Piezoelectric Transformer operation in ignition systems

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Abstract

This work presents results about the feasibility of using Piezoelectric Transformers in electronic ignition systems. Experimental circuits are described as well as the results of investigations of Piezoelectric Transformers driven by these circuits. Analysis of experimental results gives us the right impression about the possibility of creation of well running closed loop precise ignition systems on the base of Piezoelectric Transformers.

Introduction

Piezoelectric Transformers (PT) are electromechanical transducers with double conversion of electromechanical energy. In the input part - called exciter - an applied ac voltage at the electrodes causes mechanical vibrations in accordance to the reverse piezoelectric effect. These mechanical vibrations propagate within the solid body as waves and penetrate to the output part - called generator - where the mechanical vibrations cause an ac voltage at the output electrodes in accordance to the direct piezoelectric effect. The most efficient transportation of mechanical energy from exciter to generator occurs when mechanical waves, moving from exciter to generator and back, coincide in phase (standing waves vibration). This is the so called "resonance regime", where the amplitude of mechanical vibrations achives its maximum value. Corresponding to the theory of mechanical wave propagation in solid bodies we have multiple mechanical resonance frequencies and coupled with it multiple electrical operation frequencies. The resonance frequencies have a strong correlation to the mechanical dimensions of PTs. Most of the current well known PT constructions are typical resonance devices. There are a few features of piezoelectric transformers which make it quite attractive for high voltage applications: PTs are made from nonflammable ceramic materials (normally PZT - Plumbum Zirconate Titanate - ceramics). Additionally such materials have a high resistance (more than $10^{12}\,\Omega \times \mathrm{m}$). That means it is not necessary to use any additional isolation for high voltage PT-constructions. PT-constructions do not use any windings (as known from electromagnetic transformers). PTs are normally developed as a plate, made from PZT ceramics material, with two pairs of electrodes on the main surfaces of the plate. Therefore it has a very simple construction and manufacturing technology. Piezoelectric transformers have also high level of power density and reliability [1]. Another advantage of PTs is a very low electromagnetic interference. The influence of a running PT to the operation of CRT or flat screen displays is much less in comparison to electromagnetic transformers. Therefore PT constructions are being used in low power, high voltage power supplies, e.g. for back lightning of flat screens [2]. There are some peculiarities for PT application in ignition systems, as an resonance device. It is especially important for the ingnition system of combustion engines. The shaft of the engine is operated with high speed rotation (up to 120 rotation per second and even more). The ignition device has to react very fast to all changings in the engine operation regime. We tried to get some additional information about PT operation in ignition devices and present it in this article for further discussions.

Description of measuring circuit and PT

For the investigations a Rosen-type geometry was choosen for the PT. This type of PT has the highest voltage transformation ratio. This is quite important for highvoltage ignition devices. The PT is manufactured from hard PZT material. It has the shape of a plate with the dimentions: $80 \times 24 \times 3\,\mathrm{mm}^3$. The main parameters of the material are:

- relative dielectric constant - 1200
- dissipation factor - 0.004
- coupling coefficient , k33 - 0.63
- mechanical quality factor - 1000.

This PT generates 5.5 kV output voltage with an input voltage of 20 V. The electrical circuit consists of generator with controlcircuits (GE), amplifier (AM), PT , rectifier (RE), oscilloscope, discharge device (DD) and resistors 1 and 2. The circuit and the construction of the discharge device are shown in Fig. 1 and 2.

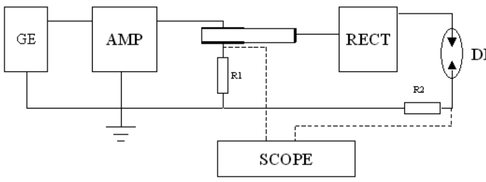

Figure 1: measuring circuit

It is possible to change the distance between the electrodes of the discharge device from 5 to 40 mm. For experiments we opted for a distance of 20 mm, that corresponds to approximately 20 kV discharge voltage. The input voltage of the PT with an amplitude of 20. . . 40 V and a frequency between 20 and 45 kHz, corresponding to the resonance frequencies of the transformer, is supplied by a signal generator and an amplifier. The sinusoidal output voltage of the transformer is rectified and then directly fed to the discharge device. The discharge current passes through a $10\,\Omega$ shunt. The scope shows the voltage across this shunt as well as the voltage across a shunt in series with the PT input to monitor the input current. The 3rd channel monitors the excitation signal.

One goal of the measurements was to investigate the behaviour of the discharge process in dependence from the control impulses. The time duration and repetition frequency of this impulses correspond to the rotation speed of the engine shaft. For four tact engine, one impulse cycle corresponds to two rotations of the shaft and it takes one fourth of the total cycle. That means for a speed of shaft rotation of 120 rotations per second, the repetition frequency of control impulses (f_C) is 60 Hz.

