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FLYWHEEL-POWERED X-RAY GENERATOR

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ABSTRACT

In order to have stop-action image quality of radiographs, high instantaneous power levels are required. When medical x-ray systems are installed in hospitals, three-phase power lines can provide power levels in excess of 100 kWp to meet this need. Mobile x-ray systems or systems for field use are limited by their power sources. Presently available power sources for these applications include: ninety volt nickel-cadmium batteries capable of 120 amperes, 220 vac power lines capable of pulse currents of 100 amperes, capacitor discharge systems using a 1.0 μF capacitor charged up to 100 kV or the use of a large electrolytic capacitor of 0.3 F charged to 330 V and discharged through a regulator-inverter circuit. In each case, instantaneous power is usually limited to 10 kWp or has some other energy restriction. In the case of the 1.0 μF system, the restriction is due to the drop of x-ray tube anode voltage during the x-ray exposure. The single phase 220 vac power line generates a non-constant voltage at the anode which is about 60% effective in producing x-rays as the more constant voltage of a three phase rectifier or of a filtered inverter. Electrolytic capacitors have other technical problems of rate limitations, fall-off during the output cycle, large size and internal heating. The use of a small flywheel appears to be a practical alternative to these power sources for mobile x-ray system applications. A 5 kg flywheel has been constructed which runs at 10 krpm and stores 30 kJ while requiring less than 500 W to bring the system up to speed. The wheel is coupled to an aircraft alternator and can yield pulsed power levels over 50 kWp. The aircraft alternator has the advantage of high frequency output which has also permitted the design of smaller high voltage transformers. A series of optical sensors detecting shaft position function as an electronic commutator so that the alternator may operate as a motor to bring the wheel up to operating speed. The system permits the generation of extremely powerful x-rays from a variety of low power sources such as household power outlets, automobile batteries or sources of poorly regulated electrical power such as those found in third world countries.

INTRODUCTION

One of the main problems in the design of mobile x-ray generators is that of obtaining the very high power levels to allow high exposure rates and short exposure times. Power lines for use by mobile systems are often limited in output or have varying line resistance so that constant output voltage cannot be assured. Storage battery power sources are also resistance limited: practical constraints of size and weight limit instantaneous power levels to about 10 kWp. The battery power is converted to high frequency alternating voltage and fed to a step-up transformer, rectified and fed to the x-ray tube. Newer systems are improved over older systems by using even larger batteries and weigh over 350 kg. They are difficult to move to the patient site except by means of motor-assisted drives (a further drain on the batteries). Real improvements may come with some new developments in the design of storage batteries. The use of a very large electrolytic capacitor feeding a commutating regulator and high frequency inverter has promise of providing the power needed but is presently limited by peak current ratings of the capacitor, internal heating of the capacitor, size and other circuit limitations to power levels of about 10 kWp. Using high voltage capacitors for storage of the actual tube anode voltage and gating the tube anode current by tube grid control have a rather severe and subtle limitation. Such circuits operate in a way similar to an electronic flash used for photography. In the flash, energy discharged through the flash tube is converted to light for as long as the gas remains ionized. In the x-ray tube, the x-ray photon energy distribution is related to the instantaneous anode voltage. As the capacitor discharges, the voltage falls and the x-ray beam energy also falls. Lower beam energies are less penetrating, cause less film darkening and produce undesirable radiation effects on the patient.

