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Breakdown Voltage Estimation of a Supercritical Nitrogen Plasma Switch

J. Zhang, E.J.M. van Heesch, A.J.M. Pemen

Abstract-- **Supercritical fluids (SCFs), characterized by a high pressure and high density, combine the advantages of gasses and liquids: high ability of mass transfer and high heat transfer. SCFs have a high potential as an electrical switching medium owing to their high breakdown strength, quick self healing, no bubble formation, high heat capacity, high heat conductivity, low viscosity, and low impact to the environment.**

In this work the thermodynamic characteristics of supercritical fluids are introduced. An experimental analysis of electrical breakdown phenomena of a supercritical plasma switch with pressure up to 180 bar is presented, focusing on the breakdown voltage variation as a function of the fluid pressure, gap width of the electrodes and fluid flow rate through the gap. A new design of a supercritical switch, with flexible gap width, flushing velocity, and repetitive voltage source is introduced.

I. INTRODUCTION

S UPERCRITICAL fluid (SCF), which has high pressure and high density, combines the advantage of gas and liquid: high ability of mass transfer and high heat transfer. Researches on the discharge behavior of SCF in high electrical fields are recently motivated by new environmental and economical reasons. Gases, liquids and solids, as the widely used switching medium nowadays, all have considerable weak points when applied to high voltage and high power. Therefore SCF is proposed as an alternative high voltage switching medium, owing to its high breakdown strength, quick self healing, no bubble formation, high heat capacity, high heat conductivity, low viscosity, and low environmental impact.

In this work, the thermodynamic state of SC nitrogen is analyzed by calculating the state equation. Experiments on a super critical nitrogen plasma switch with pressure up to 180 bar will be presented respectively in a resistive charging circuit and in a resonant charging circuit. The breakdown voltage variation of the supercritical nitrogen switch with respect to SC nitrogen pressure, gap width of switch and the fluid flow rate through the switch is discussed. A new design of a supercritical switch as well as its experiment setup is briefly introduced. This new design allows breakdown voltage and recovery rate evaluation of SCF under various parameter setting.

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II. THERMODYNAMIC STATE OF NITROGEN

The thermodynamic state of Nitrogen can be expressed by the combination of two parameters such as pressure and temperature or pressure and density. The equation of state of

nitrogen can be expressed using Helmholtz energy with independent variables of density and temperature in equation (1)[1]. $\alpha^0(\rho,T)$ stands for the ideal gas contribution to Helmholtz energy and $\alpha^r(\rho,T)$ is the Residual Helmholtz energy corresponding to the influence of intermolecular forces. Pressure of nitrogen in real fluid phase can be calculated as the derivative of the Residual Helmholtz energy, seen in equation (2), where R is the molar constant; $\delta = \rho/\rho_c$ is reduced density, which is the ratio of nitrogen density and its critical density; $\tau = T_c/T$ is reduced temperature, which is the ratio of critical temperature of nitrogen and its temperature. Figure 1 illustrates the phase diagram of nitrogen in form of pressure up to 20 MPa versus density, with temperature in range of 100 K to 300 K.

$$\alpha(\rho,T) = \alpha^0(\rho,T) + \alpha^r(\rho,T) \qquad (1)$$

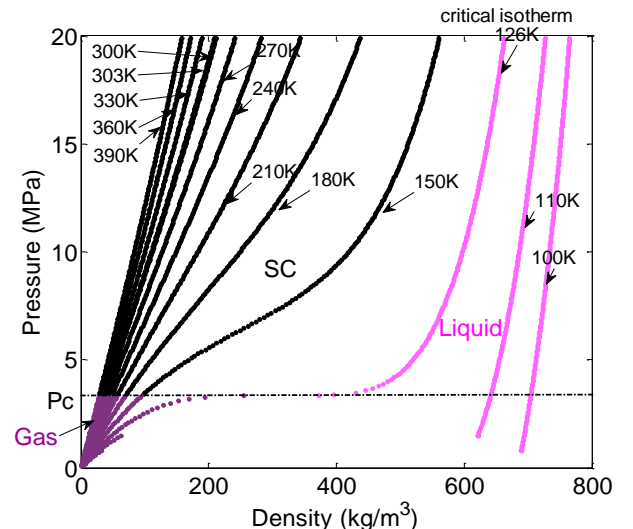$$p = \rho RT\left[1 + \delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)\tau\right] \qquad (2)$$

Fig. 1. Phase diagram of nitrogen obtained from formulations in [1].

