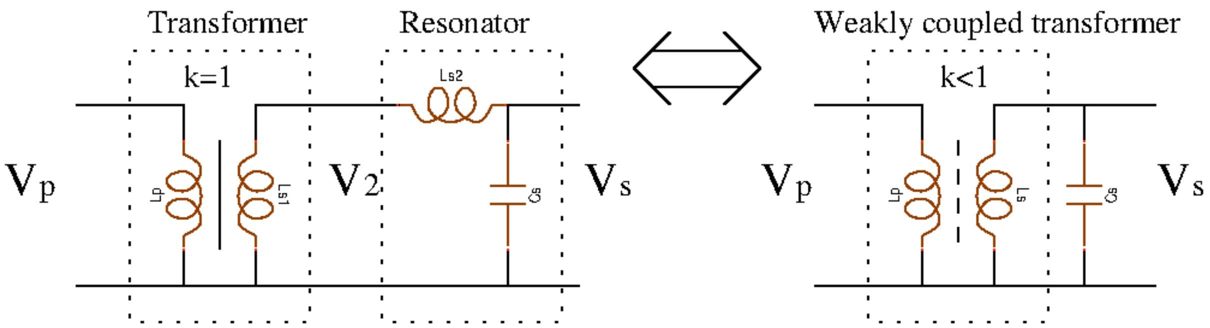

Figure 5: Equivalent circuit of the resonant, weakly coupled transformer

Because the maximum output voltage is directly proportional to the quality factor of the resonator, special care is taken to minimise the loss in the secondary circuit. As no magnetic core is used, the quality factor Q is determined by the dissipation factor of the dielectric filling material, the resistance of the secondary winding and the loss due to the outer metal tube. For example, in the API, the secondary winding has a DC resistance of about 20 Ω, the filling material has a loss tangent of 0.0006 and a copper sleeve is used around the transformer, resulting in a Q of about 70 at resonance. With a coupling of k=0.2, V_p=100 and V_s=40 kV, an inductance ratio of L_s/L_p=800 is required.

The inductance ratio can be further reduced by making the primary side resonant as well, as shown in Figure 6a. A serie capacitor C_p is added to the primary winding of the transformer L_p, so that the primary side also has a resonance frequency, which is chosen the same as the secondary side resonance frequency i.e. $L_pC_p=L_sC_s$. The effective qualtity factor of the two resonators is given by $Q_e^{-1}=Q_p^{-1}+Q_s^{-1}$. At resonance $V_s^2/V_p^2=L_s/L_p$ and $V_p/V_1=Q_e$, so that $V_s^2=V_1^2Q^2L_s/L_p$. The inductance ratio can therefore by reduced by a factor Q_e^2 compared to an ideal transformer to achieve the same voltage ratio. However, the quality factor of the primary resonator Q_p is generally lower than that of the secondary resonator due to the lower impedance of the resonator. With Q_e=30, V_1=100 and V_s=40 kV, an inductance ratio of only L_s/L_p=178 is required.

This double resonance circuit has the special feature that the maximum output voltage (for a fixed input voltage) occurs at two frequencies, one lower and one higher than the resonance frequency, as shown in Figure 6b. If the magnetic coupling between the primary and secondary winding is given by k, the two frequencies are given by $f_\pm = f_r/\sqrt{1 \pm k}$ for a loss-less system. f_+ is called the common-mode resonance, where the current in the primary winding and secondary winding is in phase, and f_- is called the differential mode resonance where the currents are 180 degrees out-of-phase.

The generated corona or spark can be modelled as a load resistance R_p on the secondary side. The effect of this resistance is to change the frequency behaviour of the circuit as shown in Figure 6b. For example as R_p approaches the value $2\pi f_r L_s$, the common-mode resonance frequency f_+ approaches 0 and when R_p is smaller than $2\pi f_r L_s$, there is no common-mode resonance frequency f_+.