Operation of these types of mobile x-ray generators is still marginal when high power levels and proper beam energy distribution are required for stop-motion images at low exposure levels to the patient. The 90 volt battery-powered machines at 10 kWp will draw about 140 amp, if we assume 80% efficiency. These batteries are quite heavy. Single phase line-powered systems operating at 100 kVp and 200 mA will draw more than 100 amps from a 220 vac power line. Operation from the common 115 vac line is obviously precluded by the 2 kW limit of such lines. Even though the input power to the x-ray tube is about 20 kWp, the waveform of the anode voltage reduces the actual x-ray output to almost the same level as that produced by constant potential power of 10 kWp. Power lines rated at peak current levels of 100 amps and 220 vac can be wired in hospitals and factories but are not usually found in the field. Small and portable 60 Hz power generators are usually rated at peak power levels of 5 kW or less. The capacitor discharge machine using a 1.0 μ F capacitor (actually 29 2.0 μ F capacitors in series, one at the anode and one at the cathode of the x-ray tube) will drop 1 kV for each 1 mA discharged at the capacitor. The capacitor can be charged at a low rate, well within the capability of the small power generator. Film darkening as a result of passage of x-ray photons through the patient is proportional to the 5th power of anode voltage. To compare the effective mAs of the capacitor discharge circuit to that of a constant potential generator, the voltage waveform of the linear discharge to the 5th power can be integrated from 100 kVp to 0 kVp:

$$\begin{aligned} \text{Eff. mA/s} &= 100 \int_0^1 (1-v)^5 dv \\ &= 17 \text{ mA/s} \end{aligned}$$

This can be interpreted as meaning that the total effective x-ray energy of a 1.0 μF system discharged to 0 KVp is less than 17 mAs of the energy produced by a constant potential machine. This low total energy is not sufficient for many diagnostic procedures. The capacitor discharge machine is limited to the radiography of the chest or the extremities and cannot take high-quality pictures of the abdomen or the head. Battery-powered or line-powered machines can take pictures of any body part but the power rating may require that the exposure time be increased and some image motion blur may occur. The use of very large electrolytic capacitors coupled to switching regulators and high-frequency inverters is a recent development. The switching regulators compensate for the falling voltage of the capacitor as charge is withdrawn to feed the inverter. Internal series resistance and effective inductance of the storage capacitor as well as size are limitations to this approach.

The study at the University of Wisconsin has shown that power levels in the 30 kWp range and above are achievable using a flywheel alternator system. While the use of a common shaft with the motor-alternator has not been successful, a simple spline (quill) coupling and separate suspension and bearings for the wheel assembly have resulted in a simple low-loss design of very high peak power capability.

FLYWHEEL ENERGY STORAGE

In the flywheel energy storage system the alternator is operated as a motor to bring the flywheel up to speed. The circuits are then switched back to the alternator mode and power is taken from the flywheel to drive the alternator with the field current of the alternator controlled to produce a particular constant potential at the anode of the x-ray tube despite changes of wheel angular velocity, tube current or other factors. The power ratio between alternator and motor modes can exceed 100. Figure 1 is a block diagram and shows the relationships between the major components of the system.

A standard 115 vac power source rated at about 1 kW provides power to the motor drive, to the various control circuits and to the rotor and filament circuits of the x-ray tube. The motor drive circuit is shown in Figure 2. The 115 vac is fed to a transformer and an SCR bridge to provide a voltage controlled to between 15 and 55 vdc which is then fed to a six step driver circuit. The switching control for the six step driver is obtained from three optical sensors (retro-reflective LED-transistors, sensing shaft position - a special form of a shaft position encoder.) The output of the three sensors is fed to a 32x8 ROM where the other two inputs are determined by a simple tachometer circuit.

Thus, the output of the ROM consists of the six step drive signals with four modes of phase shift as a function of shaft speed. Final speed control is done by controlling the power supply voltage by means of the SCR's.

Relays disconnect the motor-alternator from the drive circuit and connect it to the high tension transformer. The field excitation is used to control the output of the alternator during the exposure to set the voltage at the x-ray tube. Feed-forward control maintains this voltage at the pre-set value over the changes of rotor speed and the effects of the changes of excitation due to field reactance and other factors.