Three fluid phases: gas, liquid and supercritical are shown in the phase diagram of nitrogen. From the curves it can be seen that within the three phases, nitrogen can transfer from one to another via changing either its pressure or temperature. The critical values for nitrogen transfer from normal gas or liquid phase to supercritical phase are:

$$T_c = 126.192 \pm 0.010K, \quad P_c = 3.3958 \pm 0.0017 MPa$$

The density of nitrogen at this point is:

$$\rho_c = 313.3 \pm 0.4 kg/m^3 = 11.1839 \pm 0.014 mol/m^3 \quad .$$

On the left side of 126K isothermal line, nitrogen with pressure smaller than P_c is in gas phase, while with pressure larger than P_c is in supercritical phase. Nitrogen on the right down side of critical isotherm line (126 K), is in liquid phase. The interesting research region for plasma discharge in supercritical nitrogen locates from 270 K to 350 K at pressure up to 30 MPa. A limited range equation of state was developed valid in this region [1].

$$P = \rho RT(1 + 0.0131 \sum_{k=1}^{10} \rho^{i_k}) \qquad (3)$$

k	1	2	3	4	5
i_k	1.0	1.0	1.0	2.0	2.0

	6	7	8	9	10
	3.0	3.0	4.0	6.0	6.0

III. EXPERIMENT WITH RESISTIVE CHARGING CIRCUIT

A. Circuit Operation

Figure 2 shows a capacitor charging setup used to evaluate a first, simple supercritical switch. In this circuit an adjustable (up to 320 V) sinusoidal voltage source is transformed to high voltage by two transformers with ratios of 3:1 and 1:360 in succession. Capacitor C1 is charged to DC high-voltage via a resistor R1 and a rectifying diode. In a second charging process, capacitor C2 is charged from capacitor C1 via a resistor R2 and a diode. Since C1 >> C2, C1 acts like a constant voltage source. Once the SC switch breaks down, energy dissipates into the resistive load R3. R2 prevents the discharge of C1 into R3. During the second charging process, the voltage on C2, i.e. on the SC switch increases until the switch breaks down. Once it breaks down, C2 is discharged almost completely and the second charging process starts again. The repetition rate of this sequence is slow and is determined by the combination of R2C2 time, gap setting and adjustable initial sine wave voltage.

The device under test is a small two electrode plasma switch filled with super critical nitrogen. The gap is adjustable and the gap width had to be measured each time again, after application of the high pressure, since the gap distance increased by the forces on the body of the device.

Supercritical nitrogen is supplied from a nitrogen cylinder,

with maximum pressure of 100 bar. The gap width of the supercritical switch is adjustable, from 0-0.5 mm. The breakdown phenomenon in the SC switch changes according to parameters like gap width between two electrodes, pressure of gas filled in the switch and velocity of gas flowing through the switch.
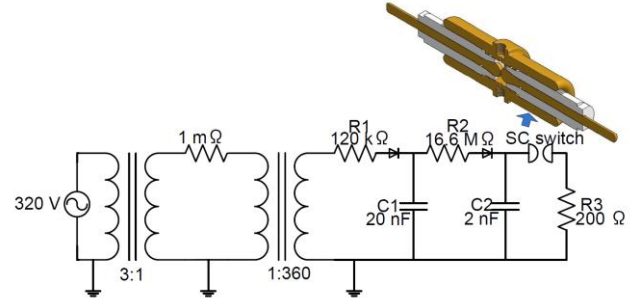

