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Digital Pulsed Power System to Drive a 20J Repetitive Plasma Focus Device

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Abstract- In this paper the digital pulsed power system to supply a very small repetitive Mather-type Plasma Focus Device (20 J) is presented. The structure of this electrical system included a pulsed power supply and a Microcontroller based control system. In Plasma Focus Devices a dc power supply charges a high voltage capacitor and then this saved energy discharges between two coaxial electrodes using a controllable spark gap switch. The procedure of control the capacitor charging and discharging are explained in this paper. Finally, the experimental results of electrical discharge and pinch shaping in plasma focus in different working conditions are presented and a good repetitive performance in a wide domain of working conditions is seen.

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Abstract- In this paper the digital pulsed power system to supply a very small repetitive Mather-type Plasma Focus Device (20 J) is presented. The structure of this electrical system included a pulsed power supply and a Microcontroller based control system. In Plasma Focus Devices a dc power supply charges a high voltage capacitor and then this saved energy discharges between two coaxial electrodes using a controllable spark gap switch. The procedure of control the capacitor charging and discharging are explained in this paper. Finally, the experimental results of electrical discharge and pinch shaping in plasma focus in different working conditions are presented and a good repetitive performance in a wide domain of working conditions is seen.

Keywords: plasma focus, pulsed power system, microcontroller, SORENA-1.

I. Introduction

Plasma Focus (PF) devices have been developed independently in 1960's in two different models by N. V. Filippov in the Soviet Union [1] and J.W. Mather in the United States [2]. These devices are good sources of high energy ion, electron beam, soft and hard X-ray and neutron (when Deuterium is used) pulses [3- 5]. They also can be used to study on dense and hot plasmas [4, 5]. Due to wide applications of PF and the simplicity of its structure and operation, in the last 5 decades, high research activities have been done in this field and several numbers of these devices with energies less than 1 J up to several Mega Joules have been constructed [6-11]. High energy PF devices can only work single shot, but small (Low energy) PF devices can operate repetitively and as a result, they can generate and emit neutron and X-ray pulses with high frequencies [8]. In recent years different laboratories have been worked on small PF devices [8, 9, 12, 13]. The smallest PF device in the world is Nano focus (0.1 J) in the CCHEN (Chile) [14].

In experiments with Plasma Focus Devices, the stored energy in a capacitor bank discharges in a low pressure gas between two coaxial electrodes to produce a dense and hot plasma column [13]. For repetitive performance, these devices need electrical systems that can act with controllable frequencies, so a digital control system must be designed & constructed which can control the working frequency, number of shots and also can control capacitor charging system.

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Partlo, William N., et al. [15] presented optimization of capacitance values, anode length and shape and preferred active gas delivery systems for plasma focus. They also include a pulse power system comprising a charging capacitor and spark gap switch, capacitor, a microcontroller as pulse controlling part. Due to importance of pulsed power system in repetitive plasma focus and other similar devices, many researchers are working on pulsed power system development [16-18]

In this article, we have explained the design and construction of the electrical system of a very small (20 J) Mather-type repetitive PF device named SORENA-1whichhas been designed and constructed in Plasma and Nuclear Fusion Research School of Nuclear Science and Technology Research Institute of Iran and finally explained the results of some experiments with it at different working conditions (different gases, initial pressures, discharge voltages, single shot and repetitive performance).Its characteristics have been completely explained elsewhere[19]. The aim of construction of this device is to extend the research activities of PF in Iran to make very small portable PF devices with repetitive performance which can be used for medical and industrial applications. The high voltage capacitor charging system of SORENA-1 is designed and constructed in Plasma and Nuclear Fusion Research School of Nuclear Science and Technology Research Institute of Iran. The pulsed power system used a spark gap as switch. The plasma focus device is modelled in electrical point of view and the proposed electrical model of device and spark gap are simulated by MATLAB/Simulink to evaluate the verification of our design, then the experimental data and simulation results of electrical system of SORENA-1 are compared and analyzed.