The flywheel is a 5 kg heat treated steel alloy 25 cm diameter disc spline coupled to a Bendix 28B262-35-B aircraft alternator. A second model is also under test using a Bendix 28B135-126-A aircraft alternator. These lightweight alternators are each rated at 20 kW with ram air cooling and are capable of short pulse loads in excess of 50 kWp. The run-up time is three minutes with a maximum line power requirement of 750 W. This will bring the wheel to 10 Krpm which corresponds to about 30 kJ of stored energy. Controlled output of over 25 kWp has been achieved.

MECHANICAL CONSIDERATIONS

The design of the system requires that the total energy be limited to that obtainable from the power line for a short period of time - less than three minutes. It must yield short bursts of power of less than one second duration. The mechanical coupling must be reasonably efficient for both motor and alternator modes. The power ratio between alternator and motor modes is quite high. Reasonable efficiency in the alternator mode results in unacceptable losses in the motor mode. For that reason, various gear and belt drives could not be used. The use of a differential gear arrangement to drive counter-rotating wheels was also discarded for that same reason. Mounting of the wheel directly on the alternator shaft resulted in a configuration that had resonant frequencies below the maximum operating frequencies (Hz vs rps) so that a separate wheel mounting with a spline coupling to the alternator shaft was used. The complete assembly can be considered as a series of coupled cylinders: the flywheel, the rotor, the shaft and the bearings. For such systems, the rotational energy E at angular velocity ω is:

$$E = 1/2 \sum_i I_i \omega^2$$

where I_i is the moment of the i th component. For a cylinder, I_i is given by:

$$I_i = 1/2 M_i R_i^2$$

where M_i is the mass and R_i is the radius of the i th component.

When power P is taken from the system, the reactive torque $T(t)$ can be found from:

$$P(t) = dE/dt = -\sum_i I_i \omega \, d\omega/dt = -T(t)\omega(t)$$

Increased ω will result in reduced reactive torque. The rate of change of torque during the x-ray exposure will be reduced with an increase of the initial stored energy. There are several practical limitations to increasing ω . These include rises in the material stresses, bearing stresses, the effects of imbalances and losses due to series reactance and other effects in the alternator.

The flywheel can be considered as a homogeneous disc of outer radius a and inner radius b . The maximum tangential stress, σ_{tmax} and the maximum radial stress σ_{rmax} are estimated:

$$\sigma_{tmax} = 1/4\rho\omega^2((3 + \nu)a^2 + (1 - \nu)b^2)$$

$$\sigma_{rmax} = ((3 + \nu)/8)(\rho\omega^2(a - b)^2)$$

where ρ is the material density, ω is the angular velocity and ν the Poisson ratio. For the 4340 steel plate used,

$$\rho = 7.8 \times 10 \text{ kg/m} \quad \text{and} \quad \nu = 0.25 \text{ to } 0.30$$

These estimates ignore localized effects due to machining and mounting. A safety factor of five times these estimates is reasonable and prudent. For the heat treated 4340 or similar steels, yield strengths of over 860 MN/m^2 are attainable with elongation sufficient for braking action of the wheel against a close-tolerance housing in the event of a material failure.

The use of conventional, high quality, grease lubricated bearings limits operation to about 18 m/s for steel caged bearings and to 24 m/s for phenolic caged bearings. Because of the need for a shaft diameter of sufficient stiffness and strength, a practical angular velocity is limited by the bearings to about 15 Krpm.

The requirements for stored energy, the limit of angular velocity and the safety factors chosen for steel are sufficient to define the dimensions of an annular disc flywheel (Fig.3). However, a dynamic system must consider vibrational modes as well. These include those due to rotor imbalance, obliquity of the disc, bearing mounting and shaft deflection. Vibrational modes include whirling and torsional and frame displacements of the system support. In this design, a separately supported flywheel was chosen over a single long shaft design because the short and stiff shaft would have a higher resonant frequency and better vibrational characteristics. The wheel was designed to store 30 kJ at 10 Krpm with a maximum stress of of 140 MN/m^2 . When dynamically balanced to within $2.8 \times 10 \text{ N-m}$, no resonant states (eigenvalues) are observed during operation.

