GENERATION AND MEASUREMENT OF AUDIO FREQUENCY POWER FOR CHEMICAL-ELECTRICAL DISCHARGE PROCESSES

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In developing equipment for use in high voltage, high frequency chemical-electrical processing, we have built a number of different types of "corona" power supplies. At the start, from the standpoint of the electrical equipment, let us use "corona" in its broadest sense. We will define a "corona" discharge as an electric discharge produced by capacitively exciting a gaseous medium lying between two spaced electrodes, at least one of which is insulated from the gaseous medium by a dielectric barrier. A corona discharge may be maintained over wide ranges of pressure and frequency, although atmospheric pressure and frequencies in the audio range substantially above power transmission values are typically employed.

Since the power which can be dissipated in a corona reactor or cell is a function of the supply frequency, we have settled arbitrarily on the audio range (3,000 to 10,000 cycles per second) as a desirable compromise. It is within the limits of rotating machinery and solid state components, presents no undue corona reactor heat dissipation problems, and provides a happy compromise between operating voltages, reactor size, and economy of operation.

The ratings for the basic electrical components are dependent upon the characteristics of the corona reactor and the impedance load which it represents to the power supply. Corona reactor values which affect these ratings are:

a. The corona power required
b. The electrode corona power density and, thereby, the electrode cooling or heat dissipation capability
c. The gaseous atmosphere present
d. The gaseous gap spacing
e. The barrier material and dielectric constant

From these values we can determine:

a. Peak voltage required to initiate corona
b. Barrier thickness required to withstand the total voltage across the barrier in the event of an arc across the gap
c. Barrier, gaseous gap, and total reactor capacitance
d. Maximum operating voltage
e. Capacitive charging, or displacement, current drawn by the reactor
f. Corona resistive current
g. Resultant load current
h. Power factor of the corona reactor load

The objectives which we attempted to meet in the design of our equipment were:

a. Suitability for use with a wide variety of corona reactors
b. Operation over a wide range of breakdown voltages
c. Flexibility over a wide range of operating conditions
d. Maximum electrical efficiency
e. Trouble-free operation and minimum maintenance over long periods of operation

Among the types of equipment built were the inductor-alternator with step-up transformer and parallel-resonant tuned circuit, the SCR inverter with step-up transformer, and the mobile vacuum tube high power-amplifier.

Motor-Alternator Set

A typical power supply based on rotating equipment consists of the following major components: an inductor-alternator, by means of which 60 cycle power is converted to 10,000 cycles, at 500 volts. This output is fed to the primary of a high voltage, high frequency transformer rated for 25 or 50 KV at 10,000 cycles. The output of this transformer is fed, in turn, to a parallel resonant tuned circuit, the discharge reactor, and the high voltage instrumentation.

The KVA rating of the M-G Set (inductor-alternator) is determined by the product of the corona operating voltage and the resultant load current (or the corona power divided by the power factor). Since the corona power generated in a gaseous gap in series with a dielectric is directly proportional to frequency, and the upper limit for frequency for commercially available rotating equipment is about 10,000 cycles per second, this has generally been considered the optimum frequency. Also, the use of lower frequencies would require higher voltages or increased corona reactor capacitance for any given power level. The output voltage of the alternator can be any value consistent with usual generator practice and with the transformer primary voltage.

The KVA rating of the transformer will usually be the same as that of the inductor-alternator. Its secondary voltage will be determined by the corona reactor requirements for voltage breakdown of the gaseous gap. Secondary or load current will be the vector sum of charging, or displacement, current and resistive, or corona, current. Primary voltage must be consistent with alternator output voltage. If experimental flexibility is required, the transformer primary should be arranged for series-parallel connection.

The corona reactor represents a capacitive load on the major items of the power supply equipment, up to the time of corona initiation. Since this generally results in a poor power factor, there are two possible means of solution:

a. The motor-alternator set must be built with sufficient KVA capacity to meet the power factor and corona power requirements.

b. The transformer secondary and the corona reactor can be tuned with a parallel resonant circuit consisting of a choke and high voltage, vacuum capacitors. This provides power-factor correction so that the high voltage transformer secondary sees mainly the resistive load represented by the corona power.