Fig. 2. Schematic of resistive charging circuit for supercritical switch setup.
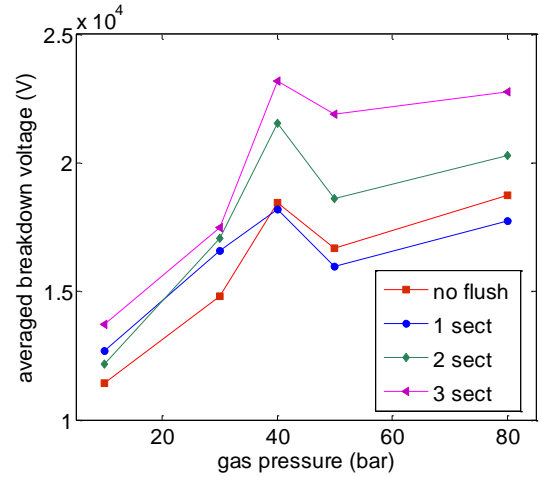
a.
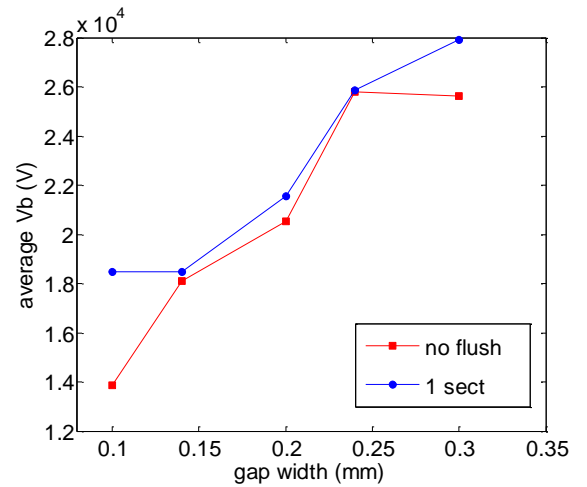
b.

Fig. 3. a. Averaged breakdown voltage of switch versus gas pressure for gap width of 0.14mm.

b. Averaged breakdown voltage of switch versus gap width for nitrogen pressure 70 bar. 1 sect means the needle valve in the supercritical nitrogen loop is opened by 1 scale division.

B. Breakdown Measurements

The experiments are performed for various combinations of

parameters. Gas pressure varies from 10 bar to 80 bar; gas flow rate with no flow, and slight flow; gap width (measured after the switch is pressurized) varies between 0.18-0.5 mm. One high voltage probe (North Star MVP 5) is placed on high voltage side of SC switch. Breakdown voltages are recorded for different experimental conditions and for each condition averaged over 200 breakdowns Figure 3 shows the averaged breakdown voltages. As can be seen from figure 3a, a voltage dip appears above a pressure of around 40 bar. This voltage dip near the critical pressure coincides with the reports about such phenomena in breakdown voltage of supercritical Carbon dioxide under negative DC voltage reported in[2]. The reason of it is assumed to be the electron clusters generations around critical points. From figure 3b it can be seen that the breakdown voltage of SC switch increases with increasing gap width and with increasing gas flushing rate.

IV. EXPERIMENT WITH RESONANT CHARGING CIRCUIT

A. Circuit Operation

A resonant charging circuit with 50 kV peak voltage was built to evaluate the breakdown voltage of the supercritical switch. It is shown in figure 4. In this circuit the 320 V sinusoidal voltage source with two transformers is used again (see section III). The Capacitor C1 is charged again via a resistor R1 and a diode. But charging of C2 occurs differently. Capacitor C2 is charged from capacitor C1 via an inductor, a air spark and a diode. A pulse voltage waveform is formed via the breakdown of a second plasma switch, and is amplified by a 4-stage TLT. The breakdown phenomenon in the SC switch changes according to parameters like gap width between two electrodes, pressure of gas filled in the switch and velocity of gas flowing through the switch. Using voltage probe (mentioned in section 3.1) on the high voltage side of the SC switch, breakdown voltages are recorded with experimental situations of a. one 200 Ohm resistive load connected behind the SC switch and b. direct short circuited to ground behind the SC switch.
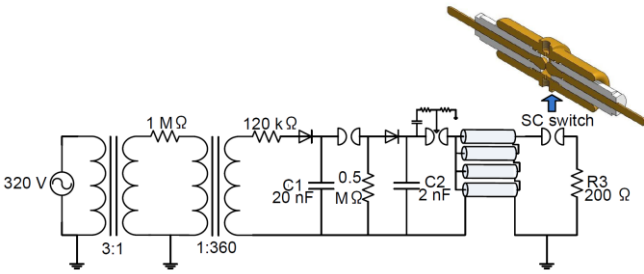

Fig. 4. Schematic of resonance charging circuit for supercritical switch setup.