ALTERNATOR CHARACTERISTICS

The mechanical characteristics of the wheel are within the range of operation of aircraft alternators. Such alternators are operated at between 8 and 12 krpm and certain models produce power at a continuous output rating of 20 kW with short time ratings of 50 kW. The power output frequency in the 400 Hz range permits the design of high voltage transformers smaller than are used in conventional 60 Hz x-ray systems. To design the control necessary to produce constant power during the high power transient operation, the alternator has been modelled as a salient pole machine of one pole pair. Transient operation requires that some form of anticipation or feed-forward control be used to overcome the inherent delays of the control windings (field reactance) in order to maintain constant output during the x-ray pulse.

MOTOR OPERATION

The alternator is operated as a motor by sensing wheel position and developing a six step drive. A tachometer circuit shifts the electrical lead angle as a function of speed and a start-up circuit limits starting current. The derivation of the six step drive (Fig. 4) and the phase shift is done by means of a 32 x 8 ROM fed by the position sensors and the 2 bit output of the tachometer circuit. The same circuit that limits the starting current also limits the operating current when a signal from the tachometer indicates that maximum operating speed has been reached.

ALTERNATOR CONTROL

The control of the alternator field is a feed-forward system of open loop control based on shaft speed and x-ray tube kVp and mA. It was found that the inductance of the rotor field was the main cause of the very slow response time (close to the short circuit response time of the alternator). For the short pulses of power required of the system, the exponential response characteristic can be compensated for by means of a step increase in the exciter current just prior to the actual application of the load. The system exposure timer and control circuits must accomplish several tasks: transfer operation of the alternator from the motor mode to generator mode, apply power to the rotating anode of the x-ray tube in anticipation of the x-ray exposure, boost the filament power of the x-ray tube to that required to produce the selected anode current, set the exciter current and wait until the operator signals the start of the exposure. When the actual exposure is required in this "ready" condition, the circuit applies the required step input to the exciter current, waits 50 ms and closes the power contactor to make the exposure for the selected pulse duration. The application of the step input assures that the output pulse will be constant during the x-ray exposure (Fig. 5).

CONCLUSION

The flywheel powered x-ray system has been constructed as described above. The total weight of the flywheel power source and control circuits is under 40 kg, far less than for comparable battery sources of lower power capability. The system has provided over 20 kWp of controlled power with levels of over 40 kWp expected as work continues. The simple approach of using the high speed, low torque wheel, the six step drive and the feed forward control appears to yield a practical solution to the problem of providing high power x-ray pulses of short duration for excellent stop-motion radiography.

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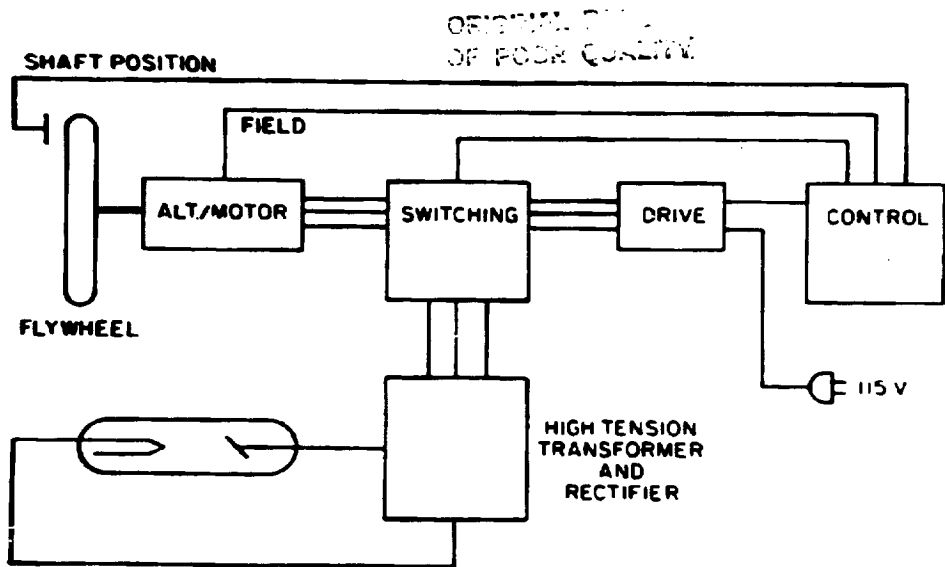