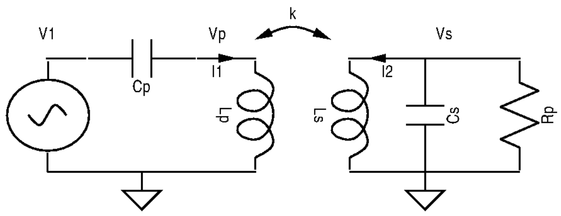

Figure 6a: *Two weakly coupled resonators with a parallel load resistor* Rp*. Simulated parameters used:* f_r*=5 MHz,* C_p*=2.0 nF,* C_s*=7 nF,* k*=0.2,* Q_p*=25,* Q_s*=50.*

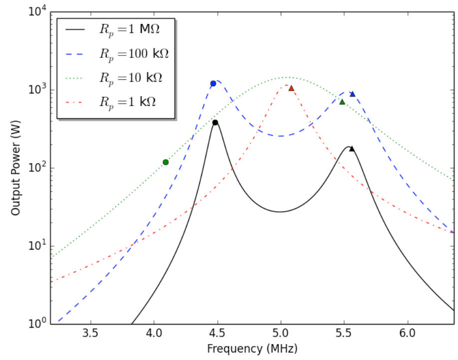

Figure 6b: *Output power against frequencies for different load resistances. The circles and triangles show the common-mode* f_+ *and differential mode* f_- *resonance frequencies respectively*

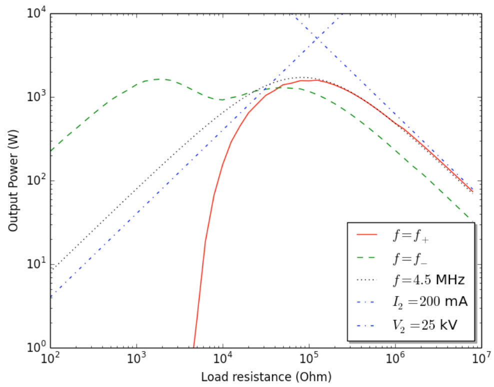

Figure 6c: *Output power against load resistance for different drive frequencies.*

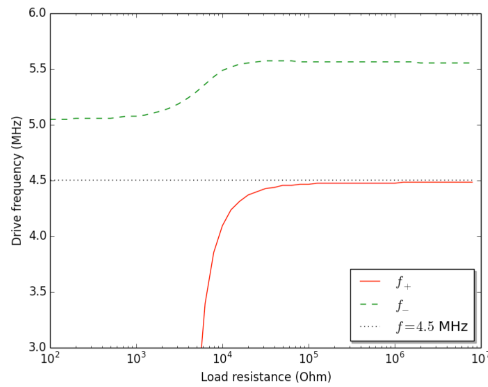

Figure 6d: *Common-mode and differential mode drive frequencies as function of load resistance.*

Figure 6: Simulation of double resonant circuit driven with a 200 V peak-to-peak voltage at various frequencies for different load resistors.

1.3 Spark quenching mechanism

API and VSI make use of current feedback from the secondary winding to determine the drive frequency. This has two advantages: It make it possible to always drive the transformer at the resonant frequency even if the frequency shifts due to changes in inductances or capacitances. Secondly, it makes it possible to vary the output power as a function of load resistance. Because the phase of the feedback is influenced by the load resistance, it make it possible to adapt the drive frequency as function of load resistance, thereby controlling the amount of power delivered to the load. This is illustrated in Figure 6c.:

- When the coil is driven at the common-mode frequency f_+ high power is delivered into large loads, but no power when the load becomes small as shown in Figure 6c.
- When the coil is driven at a constant frequency it can be made to behave similar to a conventional flyback ignition coil i.e. it acts as a constant current source with a voltage limit.
- When the coil is driven at the differential-mode frequency, the power delivered can be made almost independent of the load resistance.

In order to supress sparking in the API, the transformer is drive at its common-mode frequency (by keeping the drive signal in phase with the secondary current). When a spark is formed, the load resistance becomes small, the common-mode resonance frequency vanishes (see Figure 6c) and the system stops oscillating. For a spark ignition system, the system can be configured to keep oscillating when the common-mode frequency vanishes. The spark current is then determined by the selected oscillation frequency.

