Design Study on Ecological Accelerator

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Abstract

Design studies on high-power electron accelerator for flue gas treatment have been undertaken at the Soltan Institute for Nuclear Studies [1]. The development of the project is reported in the paper. Problems of reliability and risk of failures during continuous work as well as the protection methods are considered.

1. Introduction

The system, powered from 3-phase, 6 kV mains, consists of 6 kV and 12 kV distributors, 6 kV/1-12 kV regulating transformer, 800 kV/400 kW voltage unit and two 200 kW accelerating heads.

Voltage regulation is done by changing of stopped rotor position in relation to stator windings.

Voltage unit forms 20 - 30-stage magnetically-coupled cascaded bridge rectifier. The magnetic circuit is composed of three iron columns coupled together at the bottom and top by an iron yoke; the magnetic core is grounded. Primary windings are connected with delta configuration. Each secondary coil triplet feeds a three phase bridge rectifier. The power needed for supplying two electron guns is taken from two additional windings at - 800 kV potential level. SF_6 compressed gas and epoxy resin are used as the main insulation materials. The voltage and power are transmitted from supply unit to accelerating heads by means of h.v. cables or bus-ducts.

Accelerating head, insulated with SF_6, is composed from Pierce-type electron gun, electrostatic accelerating structure, focusing and scanning coils, scanning horn and output window with titanium foil.

2. Present State of the Project

The computer simulation and experimental verification of results in the tests of simplified models were taken as a general rule of design process.

Following phenomena were numerically investigated:

- transient states in the circuit of supply unit and accelerating head especially in the case of failures,
- electric fields in the supply unit insulating system,
- electric fields of bus-duct configuration,
- electric fields and electron trajectories in the electron gun area taking into account the space charge forces,
- potential fields, electron trajectories, charge and current densities in electrostatic multigap accelerating structure taking into consideration the transverse component of space charge,
- focusing of the beam by solenoidal magnetic field,
- heat transient states and temperature distribution in the titanium window during thermal loading by electron beam with regard to scanning frequencies, electron beam size, shape of the current impulses in the scanning coils and the air cooling coefficient.

To carry out the experimental verification the test stands and models were built:

- direct, alternating and impulse voltage test stands for testing of coil models, rectifiers, busducts, varistors and protective spark-gaps,
- test stand for testing of electron gun, transmission of electron beam through the tube segment, scanning system and extraction window,
- test stand for measuring of the influence of output window and air blowing parameters on the cooling coefficient,
- model of a multiplying section of the supply unit,
- model of a bus-duct insulated with SF6 and epoxy resin,
- model of an electron gun with LaB6 and pyrolytic graphite,
- model of an accelerator tube segment with shielding electrodes,
- model of the output system including scanning circuits and coils, scanning horn, titanium window and manifold for air blowing.

3. Operational Reliability

3.1. *Reasons of failures*

The main requirement on an industrial accelerator is the operational reliability. The most dangerous failures can be caused by electrical breakdown:

- on the insulating surface or across the accelerator tube in vacuum,
- of the cable heads,
- in the SF6 gas between the elements under HV potential and the vessel.

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The breakdown of the accelerating tube can deteriorate the tube properties and even damage it due to the energy dissipation in the tube resistance. Fast transients can be initiated by the all mentioned breakdown types resulting in overvoltages and overcurrents on the elements of the circuit. Those can cause the failure of HV diodes and coils. Diode catalogues do not contain data concerning the breakdown voltage and overcurrent resistance at voltage pulses with fast rise time. To complete these data avalanche diodes from several manufacturers were tested using HV pulses with rise time from about 30 - 40 ns. It was found that in the best cases the destructive voltage did not exceed 1.2 time the avalanche voltage given in data sheet even when rather large resistors were connected in series. The tested diodes were resistant against overcurrents. For example a diode with nominal current 0.4 A and breakdown voltage 80 kV withstood a series of 200 pulses with 10 kA crest value, 1 μs duration time, one pulse every 2 minutes dissipating about 75 J. Investigations of HV coils using series of HV pulses with 40 ns rise time shown that the breakdown strength exceeding several times the nominal voltage can be achieved in the case of proper insulation system and design.