Figure 1. Block Diagram of the Flywheel-Powered X-Ray Generator.

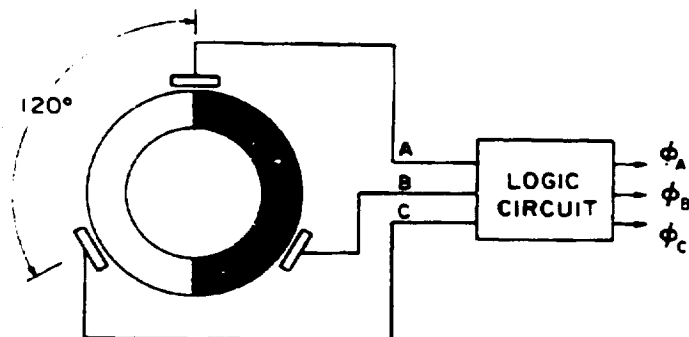


Figure 2. Diagram of Optical Commutator. In actual use, one black-white pair is used for each pole pair of the alternator-motor. Only three reflective sensors are used.

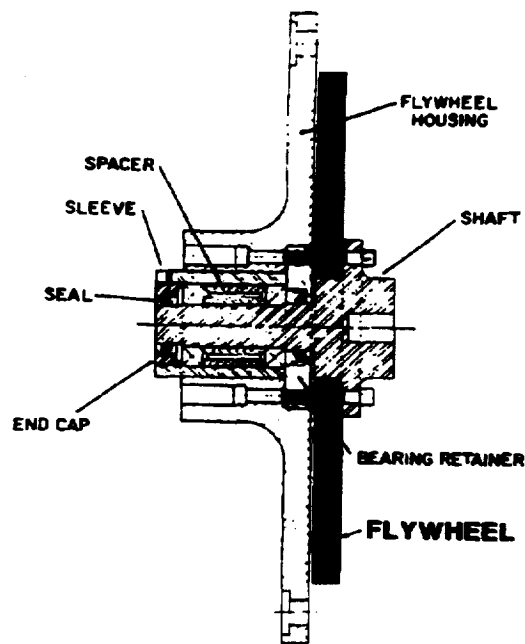


Figure 3. The Flywheel Assembly. To keep the resonance frequencies above the operating frequency, the wheel is mounted independently of the motor-alternator and is quill-coupled.

SIX STEP DRIVE SEQUENCE

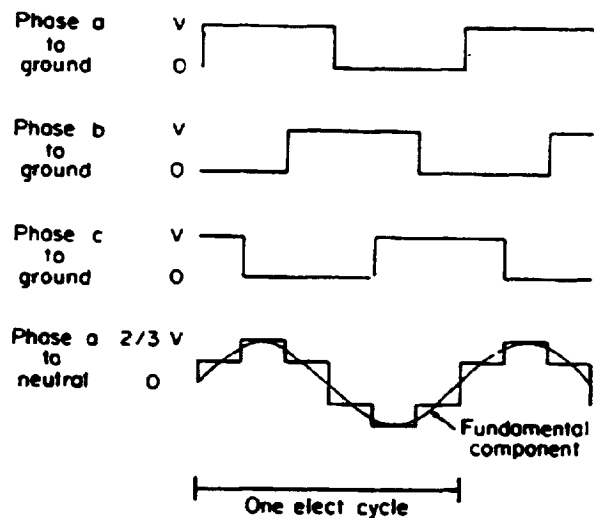


Figure 4. Six Step Drive. Because the alternator is Y-Connected, each drive signal adds within the motor. The three-phase drive is obtained by this summation.