The parallel-resonant circuit must be tuned to give maximum transformer output voltage for some arbitrarily selected value of alternator field current. With a 0.16 henry choke, for example, the capacitance required for tuning at 10,000 cycles can be found from the expression

$$f = \frac{1}{2\pi\sqrt{LC}}, \text{ or } C = \frac{1}{4\pi^2 f^2 L} \cong 1580 \text{ picofarads}$$

However, this value is reduced by the capacitance of the discharge reactor itself, by that of any instrumentation voltage dividers, and by stray capacitances, so that the actual tuning capacitance used is somewhat lower and must be determined experimentally.

The decision as to whether the motor-alternator should be built with increased KVA capacity or whether the secondary circuit should be tuned depends on the experimental versatility required, and on economic considerations. In general, the dollars per KVA for high frequency motor-alternator sets are considerably higher than for tuning circuit components.

An alternator field-control chassis supplies and regulates the current for the alternator field windings, and has a feedback system designed to meet varying conditions of high voltage output. Alternator output voltage and, thus, transformer high voltage are raised and lowered by changing alternator field current. A magnetic amplifier stabilizer circuit maintains constant high voltage output. In the event of a decrease in high voltage, it calls for an increase in alternator field current, with a corresponding output voltage increase.

Control devices and instrumentation for a corona power supply based on rotating equipment includes at least the following:

a. Provision for varying the transformer output high voltage from zero to maximum by varying alternator field current, and a means of measuring the field current.

b. Provision for measuring transformer primary voltage, current, and power.

c. Provision for measuring the peak voltage applied to the corona reactor.

d. Provision for measuring the power dissipated in the corona reactor.

e. Some form of protective current overload relay, for removing high voltage from the corona reactor in the event of a short circuit in the reactor, or a low voltage, high current arc

between the electrodes. This will prevent exceeding the current rating of the transformer secondary.

Since the use of this equipment involves working with high voltage. the control circuit includes provision for test area safety interlocks and flasher-warning lights.

Inverter

The solid state corona generator consists of a 3,000 cycle inverter utilizing silicon controlled rectifiers feeding a step-up transformer. A rectifier is a device or circuit for changing alternating current to direct-current. The inverter may be thought of as a rectifier operating in reverse, changing d-c to a-c. A combination of the two achieves a change from 60 cycle a-c to approximately 3,000 cycle a-c.

Rectifier circuits occur in several configurations such as half-wave, full wave, bridge, etc. Inverter circuits may be grouped in a similar manner. The key feature of an SCR (silicon controlled rectifier) as used in an inverter circuit is that a small current from its "gate" element to the cathade can fire or trigger the SCR so that it changes from being an open circuit into being a rectifier.

The inverter operates from a single phase, 220 volt, 60 cycle source, and by means of a full-wave bridge rectifier, rectifies it to 187 volts d-c which in turn is changed to 150 volts, 3,000 cycles, approximate sine wave through SCR's. Variac control of the 220 volt input provides a variable supply output.

The inverter output is fed to a step-up transformer delivering up to 12,000 volts rms. This transformer is a dry type, potted with RTV, with integral high voltage terminals. The particular transformer used was built as a compromise between low cost, size, and electrical capability. Rated at 3 KVA, the transformer was only 6" x 6" x 7" high overall.

What is noteworthy with this equipment is that the inverter, transformer, and corona reactor are not independently operating components. The concentric cylinder corona reactor was so designed that its capacitance, reflected to the primary of the transformer, formed a part of the inverter LC circuit, as did the inductance of the high voltage transformer. The reactor gaseous gap conductance forms a part of the inverter load circuit.

Since this is an untuned high voltage circuit, the inverter and the transformer were designed to carry the power factor loss current.

Advantages of the inverter supply over the motor-alternator is the absence of moving parts, ease of mounting and installation, and the "module" or building block concept whereby units can be stacked to increase voltage and current capability.