1.4 Push-Pull drive circuit

Two MOSFETs in a patented push-pull configuration with two bifilar primary windings is used on the primary side, as shown in Figure 7. This configuration has been found to be much more reliable than a conventional push-pull configuration. The drive circuit PCB consist of the two power MOSFETs and an analogue gate drive circuit. The gate drive is designed so that the output voltage of the push-pull stage is in phase with the current in the secondary winding. This ensures that the circuit resonant at the common-mode frequency and that the MOSFETs switches when the current though them is small.

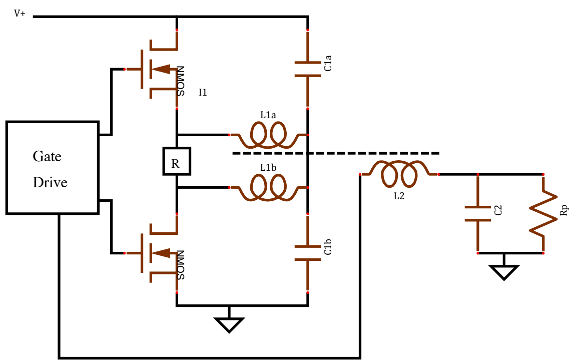

Figure 7: *Patented Push-pull drive circuit configuration.*

2. Prototypes

First a Variable Spark Ignition (VSI) system, called VSI1, was developed that makes use of a normal sparkplug and which is driven at a fixed frequency. It makers use of the resonant drive (1.2), push-pull drive circuit (1.4) without feedback and has a segmented core transformer [3].

The next prototype, called the VSI2, added secondary feedback. It is currently being commercialised by Ambixtra (Pty) Ltd. in co-operation with the North-West University and has been tested on several engines.

The latest prototypes, called VSI3 and API1, make use of the corona plug (1.1) and do not have a segmented core transformer (1.5).

2.1. VSI2

In order to reduce the formation of a corona at the back of the spark plug, it is operated at lower frequencies (around 400 kHz) compared to the API (around 5 MHz). For this, segments of magnetic material [3] are used in order to achieve a small transformer with a high energy density.

The maximum output voltage is 45 kV and it can deliver up to 1 J of energy at a rate of up to 2 kW.

2.1.1 Homogenous operation test results

VSI2 was compared to a conventional ignition coil under the same homogenous engine conditions on one of IAVs single cylinder research engines. The same sparkplug configuration was used and both EGR and lambda was varied to compare the systems at critical conditions. It was required that the Coefficient of Variance (COV) of the IMEP (indicated mean effective pressure) be smaller than 3%. Spark advance was determined by requiring less than 1% knocking while trying to achieve 50% heat release at 8^o CA (crank angle). Table 1 gives a summary of the EGR and Lambda limits obtained with the standard and VSI2 system. Figure 8 shows how the EGR range is extended with VSI2 at 2000 rpm and 14 bar IMEP.

Speed	IMEP	Max EGR % for COV<3%			Max Lambda for COV<5%		
		Lambda=0			EGR=0%		
(rpm)	(bar)	Std	VSI2	Diff	Std	VSI2	Diff
2000	14	23	33	10	1.35	1.40	0.05
1500	7	30	32	2	1.70	1.75	0.05
2000	2.8	21	22	1	1.50	1.55	0.03
1500	20	16	20	4			

Table 1: *VSI2 homogenous engine test results.*

The test report [4] concluded that

- “VSI2 system enables improvement of combustion stability for all investigated operating points (at critical mixture conditions)
    - due to that depending to operating point partly crucial extension of EGR and lean burn limit compared to standard ignition system [X]
- With increasing critical inflammation conditions, given by operating point (turbulence level), Lambda and EGR, increasing benefit from VSI2 in terms of ignition delay
- For homogenous lean operation at EGR 0% no potential for ISFC reduction by VSI2, as minimum always located within [X] robustness limits
    - however, slight ISFC advantage gained by VSI2 at iso-IMEPCOV