3.2. *Numerical simulation*

Numerical calculations have been performed to estimate the hazards of overvoltages and overcurrents in the circuit. To start the calculations from the breakdown of the accelerating tube it was necessary to assume the dependence of breakdown channel resistance versus time or versus time and current. Resistance of a surface discharge in vacuum can be expressed by formula:

$$R(t)=R_{ik}-(R_{ik}-R_{ip})^{-t/T} \tag{1}$$

where R_{ik} represent the end value, R_{ip} the start value of resistance and T the time constant.

Resistance of a discharge between electrodes in vacuum was calculated from Rompe-Weizel expression:

$$R(t)=\frac{s}{\left[2(a)\int_0^t i^2 dt\right]^{1/2}} \tag{2}$$

where s - is the distance between electrodes, a - constant, i the current passing between electrodes.

The characteristics of resistance vs time during the discharge in vacuum were measured. In accordance with these measurements T = 3 ns and R_{ik} = 0.3 Ω for surface discharge and a = 0.001 $V^{-2}s^{-1}cm^{2}$ for discharge between electrodes were assumed in computations.

For preliminary computations of energy dissipation during the breakdown of the accelerating tube simplified circuit scheme shown in Fig. 1 was applied.

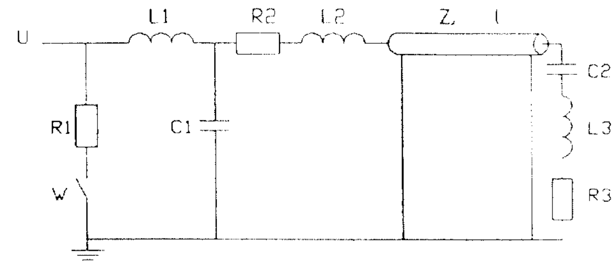

Fig. 1 Scheme of simplified circuit

Following denotations were used:
L2, L3 - inductance of the cable heads, L1 - inductance of discharge across the tube, R1 - time dependent resistance of the discharge, R2 - matching resistance, R3, C2 - equivalent resistance and capacitance of the supply system, Z, l - impedance and length of the cable line.

A scheme with a multipole shown in Fig. 2 was built to study the transients.

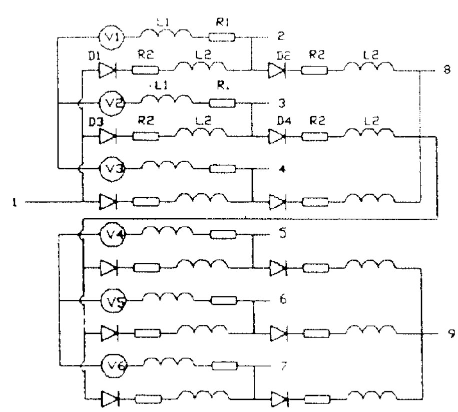

Fig. 2 Scheme of multipole

The multipole represents one stage of the voltage multiplying system of the supply unit and is utilized to create a diagram of equivalent circuit of the system shown in Fig. 3.

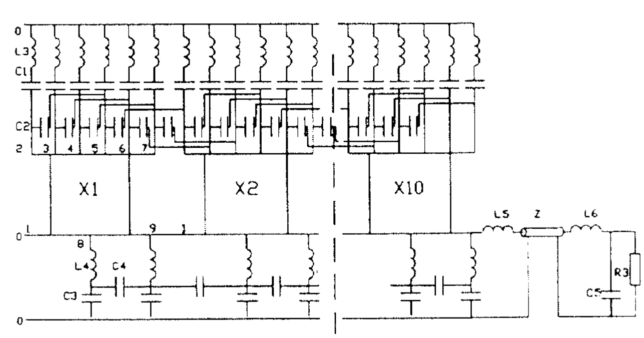

Fig. 3 Equivalent circuit of the system with multipoles X from Fig. 2

The symbols used in Fig.3 and 4 represent:
V1...V6 - EMF, properly shifted in phase, L1, R1 - inductance and resistance of the HV coil, D - avalanche diodes, L2, R2 - inductance and resistance in diode branch, L3 - inductance of the branch from HV coil to the earth, L4 - inductance of the ring-shaped screens, L5, L6 - inductances of the cable heads, C1 - input capacitance of the HV coil, C2 - capacitance between HV coils in the same phase, C3 - capacitance from the screen to the earth, C4 - capacitance between screens, C5 - input capacitance of the accelerating tube, Z - impedance and length of cable line, R3 - load resistance.