B. Breakdown Measurements

Figure 5 shows the measured breakdown voltages (each data point is the average of 200 pulses) of the supercritical switch versus gas pressure in the situations of load connected (blue curve) and short circuited (red curve). The high voltage probe (North Star MVP 5) is connected before the SC switch. From the figure it can be seen that the measured voltage has different values under situation of load connected and short circuited. This is because the voltage measured before the switch is composed of two components in series: the voltage across the switch and the voltage across the load. In the scenario of 200 Ohm load connected behind the switch,
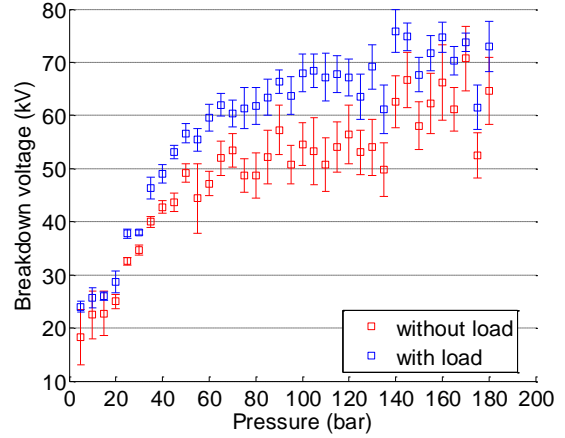

Fig. 5. Average voltage across SC switch plus load at switch breakdown for 200 shots, in relation to pressure at gap width 0.31 mm.
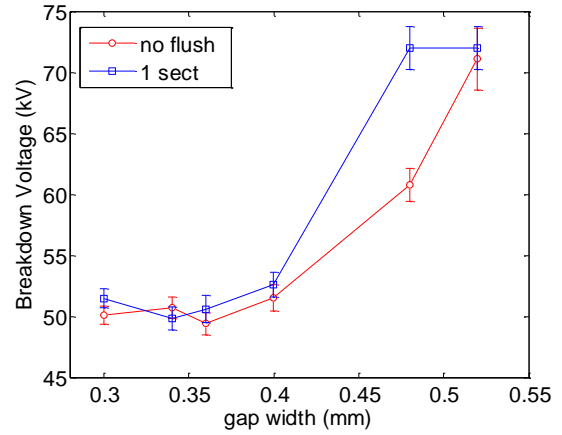

Fig. 6. Averaged breakdown voltage for 200 shots(with error bar) of SC switch (no load) in relation to gap width for a SC nitrogen pressure of 70 bar. 1 sect means the needle valve in the supercritical nitrogen loop is opened by 1 scale division.

since there is voltage building up across the load during the charging process of the switch capacitance, the voltage drop across the switch is lower than the charging voltage measured before the switch. In the scenario of zero resistance connected behind, most of the charging voltage appears across the switch, so the measured voltage before the switch in this case more closely represents the breakdown voltage of the switch. The difference between the two measured voltages (200 and zero Ohm cases) before the switch is larger above the critical pressure. The reason of this phenomenon is unclear yet. Possible effects mentioned here are: above critical pressure the switch capacitance may be higher but also the plasma resistance may be higher. It is interesting to see the characteristic of breakdown voltage of SC switch: when gas pressure goes higher, the breakdown voltage of the switch increases, and tends to saturate under high pressure. The

scattering of breakdown voltage constricts at pressure nearby critical value. Figure 6 shows the increase of breakdown voltage (case no load) with gap width at a pressure of 70 bar. Clearly the breakdown voltage increases with larger gap width, and flushing through the switch contributes to higher breakdown voltage.

The breakdown voltage of nitrogen is estimated using the well-known Paschen's law shown in equation (3), where p is pressure, d gap width, γ the secondary ionization coefficient, A and B constants depending on gas composition, related to the primary ionization coefficient (A is the saturation ionization in the gas at particular E/p (electrical field stress/pressure), and B is related to the excitation and ionization energies[3]). The constants A and B have values of 90.0 and 2565.00 respectively[4][5]. The value of secondary ionization coefficient is taken from [4], which was estimated using the breakdown criterion $\gamma(\exp[\alpha d]-1)=1$.