II. Design & Construction of the Electrical System

The electrical system of SORENA-1 consists of a 25 kV dc power supply for charging the capacitor, one adjustable Spark gap (5 - 20 kV) and its triggering system, a fast high voltage capacitor (200 nF, 5 nH, 25 kV) used as capacitor bank) (Figs. 1&2), and a digital control system (voltage control and monitoring system). The frequency of discharges is controlled by this control system. It is a simple circuit based on AVR microcontroller (Atmel Company);by using this system the frequency of charging and discharging & the charging voltage can be adjusted. The proposed microcontroller circuit diagram is shown in Fig. 3. The control system can be used either automatically or manually. The frequency of discharges can be adjusted from 0.1 to 10 Hz. Capacitor charging voltage is regulated at desired voltage (7-14 kV) and after that the dc power supply will stop to charging capacitor, then spark gap will be triggered when microcontroller program comment to triggering system.

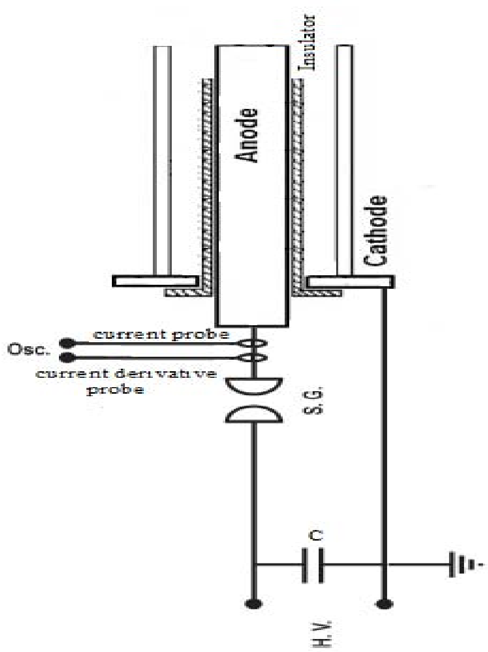

Fig. 1: General structure of electrical connections between capacitor bank and electrodes of. SORENA-1.

III. Experimental Set-Up

As shown in Fig.4a, the whole system of SORENA-1 included its electrical power supply, gas puffing and vacuum system, gas cylinder, vessel of PF, capacitor, sparkgap and other parts of system. DC power supply to charging capacitor included manual commander (Fig. 4b), digital control box (Fig. 7), high voltage transformer (Fig. 4c), charge and discharge system (Fig. 4d), and capacitor that is connected to sparkgap directly (anode of sparkgap connected to anode of capacitor), then the other side plate of sparkgap by 12 coaxial short cable are connected to anode of PF as shown in Fig. 4e, the negative point of capacitor and the cathode and body of steel working table, all are earthed.