Experimental results

Fig. 3 shows voltage and current of the control impulse as well as the discharge current for a repetition frequency f_C of 1 Hz. The PTs input voltage is 20 V with a frequency equal to the resonance frequency $f = 42.63$ kHz. For low f_C (1. . . 3.5 Hz) we can see a few discharge sparks during one impulse. The reason is due to the working principleof PT. When the control impulse changes from "low"-state to "high"-state, there is for the first moment no discharge and the PT works in regime without load. In this regime the PT has the highest voltage gain and the PT output voltage grows rapidly untilhigh voltagesparkoccures. At this time the workingregime changes. The load is now defined by the spark, it is a low impedance load. Therefore the voltage gain of the PT decreases, the output voltage decreases rapidly. The discharge process stops. Without discharge spark the PT again changes to "no load" regime and the output voltage raises to start the dis-

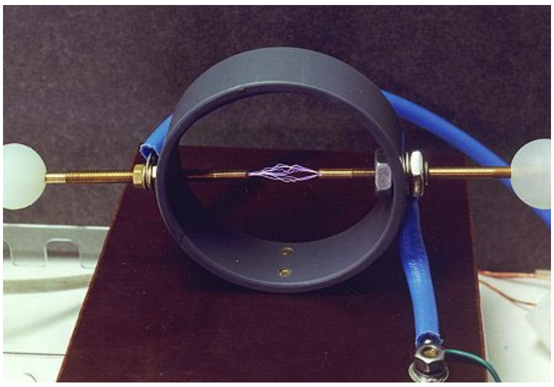

Figure 2: discharge gap

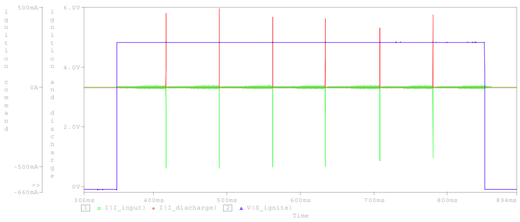

Figure 3: multi discharge

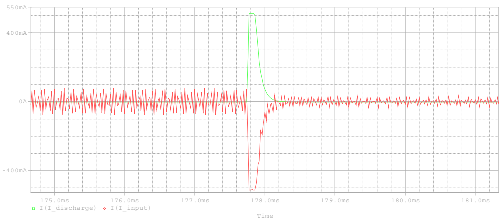

Figure 4: current slopes

charge cycle again. This happens as long as the control impulse has “hig”-state. This cyclic discharge process (multi discharge) runs automatically and doesn’t need any special electrical circuit arrangements. It can be useful for starting the engine under cold temperature conditions. For $f_C = 1\,\mathrm{Hz}$ there are five discharge sparks and for $f_C = 3.5\,\mathrm{Hz}$ there are only two discharge sparks. When the input voltage of PT was changed to 40 V, the discharge process became faster. This results in more discharge sparks per control cycle. There is a direct proportion between the quantity of the discharge sparks per control cycle (dis/cycle) and the PTs input voltage. Not as noticable is the dependency between the dis/cycle rate and the operation frequency of the PT. The possible value of f_C is limited by the reaction speed of the PT. The increase of the output voltage of the transformer is transient. If f_C is too high,the voltage increase at the output of the PT will not be fast enough to cause a discharge. The highest possible value of f_C (at a fixed input voltage) is where the system is able to cause at least one discharge spark. For the 1st mode resonance frequency of the used PT ($f = 21.53\,\mathrm{kHz}$), the highest possible control frequency f_C was 18 Hz. For the 2nd mode resonance frequency of PT ($f = 42.63\,\mathrm{kHz}$), it was 20 Hz. If it is necessary to get control frequencies f_C with more than 60 Hz, the input voltage of the used PT would have to be increased four times to a value of 160 V. Also, the use of a PT with a higher operation (resonance) frequency - up to 150 kHz - would accelerate the output voltage rise. Such PTs have to be developed from piezoceramic material with lower mechanical quality factor. The reaction time of the PT output voltage (transient time) is in direct proportion to the mechanical quality factor of the piezoelectric material and is inversely proportional to the working frequency of the PT.

Fig. 4 shows a good correspondence in shape and time position of discharge current and PT input current. The front slopes of both currents have a very short rise time. If one needs information about the discharge timing, it is possible to get it from measuring the PT input current instead of measuring the real discharge current. This will be useful for the realization of precise ignition devices. Finally, a complete ignition system was build on the base of another PT made from hard PZT material. The size is $70 \times 16 \times 3\,\mathrm{mm}^3$ The output voltage is between 20 kV and 30 kV, the PT driver circuit is self oscillating and has one input for switching on/off, which can be set by a controller. The whole circuit is compact, fully isolated (high voltage parts) and housed in a practical way.

Conclusion

For a PT with an operation frequency of approximately 40 kHz and input voltage $V_{in} = 40\,\mathrm{V}$ it was possible to obtain (at least) one discharge spark at the discharge device for control impulse repetition frequencies f_C up to 20 Hz. For lower f_C it is possible to get multiple discharge sparks: at least 2 sparks for $f_C \leq 9\,\mathrm{Hz}$ and 5 sparks for $f_C < 3.5\,\mathrm{Hz}$. Two parameters influence the number of discharge sparks for one ignition period (multiple discharge): the operation frequency of the PT and the input voltage of the PT, whereby the influence of the PTs operation frequency is almost not noticable. For high multi discharge repetition rates it is necessary to increase the input voltage. The PTs input current shows a good correspondence in time to the discharge current in the plug. Therefore it is possible to get a feedback signal of the start time of discharge by measuring the PTs input current instead of the discharge current, to build cloose loop presision ignition system.

References

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[2] H. Sasaki, K. Iguchi, S.Kawashima, NEC Corp. Japan *Development of High Voltage DC Power Supply Using Piezoelectric Transformer.*