Vaccum-Tube Amplifier

The mobile corona generating equipment was designed for operation over a wide range of frequency and voltage. Corona power is generated by a vacuum tube, high-power amplifier driven by a stable low-power, audio-frequency sine-wave oscillator. Power is taken from the secondary winding of a high-voltage step-up transformer, with one end at ground potential.

The corona output voltage may be varied from zero to 50,000 volts, depending on the impedance of the applied load, and on the settings of the frequency and amplitude controls located on the master sine-wave oscillator panel. The frequency of the output voltage is determined by the master oscillator and is independent of load impedance or output voltage level. The frequency may be varied instantaneously between the rated limits of 3 to 10 kilocycles per second.

The a-c power from the 60 cps line is converted into the high voltage variable frequency output as follows:

A master oscillator feeds a driver amplifier. This is turn drives a tetrode power amplifier stage and the output step-up transformer. A d-c plate supply source, a screen grid voltage supply, a control grid bias supply, and an a-c filament supply feed power at appropriate voltage levels to the tetrode amplifier stage. The power line control circuitry incorporates on-off switching, circuit breakers, and starting contactors for the power amplifier supplies.

Power amplification is produced by four tetrode vacuum tubes connected in pushpull-parallel as a Class AB_2 amplifier. Control of the master audio oscillator signal amplitude is provided by a potentiometer on the master control panel. The output voltage of the equipment may be reduced to zero even when full voltage is applied to the plates of the power tetrodes.

Power delivered by the tetrodes to the output transformer, and thence to the corona reactor load, is controlled by the oscillator and the variable autotransformer in the tetrode plate power supply. The autotransformer control keeps the total power consumed by the equipment during an experiment as low as possible, to minimize heat developed in the cabinet and to extend tube life.

The corona cell impedance, which is mainly capacitive before corona breakdown, acquires a resistive component after breakdown which depends on the rate of production of ionized and electrically conducting chemical entities. The a-c voltage at the plates of the power tetrodes will lag the plate current by a large angle before power is consumed, and the plate current will be collected at a high rather than a low value of plate voltage. Thus, the power dissipated by the tetrodes will be high under no-load conditions.

The high voltage transformer has an effective primary to secondary step-up ratio of 11 to 1. The maximum a-c current that can be drawn from the secondary winding of the transformer is 60 milliamperes rms.

Reactor

The corona reactor or cell represents a capacitive load to the power supply equipment up to the time of initiation of the electrical discharge. The total reactor capacitance consists of the series combination of dielectric barrier and gaseous gap capacitance. The voltages appearing across the barrier and the gap divide inversely as their capacitance.

Before corona starts, the reactor current consists of the charging, or displacement, current which is proportional to the applied voltage, frequency, and cell capacitance. After the start of corona, the cell acts as an impedance load consisting of a conductance across the gaseous gap, in addition to the gap capacitance. The total current drawn by the reactor then is the vector sum of charging plus resistive currents.

If the corona reactor power supply has a tuned circuit in the transformer high voltage secondary, for power factor correction, the corona reactor capacitance functions as part of the tuning capacitance, and the reactor charging current is a part of the circulating current in the parallel resonant circuit. The total load current through the transformer secondary winding then consists chiefly of corona current plus whatever capacitive current might be present as a result of tuning unbalance.

If the power supply is untuned, the total power available for chemical processing is the product of supply volt-amperes times the power factor of the load, and in this case transformer secondary winding must carry the full reactor impedance current.

The dielectric barrier in the corona reactor serves as a built-in current-limiting device, or ballast in the event of a short circuit or arc between the cell electrodes, so that the stored energy is dissipated in the barrier at breakdown.

The maximum power density at which a corona reactor can be operated without puncturing the barrier is a function of the dielectric strength of the barrier material, the total thickness of the barrier, the ambient temperature in which it is operated, and the gap spacing between barriers. The dielectric constant of the barrier affects both the voltage gradient across the barrier, and the corona power which can be dissipated in the reactor. The dissipation factor is a measure of the electric losses which produce heating of the barrier.