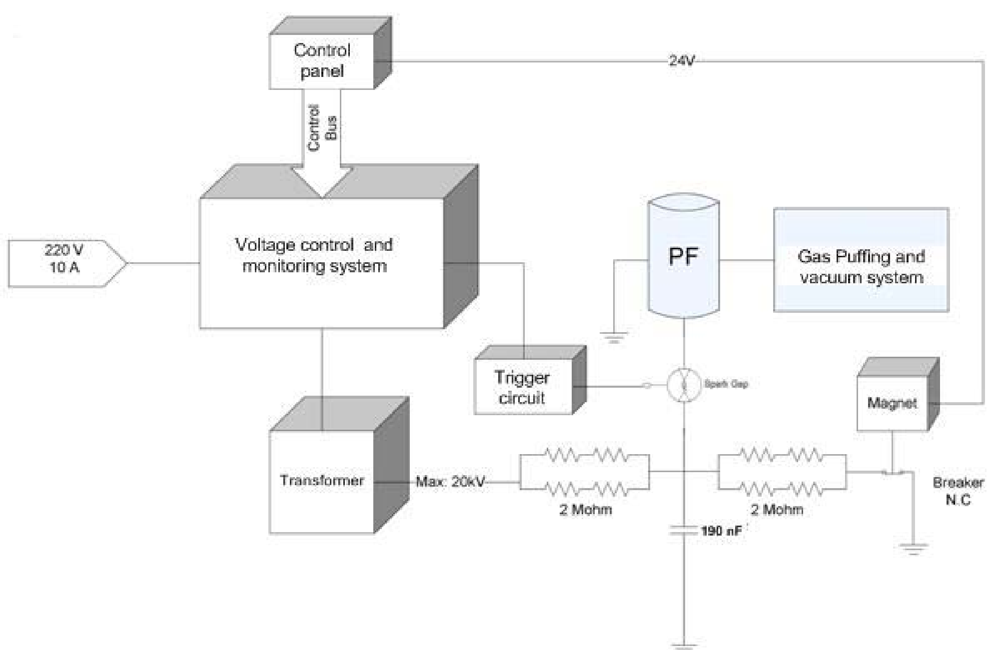

Fig. 2: Schematic of the electrical and mechanical systems of SORENA-1.

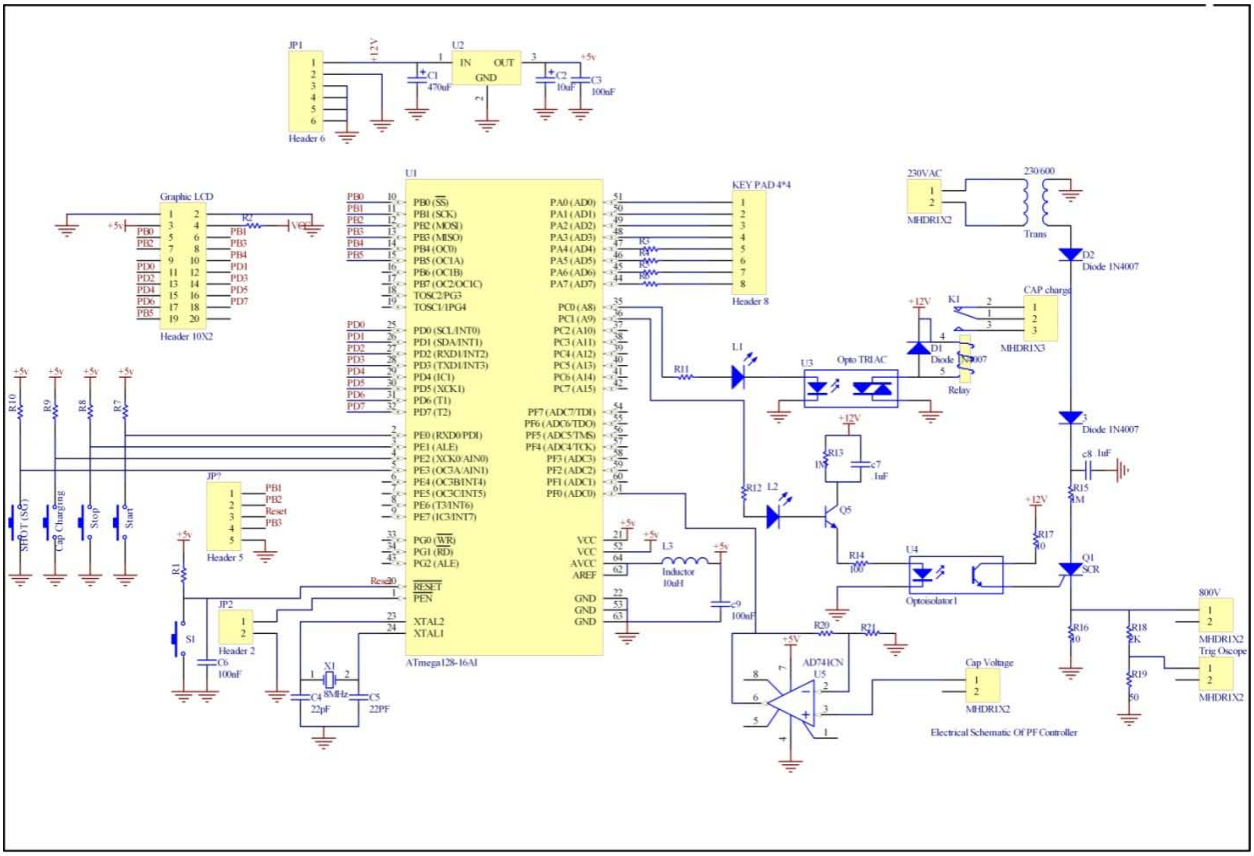

Fig. 3: AVR Microcontroller Circuitry.

