# APPLICATION OF POWER CONDITIONING TO HIGH-VOLTAGE DC ELECTRIC POWER SYSTEMS FOR FLIGHT VEHICLES

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## *ABSTRACT*

*This paper discusses the functions of power conditioning for application to a high-voltage dc electric power system. Sample load profiles of an SST-type aircraft are presented, and the power conditioning needs are outlined. Present and projected power levels of power conditioners for different high-voltage dc distribution systems are discussed. The characteristics of thyristor switches are reviewed, and the technology status of thyristor power conditioners is discussed. Two classes of thyristor power amplifiers are identified for application to the flight vehicle.*

## INTRODUCTION

High-voltage dc electric power systems are seriously being considered as candidate systems for future flight vehicles, since these systems appear to offer high reliability and light weight in power generation and distribution. In these systems, power conditioning performs the vital link of providing the matching interface between the power source and the individual load demands. These interface requirements include the electrical transformations required by the individual loads, while maintaining the static and dynamic stability of the entire electric power system.

The functions of power conditioning in HVDC electric power systems include line regulators, dc-to-dc converters, dc-to-ac inverters, and dc-to-ac motor drives. Line regulators maintain the voltage stability of the dc bus. Dc-to-dc converters function as dc transformers in that they process power from one dc level to another dc level. Dc-to-ac inverters process the dc input power into ac power for use with ac connected loads. Dc-to-ac motor drives are power controllers for driving brushless motors.

Power conditioners that must provide precise and efficient control of electric power, with the constraint of minimum size and weight, generally require solid-state switching techniques. The present technology, of the various power conditioners described, is relatively well advanced for applications to low input dc voltages and to low-power levels. This present technology almost exclusively, makes use of power transistor circuit techniques.

Because of the expected high power levels associated with HVDC electric power systems, power conditioners must be developed for high-power operation. The thyristor power semiconductor switch is ideally suited for this purpose, since it is a high-voltage, high-current device. Application of this device requires advancing the technology development of thyristor circuit techniques. The design philosophies and the circuit and component requirements must be established to achieve satisfactory power conditioners for HVDC electric power systems for flight vehicles.

## SYSTEMS CONSIDERATIONS

The functions of power conditioning in HVDC electric systems are illustrated in Figure 1. As shown in the figure, the power conditioners required are line regulators, dc-to-dc converters, dc-to-ac inverters, and motor drives. Line regulators maintain the voltage stability of the dc bus, and can, if necessary, provide decoupling from the dc bus. The dc-to-dc converters function as dc transformers in that they process power from one dc voltage level to another dc voltage level. The dc-to-ac inverters process the dc input power into ac power for application to the ac connected loads. The motor drives are special purpose inverters for driving brushless dc motors. The motor drive power conditioners can control the motors for any desired speed-torque loading. Variable speed control as well as constant speed control are possible through the motor drive power conditioner. Only a single block is shown for each power conditioning function. In practice, the choice is open to the systems designer to select from configurations shown in the figure to one where a power conditioning block exists for each load function. The possible configurations are many, since the power conditioner does provide the matching interface between power source and load demand. Also, there exist classes of loads capable of functioning directly from the high-voltage dc bus, thus requiring no power conditioning.

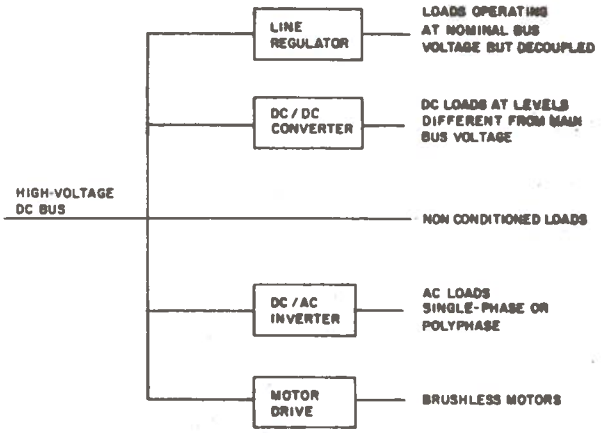

Figure 1.- Functions of Power Conditioning in HVDC Electric Power Systems

A typical load profile for a large commercial transport is shown in Table I (ref. 1). The table shows a sample SST load analysis. It is evident from this table that power conditioning is required for all loads, with the possible exception of the galleys and other heat loads. Examples of loads that would require either line regulator or dc/dc converter power conditioners are the electronics load and transformer/rectifier unit. An example of a load that would require the dc/ac inverter is the lighting load, particularly if fluorescent lighting is used. Loads requiring the motor drive power conditioners are the fuel pumps. Note that the fuel pumps represent the principle load demand. Motor drive power conditioning, therefore, represents one of the main entities for any high-voltage dc distribution system. Figure 2 (ref. 1), a plot of Table I, illustrates a sample SST load profile, showing load demand as a function of mission profile.