$$V_b = \frac{Bpd}{\ln[Apd/\ln(1+1/\gamma)]} \qquad (4)$$

The measured breakdown voltages in our supercritical nitrogen switch are compared with the predicted values from Paschen's law for nitrogen. The result is given in figure 7. It can be seen from figure 7 that the experiment detects a deviation of breakdown voltage from Paschen's curve in supercritical nitrogen. It increases with larger value of Pd. The detected deviation starts to occur above Pd=9 which coincides with SC pressure times lowest gap setting, i.e. all deviations occur above the critical pressure and all regular ones occur below the critical pressure. Further investigations are needed into unrecognized sources of error in the present setup.
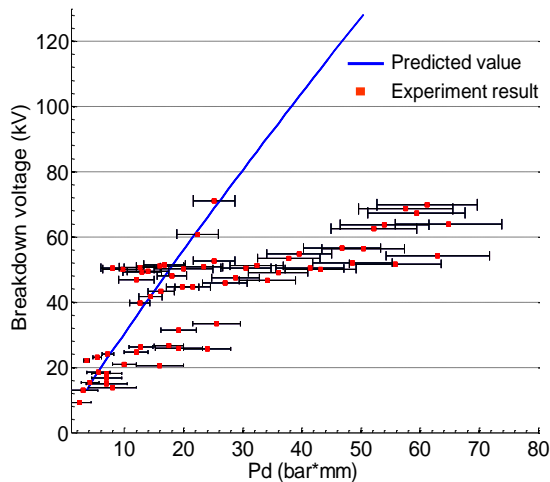

Fig. 7. Comparison of experimental data on the breakdown voltage in a supercritical nitrogen switch with Paschen's curve. The error bar represents measuring error of 0.1 mm for gap width.

V. NEW DESIGN FOR SC SWITCH

A new design for a versatile high-power supercritical media plasma switch with pressure up to 250 bar is explained. Integrated charging capacitor, adjustable heavy duty electrodes, and imbedded current and voltage sensor ensure the multi functionality of the supercritical media plasma
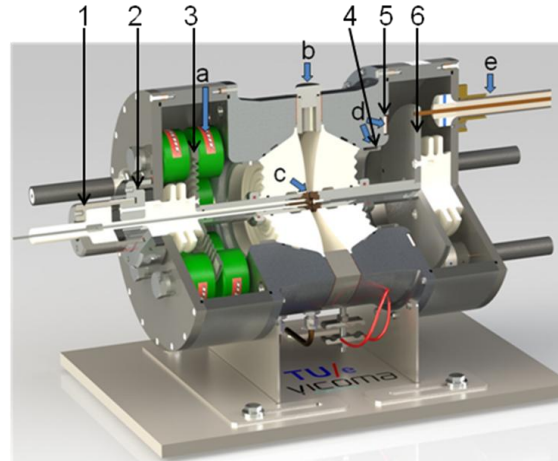

Fig. 8. Versatile supercritical medium switch and the schematic of its setup a. integrated capacitor; b. optical sight plug; c. adjustable gap width; d. embedded voltage and current sensor; e. 4-srtage TLT voltage amplifier; 1. Adjusting knob for trigger electrode; 2. Adjusting knob for main electrode; 3. flexible aluminum disk for gap width adjustment; 4. Rogowski coil; 5. Copper plate for voltage sensor; 6. Stainless steel plate for voltage sensor.
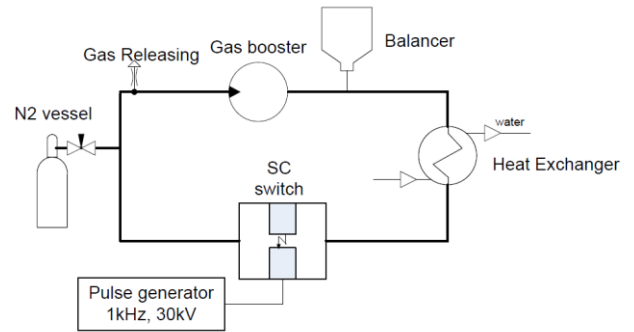

Fig. 9. Schematic of experiment setup for Versatile supercritical medium switch.

switch. Figure 8 shows the design of this versatile supercritical switch. The capacitors are discharged via the corrugated aluminum disk 3, to the high voltage electrode. Through applying force to disk 3 via tuning the knob 1, disk 3 can be bended, to accomplish the movement of high voltage main electrode, adjusting the main gap width. The trigger electrode is adjusted by tuning knob 2, so as to keep it being aligned with the high voltage main electrode. One Rogowski coil 4 is mounted in the housing of the SC switch, to detect the current flowing through the grounded electrode, as well as to shape the electrical field a Semi-rigid coaxial cable is soldered to the