(a)

(b)

(c)

(d)

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(e)

Fig. 4: a) General view of SORENA-1 b) power supply box c) transformer d) charge and discharge resistances and damper e) capacitor and its connections to spark gap

Fig. 5 shows the equivalent circuit diagram of charging system in MATLAB/Simulink. Equivalent resistance of charging and discharging system is equal to 2 Mega Ohm that connected to charging capacitor. The AC voltage from mains is increased by transformer and then rectified by diode rectifier that shown in Fig. 5.

The energy that charged in capacitor can be discharged between anode and cathode of Plasma Focus by a sparkgap switch as shown in Fig. 6. In this simulation resistance and inductance of plasma during discharge time is represented as R_p and L_p.

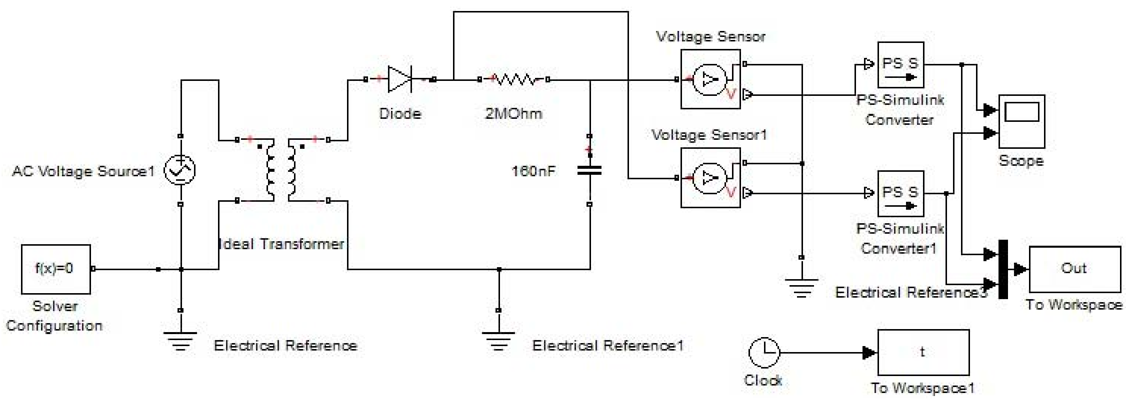


Fig. 5: Equivalent Circuit diagram of charging system in MATLAB/Simulink

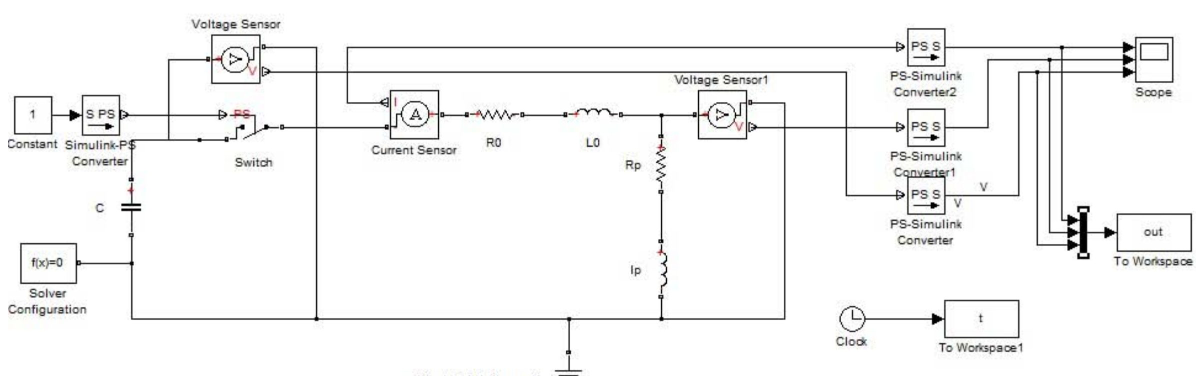


Fig. 6: Equivalent Circuit diagram of plasma and spark gap in MATLAB/Simulink

IV. Control System

The control system included microcontroller and the system monitoring part is installed in a special box (Fig. 7). In this box the input data to order the microcontroller are provided using simple keyboard that it determines the charging voltage, repetition rate of charging (time interval between discharges). This control system can work manually or automatically. In automatic mode, after every shot the number of shots compares with primary regulated shots and if these numbers are not equal, the system will continue to shot again.