Power conditioners that must provide precise and efficient control of electric power, with the constraint of minimum size and weight, generally require solid-state switching techniques. At the present time, there exist two techniques for solid-state power conditioning, namely, transistor power conditioners and thyristor

TABLE I.- SAMPLE SST AC LOAD ANALYSIS LOADS IN KVA*

| Item | Conn Load | Engine Start | Taxi | Takeoff and Climb | Supersonic Cruise | Subsonic Cruise | Holding Pattern and Landing | Rollout | Taxi |
|---|---|---|---|---|---|---|---|---|---|
| Lighting | 25.2 | 13.3 | 14.2 | 15.0 | 13.0 | 14.0 | 15.9 | 15.9 | 14.0 |
| Electronics | 7.3 | 3.5 | 3.6 | 4.0 | 4.0 | 3.0 | 2.9 | 2.9 | 3.5 |
| Trans/Rect Unit | 6.4 | 1.3 | 2.0 | 2.1 | 2.6 | 2.4 | 2.1 | 2.1 | 2.1 |
| MUX, El, Throttle, Misc. | 9.5 | 7.7 | 6.5 | 7.1 | 7.1 | 6.7 | 6.5 | 6.5 | 6.5 |
| Lavatories | 5.2 | .2 | .2 | .2 | 2.2 | 2.2 | .4 | .4 | .4 |
| Elec. Equip, Racks and ADS Cool | 14.3 | 14.3 | 14.3 | 14.3 | ----- | ---- | 14.3 | 14.3 | 14.3 |
| Brake Cool | 16.0 | 16.0 | ----- | ----- | ----- | ---- | ---- | ---- | ---- |
| Windshield Heat | 7.7 | ---- | 5.8 | 5.8 | ----- | ---- | 5.8 | 5.8 | 5.8 |
| Fuel Pumps | 135.6 | 20.0 | 50.4 | 51.2 | 68.0 | 51.2 | 40.0 | 40.0 | 40.0 |
| Galleys | 20.4 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 5.0 | 5.0 | 5.0 |
| Demand on Power System (KVA) | ----- | 92.3 | 112.4 | 116.2 | 112.0 | 98.1 | 91.7 | 91.7 | 98.2 |

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*Sum of connected loads: 243 KVA

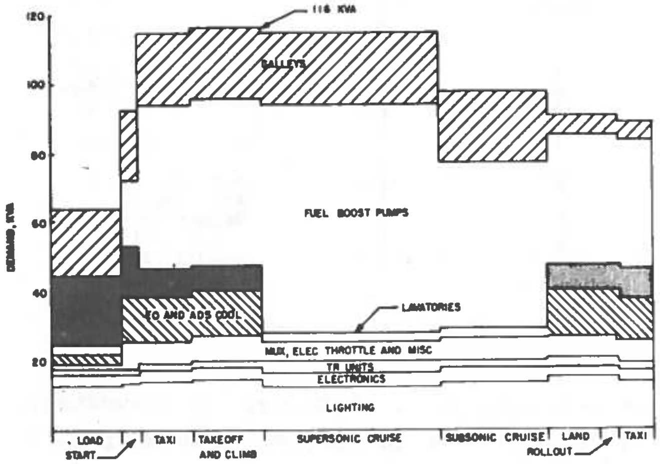


Figure 2.- Sample SST Load Profile

power conditioners. Table II lists the power rating capabilities for single-module power conditioners for various dc bus voltages. This table shows power ratings for present applications and projected power ratings for application to the 1975 to 1980 time period. This table is based on an evaluation of the voltage and current ratings of the semiconductor switches for present and projected applications (ref. 2). It is evident that for present consideration the transistor power conditioner is applicable only for the moderately low voltages and power levels. For the medium dc bus voltage, the thyristor power conditioner offers sufficient power capability for immediate application. The table clearly shows that only the thyristor power conditioner offers the greatest growth in power capability.

The present technology of power conditioning for flight vehicles is relatively advanced for applications to low-input dc voltages and to low-power levels. This technology, almost exclusively, makes use of power transistor circuit techniques. Thyristor circuit technology has advanced only for industrial applications, and the use of these approaches to flight vehicles, where light weight and high performance are necessary, appears to be inadequate.