- At lower part load same behaviour for EGR application as with enleanment
    - however, in general lower potential for ISFC reduction by dilution with EGR compared to air
- At knock limited engine operation increasing predomination of positive effects of EGR to knock mitigation and thus optimisation of combustion phasing
- Extensions of EGR limit by VSI2 directly visible in ISFC reduction”

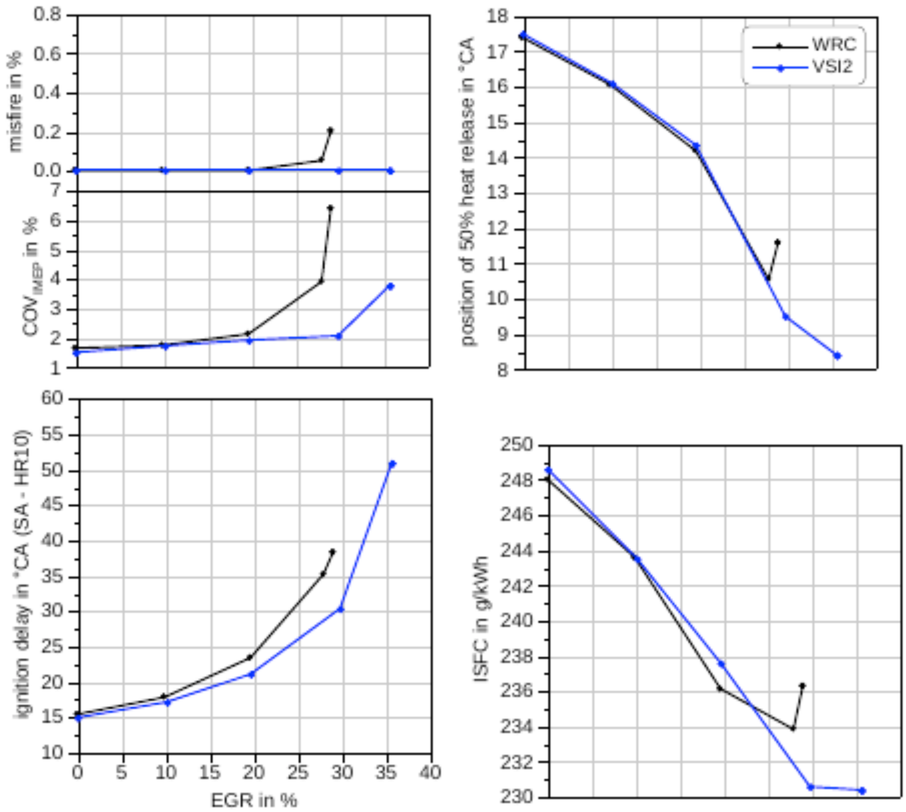

Figure 8: *Comparison of VSI2 (blue) against a standard ignition system (black) at 2000 rpm and 14 bar IMEP. Spark advanced is limit by the requirement of less than 1% knocking.*

2.1.2 Stratified operation test results

VSI2 was also compared to a standard ignition system as well as a prototype high power ignition system at stratified engine conditions. The aim was to evaluate the best ignition system for robust misfire free operation in stratified mode at optimised injector position. Tests were done at 1500 rpm, 7bar IMEP (see Figure 9) and 2000 rpm, 2.8bar IMEP.