The voltage at which breakdown will occur between a set of electrodes in a corona reactor depends upon the gaseous atmosphere present, the density (pressure, temperature) of the gas between the electrodes, and the gap length.

The corona power dissipated in a gaseous gap in series with one or more dielectric barriers can be calculated from the expression

$$P = 4f\, C_b\, V_{gas}\, (V_{max} - \frac{C_{gas}}{C_t}\, V_{gas}), \text{ where}$$

P = Corona power in watts

f = Power supply frequency in cycles/second

C_b = Dielectric barrier capacitance

C_{gas} = Capacitance of corona cell gas gap

C_t = Total corona cell capacitance

V_{gas} = Peak voltage across the gaseous gap at the time of corona initiation

V_{max} = Total operating voltage applied to the corona cell

This can be re-written as:

$P = 4f\ C_b\ V_{gas}\ (V_{max} - V_t)$, where

$V_t = \frac{C_{gas}}{C_t}\ V_{gas}$ = voltage across the corona cell at the instant of corona initiation

An item of concern to all, in evaluating an experiment, or in scaling up for pilot plant operation, is the electrical efficiency of a process. Care must be taken not to confuse equipment power factor with what might be called "electrical efficiency of conversion", though both may contribute to the same end result. Power factor relates to ability to convert equipment input volt-amperes (not necessarily in phase) to available chemical-result-producing "watts". This is a function of electrical equipment and electrical circuit design.

"Electrical efficiency of conversion" may be considered as the effectiveness in utilizing all or most of the available wattage in the corona reactor. This is a function of reactor design, with particular emphasis on relative barrier and gap capacitance and gap spacing. As a matter of practical design, the cell geometry and gap spacing present limits to the power which can be dissipated in any given cell.

Power Measurement

The power consumed in the discharge cell is determined by means of the parallelogram-oscilloscope technique which shows the relationship between the voltage on the cell electrodes at any instant, and the charge flow in the circuit up to that instant. Before corona initiation, the corona null value is seen on the oscilloscope as a closed figure, or slant line. With the initiation of the electrical discharge, the figure opens up into a parallelogram, and the discharge power is represented by the area of the parallelogram.

The bridge circuit for power measurement consists of two branches between the high voltage terminal of the reactor and ground, called "Voltage" and "Charge". The "Voltage" branch consists of a capacitance

voltage divider giving an approximate 10^4 to 1 voltage division. The "Charge" branch consists of the corona reactor in series with some value of capacitance such that a voltage division of 10^4 or 10^3 to 1 will be obtained across the divider. The outputs from the low voltage ends of these dividers are fed to the X and Y axes of the oscilloscope. A variable potentiometer across the lower end of the "Charge" divider provides phase shift control to bring the "Voltage" and "Charge" branch outputs into phase for a null reading on the scope.

It should be noted that two signals, of equal amplitude, in phase, fed to the X and Y axes of a scope, give a 45-degree line on the scope. Any variation of relative amplitude shifts the angle of the line.

The area of the parallelogram represents the total power dissipated in the cell when the parallelogram bridge circuit and the oscilloscope are calibrated in the following manner:

The X-axis deflection is calibrated with a peak reading voltmeter so that reactor voltage (peak-to-peak) is presented as volts per cm of scope deflection.

The Y-axis deflection is calibrated with the known value of capacitance in the grounded end of the "Charge" branch so that the charge flowing through the reactor is presented as coulombs per cm of scope deflection.

The X - Y product, then, is:

$$\left(\frac{\text{volts}}{\text{cm}}\right)\left(\frac{\text{coulombs}}{\text{cm}}\right) = \frac{\text{volts - coulombs}}{\text{cm}^2}, \quad \text{or} \quad \frac{\text{watt-seconds}}{\text{cm}^2}$$

Since this is the energy per cm^2 in one cycle, the power per cm^2 of parallelogram area is obtained by multiplying the energy per cycle by the frequency in reciprocal seconds. The parallelogram area can be determined by planimeter measurement of a polaroid picture, or by direct measurement.

With a dual beam oscilloscope it is also possible to view the voltage and charge waveforms simultaneously.