Fig. 7: The box which includes the control system and the system monitoring part

The control algorithm contains 3 phases:
Phase 1 (Preparation of the System)
Phase 2 (Main Process)
Phase 3 (Data Logging)

Fig. 8 shows Executive flowchart of SORENA-1 control system. The control process of PF can be manual or automatic. After Start, we should choice or mode as described, then if it choices as manual we can start the charging of capacitor and then order to shot (discharge capacitor to PF), of x but if we choice automatic, the number of shots should be define as positive integer value of x, then define capacitor charging frequency (w) and the current shot frequency (y), if $w>y$ then capacitor will charge to defined voltage, and then the capacitor will separate from charging power supply, so if we have enough delay from last shot, will shot again, then compare the number of shots to defined value, if the number of shots $< x$ then capacitor will charge again but if number of shots $= x$, end of shot cycling and we can save data in data logger and see in LCD monitor.

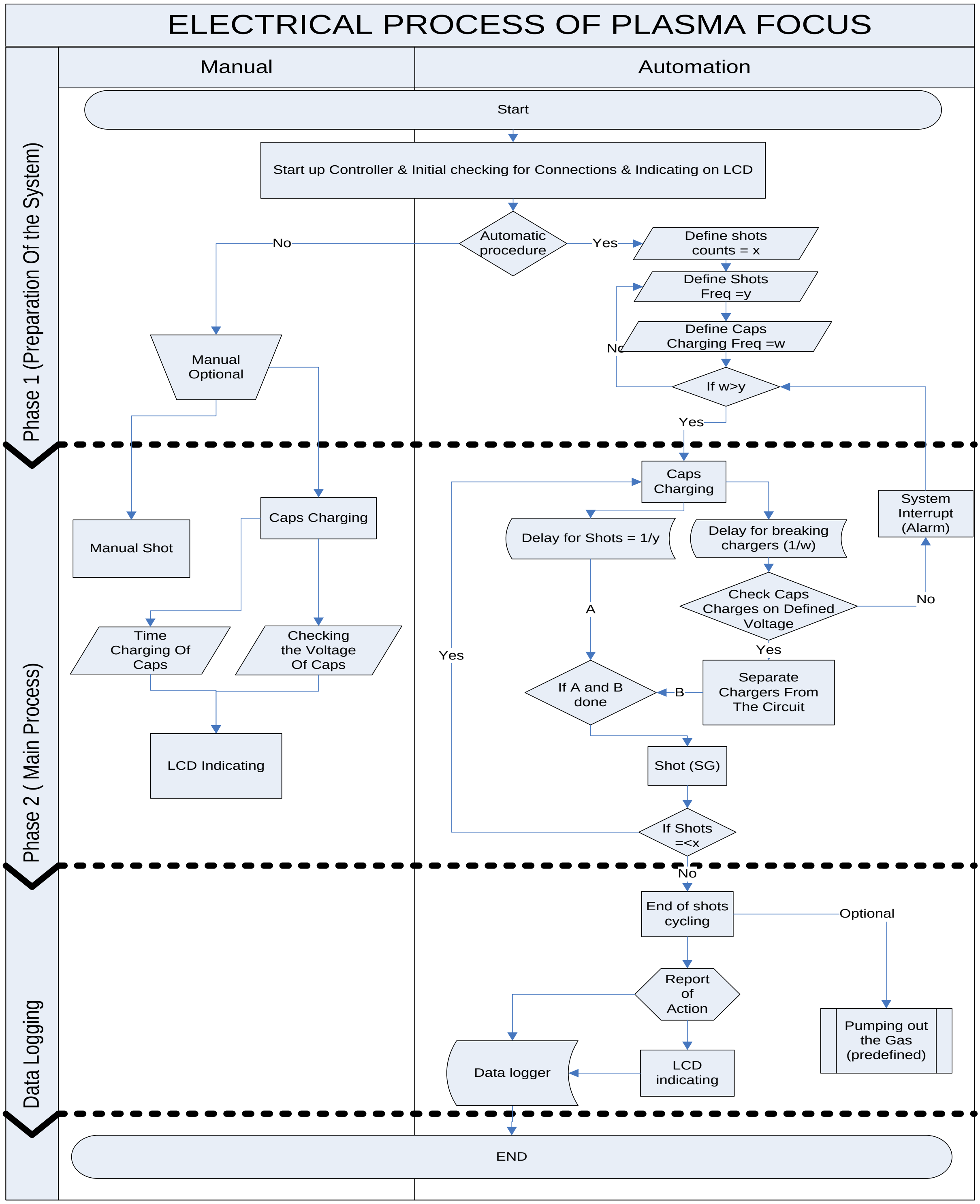


Fig. 8: Executive flowchart of SORENA-1 control system.

The second part of our control system is used for data acquisition from our diagnosis system like hard and soft x-ray and neutron detectors and plasma current measurement system.

V. Results and Discussions

The experiments with SORENA-1 started at December 2012. We have done a lot of experiments in pressure range 0.1 -10 mbar and discharge voltages 7-14 kV and using Ar, Ne & D2 as working gases. In these experiments, the current and current derivative signals have been measured by a Rogowski coil (shown in Fig. 4e) and a magnetic probe, respectively, and displayed on a 200 MHz digital oscilloscope TDS-2022C.