The results of computations can be summarized as follows:

- in certain cases a considerable portion of energy stored in the cable is dissipated in the accelerator tube during collapse,
- the overvoltages on the diodes exceed 4.5 times the working voltage,
- the rise time of the overvoltage is about 40 ns,
- the currents in the diode branches reach a crest value of about 2 kA.

4. PROTECTION METHODS

To diminish the energy dissipation in the accelerating tube a matching resistor should be installed between the cable head and the tube. The influence of this resistor on the diminishing of dissipated energy is more significant in the case of surface discharge as in the case of discharge between electrodes (see Fig.4 and 5). Effort was made also to decrease the amount of energy dissipated inside the tube by means of protection spark-gaps installed outside the tube in surrounding gas.

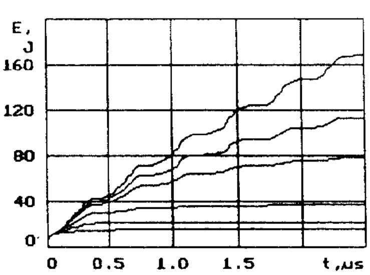

Fig.4 Energy dissipated in the tube, surface discharge, matching resistance from bottom: 100, 39.5, 15, 5, 2.5, 0.5 Ω

Metal-oxide varistors were considered to protect the diodes and coils against overvoltages. Since, the characteristics of varistor residual voltage as the function of the current surge rise-time in the range from 40 to 1000 ns were not known, investigations were undertaken to complete them. Protection characteristics were elaborated assuming that the protection coefficient $K = V_r/0.8V_{min}$, where V_r - residual voltage at given current surge rise-time and V_{min} - minimal non-conduction voltage.

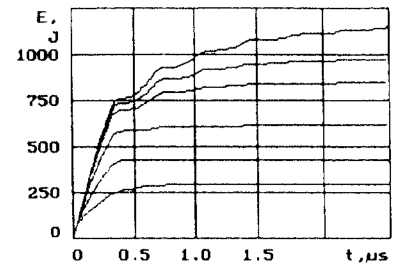

Fig. 5 Energy dissipated in the tube, discharge between the electrodes, matching resistor values as in Fig. 4

It was found that the protection coefficient depends on the current surge rise-time and on the current surge crest value. For example at 50 ns rise-time the coefficient changes from 3.8 at 0.2 kA to about 7 at 6 kA. Better results have been obtained during tests of an irradiated spark-gap with homogenous field (see Fig.6).

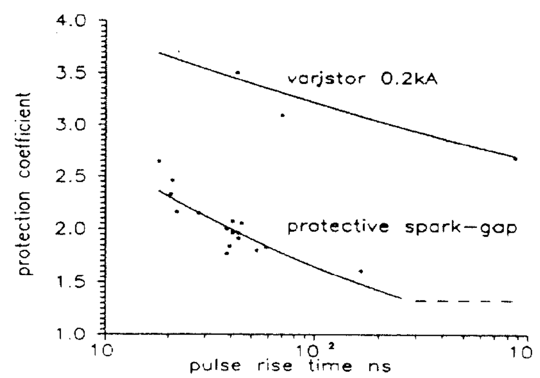

Fig. 6 Comparison of varistor and spark-gap protection coefficient characteristics

5. REFERENCES

[1] W. Drabik, J. Bigolas, J. Janiczek, R. Kiełsznia, Proc. of the 3rd Europ. Particle Accelerator Conf. Berlin, 1992, p.1718 - 11720