The test report [5], concluded that

- “Comparison of VSI system with reference ignition system [X] shows marked improvement regarding inflammation probability and combustion robustness
    - [the reference ignition system] enables no misfire free operation at all
- Compared to high power (HP) ignition system improvement of stratified combustion robustness and ignition delay (advanced CA50)
- VSI system especially enables misfire free operation of retarded SA (to EOI) and thus application of ISFC and soot beneficial settings“

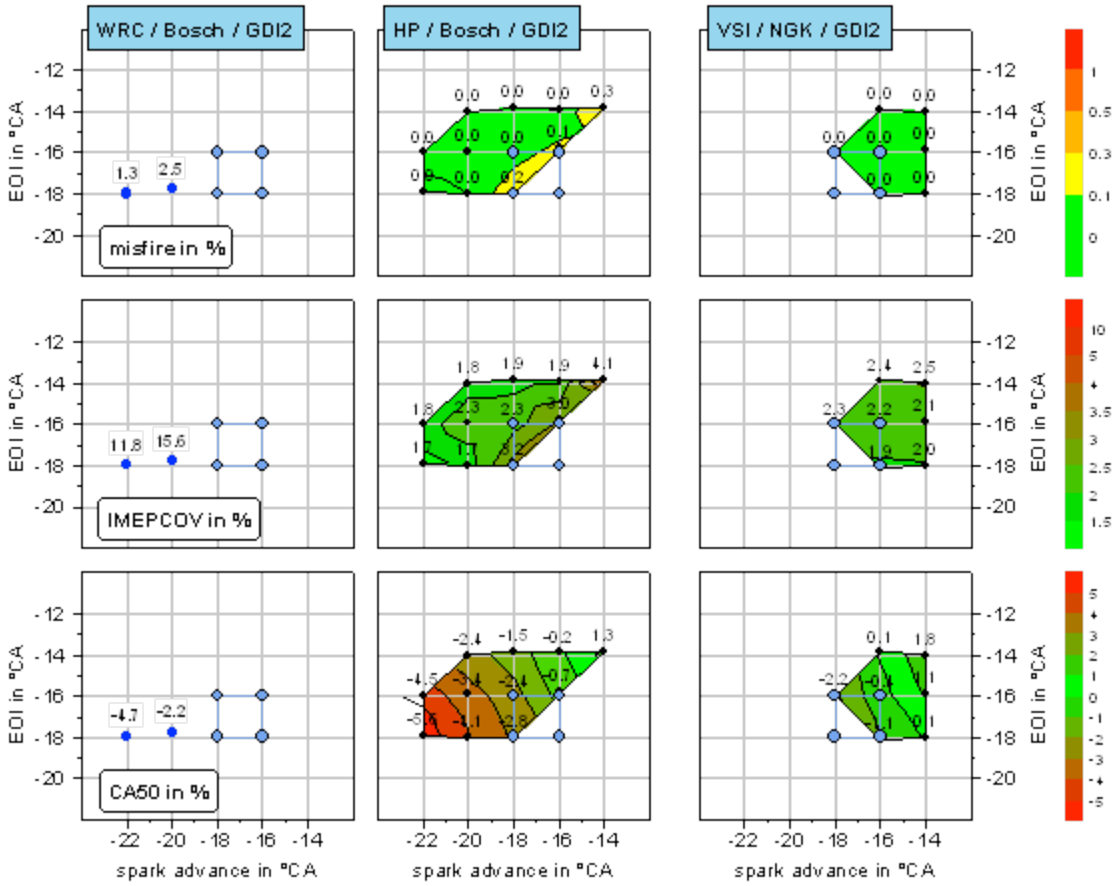

Figure 9: Comparison of ignition systems under stratified operatation at 1500 rpm, 7bar IMEP.

2.2. API1

A first API1 (Figure 1) and VSI3 prototype has been developed and tested in a pressure chamber. It delivers power at 1 kW into a 100 kΩ load at more than 50% efficiency as expected from the simulation, Figure 4c. This means a 1 ms enabled pulse will result in 1 J being delivered to a 100 kΩ load.

Pressure chamber test has shown that the corona system is able to generate a corona discharge in air at room temperature up to 24 bar pressure (API) and a spark discharge up to 26 bar (VSI). Preliminary durability tests show minimal wear of the ceramic and central electrode and no electronic failures. Reliability and functionality testing has been performed on a normal commercial vehicle. However, proper testing on a research engine, as was done with VSI2, still needs to be performed.

Literature

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