In the experiments with this device, the maximum value for current peak was about 14 kA.

In using of each gas, the pinch formation (a negative spike in current derivative signal) for discharge voltages more than 8 kV & an initial proper pressure domain was observed (Table 1). Three typical signals of derivatives and discharge currents obtained in different PF discharges of SORENA-1are shown in Fig. 9. It is seen that similar to other PF devices, pinch formation happens in wider domains for lighter gases.

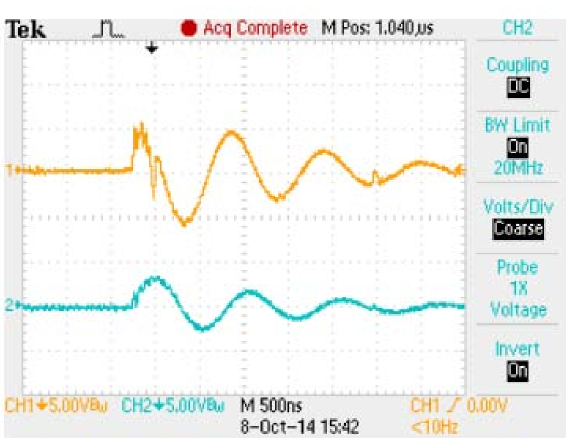
The repetitive performance (repetitive pinch formation) of SORENA-1 by using Ne & D2 as working gases is acceptable. When Ne is used, the device showed a repetitive performance in pressure range 0.1-0.6 mbar (Figs 10 and 11) and the maximum working frequency is about 0.7 Hz (discharge voltage: 12 kV, initial pressures: 0.1-0.4 mbar), using D2 as working gas, the pressure range for repetitive performance is 0.3-0.5 mbar and the maximum working frequency is 1 Hz (discharge voltage:13 kV, initial pressure: 0.3 mbar). It is seen that the frequency and its limits change with discharge voltage, initial pressure and working gas (Fig. 12).

Using the Ar as working gas, only in 11 kV discharge voltage and 0.1 mbar initial pressure, repetitive operation has been observed (f=0.2 Hz).

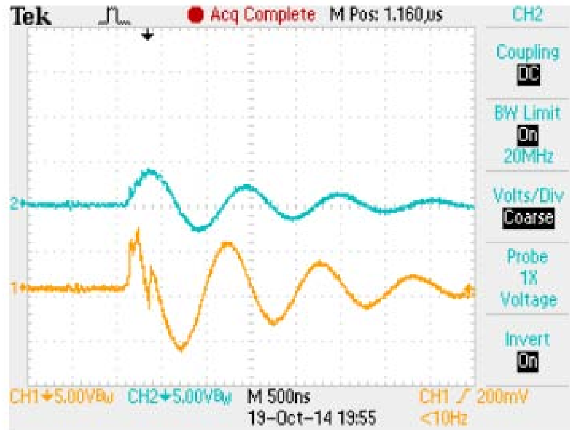
All experiments show fast response of electrical system as spark gap triggering system and charge and discharge process. Charging of capacitor is done in a seconds as is shown in Fig. 13 (experimental result) and Fig. 14 (Simulation by Multi Sim software).