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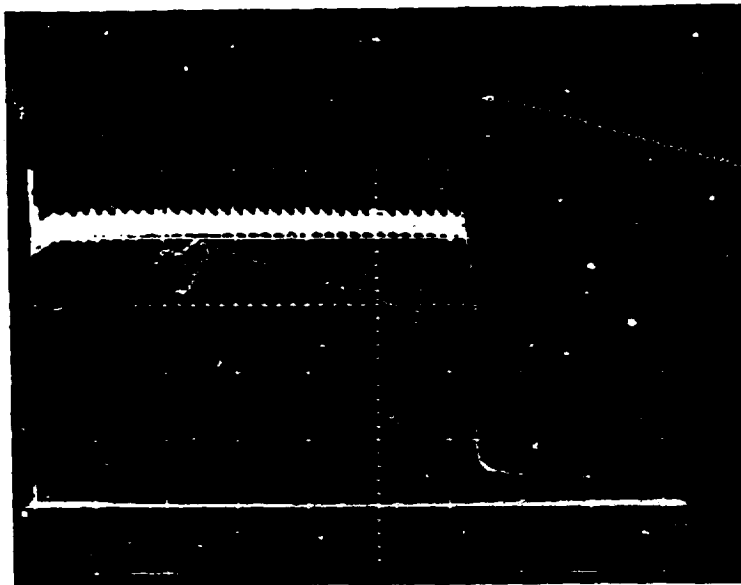
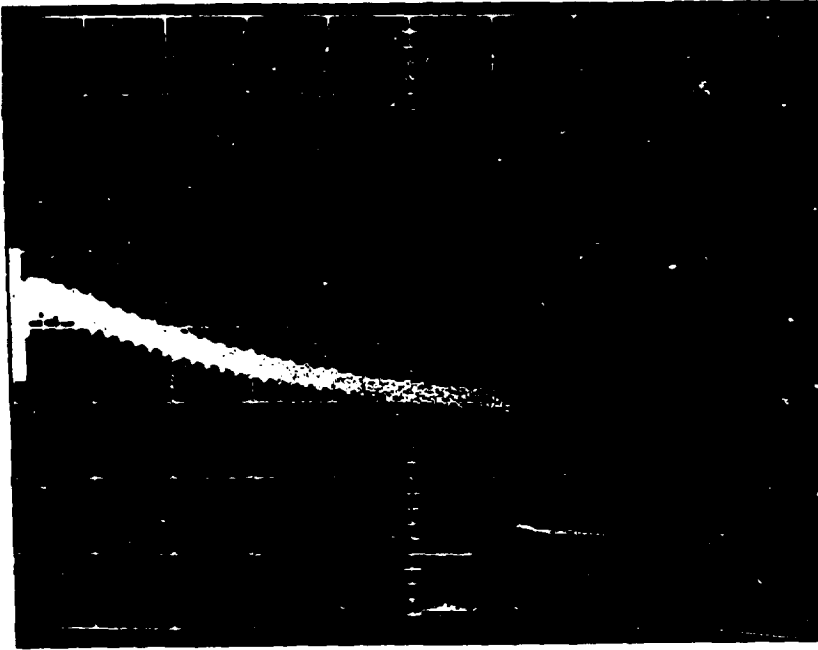


Figure 5. X-Ray Tube Anode Waveforms. Scale: 20 KVp/cm and 10 ms/cm. Tube current is 100 mA. The transient recovery time of the alternator is almost 0.25 sec., too long for x-ray applications. The use of feed-forward control corrects the output sag due to the short output pulse.