Rogowski coil and transmits current measurement to the oscilloscope. A copper plate 5 is embedded to the housing of SC switch, forming a capacitive voltage sensor together with the stainless steel plate 6 integrated with grounded electrode. A semi-rigid cable is installed, to transmit the voltage measurement. Figure 9 illustrates a schematic of SCF loop for this supercritical switch. Supercritical nitrogen is supplied from a nitrogen cylinder. The pressure of supercritical nitrogen is amplified to 250 bar via an air driven gas booster pump. A balancing tube is connected to the loop, to smooth the pressure fluctuation caused by the pulsing operation of the pump and keep the SCF pressure more constant. One heat exchanger (water cooling) is applied to cool down the supercritical nitrogen coming out of gas booster pump. High pressure flow meter(flow rate 0.5-700 L/h) is installed before the SC switch. Two pressure gauges up to 250 bar are mounted before and behind the SC switch respectively, to evaluate the supercritical nitrogen pressure inside the SC switch. ¼ inch diameter high pressure tubes connect all the elements together, forming a closed SCF loop for the fluid supply of SC switch. The power source for the SC switch is realized by modifying the 30 kV, 1 kHz voltage source introduced in section 2. In the experiment in the future, a 10 kHz, 40 kV pulsed voltage source could also be used as the power source of the SC switch, which allows recovery rate analysis of the switch under repetitive voltage source.

VI. Conclusions

In this work thermodynamic state of Supercritical nitrogen is introduced via the calculation of state equation of nitrogen. A simplified equation of state of nitrogen in limited range is applied. Experiments on supercritical switching in both resistive and resonant charging circuit setups are processed. Breakdown voltages of supercritical nitrogen are analyzed by experiment and compared with predicted values of Paschen's law. Breakdown voltage inside supercritical nitrogen increases with higher pressure, and tends to saturate under higher pressure. Scattering of breakdown voltage constricts around critical fluid pressure. Under certain pressure the breakdown voltage of SC switch increases with larger gap width. Deviation of breakdown voltage from Paschen's curve in supercritical nitrogen appears at larger product of pressure and gap width. A new design of supercritical switch as well as its experimental setup is briefly introduced. This new design allows breakdown voltage and recovery rate evaluation of SCF under various parameter settings.

VII. References

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VIII. Biographies

J.(Jin) Zhang was born in Jiangsu, China, on December 12, 1985. She obtained her Bachelor of Science degree in thermal energy and dynamic engineering from Nanjing Normal University in Nanjing, China, in 2007. She graduated from RWTH-Aachen University in Aachen, Germany, as a Master of Science of electrical power engineering in 2010. In the same year, she started her Ph.D. program on exploring a new medium for high power pulse voltage switch in the Electrical Energy Systems (EES) group of the Electrical Engineering department at the Eindhoven University of Technology (TU/e), Eindhoven, the Netherlands.

E.J.M. (Bert) van Heesch was born in Utrecht, the Netherlands in 1951. He obtained a master's degree in Physics from Eindhoven University of Technology in 1975 and he has a Ph.D. in plasma physics and fusion related research from Utrecht University (1982). From 1975 till 1984 he was a researcher at the FOM-institute for Plasma Physics Rijnhuizen, the Netherlands. During 1978 he was a visiting researcher at the Fusion research facilities in Sukhumi former USSR. From 1984 till 1986 he did fusion related research at the University of Saskatchewan in Saskatoon, Canada. Since 1986 he is an assistant professor at the Eindhoven University of Technology. Here he is a key scientist in pulsed power research and pulsed plasma processing applications. He organizes projects with national and EU research agencies and industry. He is (co-) author of more than 200 international publications including more than 60 journal publications and 5 patents.

A.J.M. (Guus) Pemen was born in Breda, The Netherlands, in 1961. He recieved the B.Sc. degree in electrical engineering from the College of Advanced Technology, Breda, in 1986, and the Ph.D degree in electrical engineering from Eindhoven University of Technology, The Netherlands, in 2000. He worked for KEMA T&D Power in Arnhem, The Netherlands. He joined TU/e in 1998 as assistant professor, and his research interest includes high-voltage engineering, pulsed power and pulsed plasmas. Among his achievements are the development of an on-line monitoring system for partial discharges in turbine generators and a pulsed-corona tar cracker. He is the founder of the Dutch Generator Expertise-Centre.