Table 1: The pressure domains of Ar, Ne and D2 gases for pinch formation.

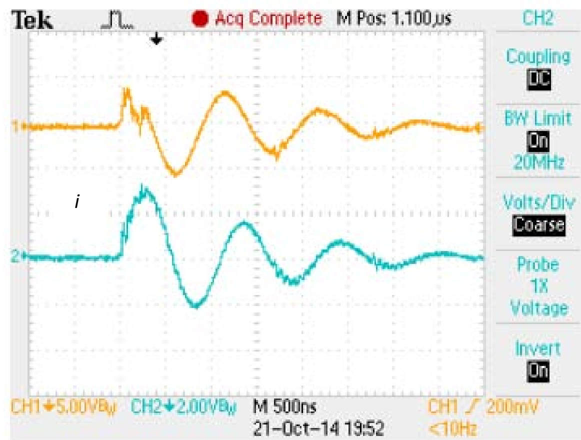
Gas	Pressure domain, mbar
Ar	0.1 – 0.2
Ne	0.1 – 0.8
D2	0.1 – 1.5



(a)



(b)



(c)

Fig. 9: Typical oscillograms of derivatives $\frac{di(t)}{dt}$ and discharge currents $i(t)$ obtained in different PF discharges of SORENA-1.a) Ar, 0.12 mbar, 9 kV; b) Ne, 0.38mbar, 10 kV; c) D2 , 0.44 mbar, 8 kV.

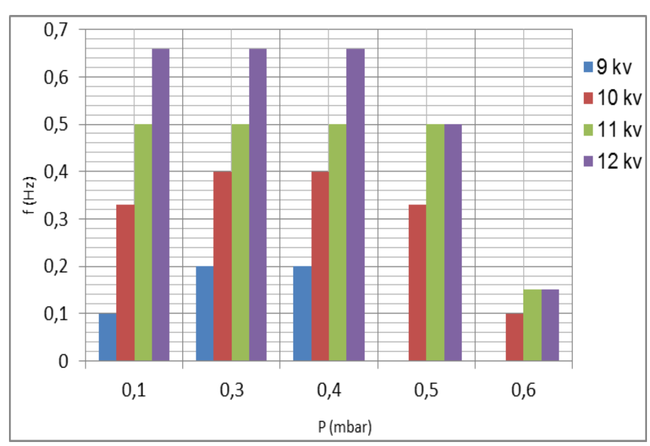


Fig. 10: Variation of repetition frequency for the SORENA-1 PF discharges with initial pressure of working gas. Working gas: Ne; discharge voltage: 9-12 kV.

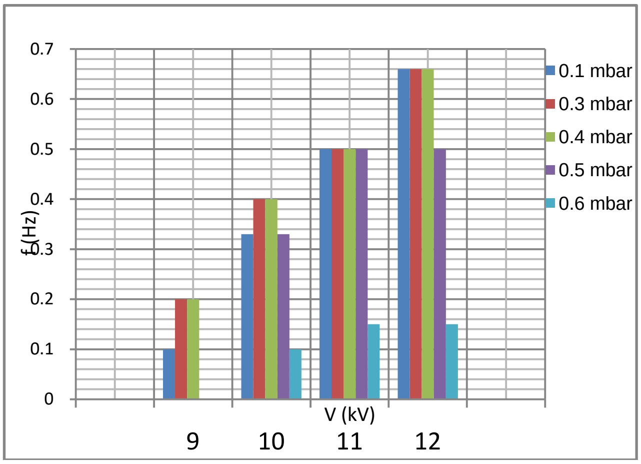


Fig. 11: Variation of repetition frequency for the SORENA-1 PF discharges with discharge voltage. Working gas: Ne; range of initial pressure: (0.1 - 0.6) mbar.

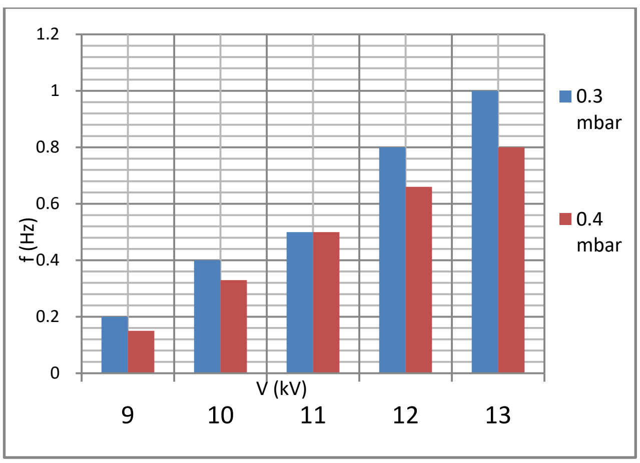


Fig. 12: Variation of repetition frequency for the SORENA-1 PF discharges with discharge voltage. Working gas: D_2; range of initial pressure: (0.3 - 0.4) mbar.

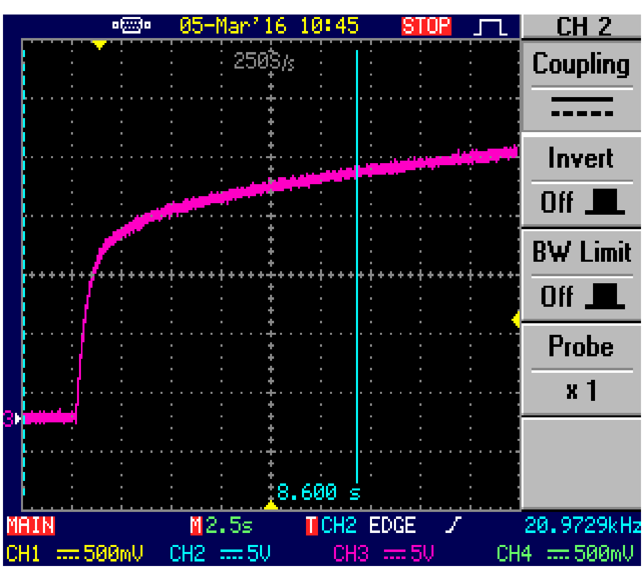


Fig. 13: Charging of capacitor by DC power supply

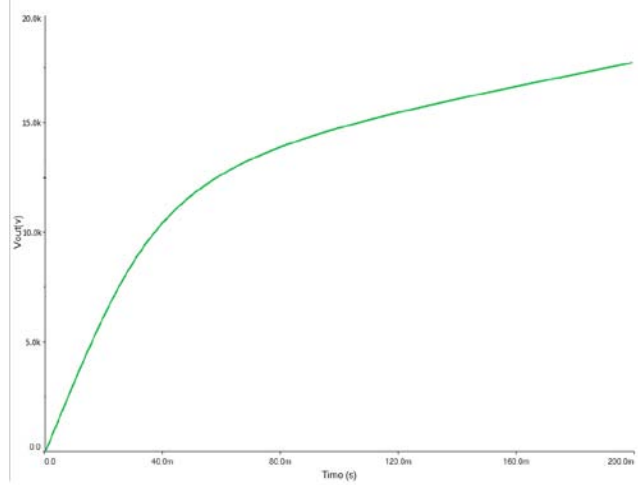


Fig. 14: Charging of capacitor by DC power supply simulated by MultiSim

VI. Conclusion

In this paper, the controllable pulsed power system of a very small (20 J) repetitive Plasma Focus device has been presented and the results of the experiments with it in different working conditions (different discharge voltages, initial pressures &using Ar, Ne & D2 as working gases) are analyzed. All experiments show fast response of electrical system as sparkgap triggering system and charge and discharge process.

From the experimental results, by using this controllable pulsed power system, the pinch formation has been observed for each working gas in different discharge voltages & initial pressures domains, but only in the experiments with Ne and D2 this device showed good repetitive performance in a notable pressure domain, and in the experiments with Ar it the repetitive performance only observed in one working condition.

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