TABLE II.- POWER RATING CAPABILITIES FOR SINGLE MODULE POWER CONDITIONERS

| Type Power Conditioner | DC Bus Voltage (V) | Power Ratings Present | - 1975 - 1980 (KW) |
|---|---|---|---|
| Transistor | 100-150 | 7.5 | 25 |
| | 400-600 | --- | 30 |
| | 800-1200 | --- | -- |
| Thyristor | 100-150 | 15 | 100 |
| | 400-600 | 50 | 300 |
| | 800-1200 | -- | 500 |

THYRISTOR CHARACTERISTICS

The principle element of the thyristor power conditioner is the thyristor switch, also known as the silicon controlled rectifier (ref. 3). This element is a four-layer silicon device which can block forward and reverse voltage until triggered into conduction in the forward direction. Typical thyristor characteristics are shown in Figure 3. Thyristors are normally brought into conduction by passing current from gate to cathode but there are other ways in which the device can be caused to switch to its low-impedance condition, as follows:

(a) Increasing the anode to cathode voltage above the device rating causing sufficient increase in leakage current for the device to conduct.

(b) Rapidly changing anode to cathode voltage which, because of junction capacitance, causes sufficient current to flow through the device to initiate conduction.

(c) Increasing junction temperature above rated junction temperature causing the leakage current to increase to a level sufficient to cause the device to conduct.

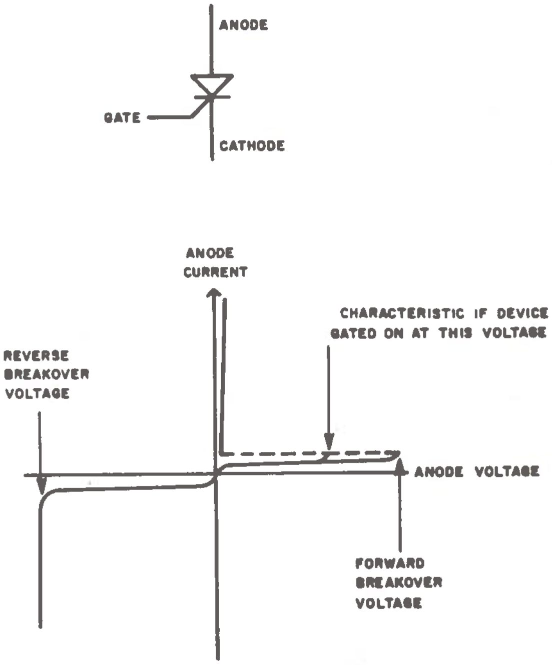


Figure 3.- Thyristor Characteristics

Each of these three effects can cause the device to conduct at a time when it is required to be blocking. As a result, it is necessary to protect against these unwanted low impedance conditions by the following methods:

(a) Selecting devices such that they are always operated below their maximum voltage rating, particularly during transient overvoltage. Protection against transient overvoltage can be achieved by using a voltage-clipping element or filter.

(b) Using suitable filters to limit the maximum rate of change of voltage, dV/dt, to which the devices are subjected.

(c) Supplying adequate heat sinks and taking into account the effects of overload and surge currents on junction temperature.

The rate of current change, dI/dt, upon turning on the device, must be considered in thyristor application. If the current in the device is allowed to build up too rapidly at turn on, a current crowding effect occurs in the area where gate current is flowing. The current crowding effect causes local overheating which may destroy the device. In any event, repeated local overheating causes a degradation in device characteristics eventually leading to failure. Therefore, if the basic external circuits allow the rate of change of current in the device to be larger than a certain critical rate, then the external circuit must be modified by introducing sufficient inductance to reduce this rate.

Once the thyristor is conducting and the anode current has risen above some critical level, the gate current can be removed and the device will continue to conduct. The device cannot be made to cease conducting by reverse gate current. To switch off the device, the anode current must be reduced below some very low level known as the holding-current level. This anode current reduction below the holding current causes the device to regain its blocking properties. The time required for the device to regain its blocking properties (known as the turn-off time) can be reduced if the device is reverse biased (i.e., the cathode is driven positive with respect to the anode).

THYRISTOR POWER AMPLIFIERS

A simplified block diagram of a power conditioner is shown in Figure 4. The power amplifier processes the output power from the HVDC input power, and the controller regulates the power amplifier according to the load function. The key element of the power conditioner is the power amplifier. Thyristor power amplifiers which operate from a dc bus can be classified by the method of commutating the thyristor switches. Two different classes of power circuits exist that can accomplish commutation, namely, the forced commutated thyristor circuit and the natural commutated thyristor circuit.

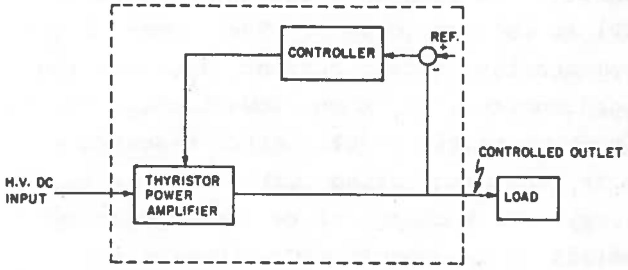


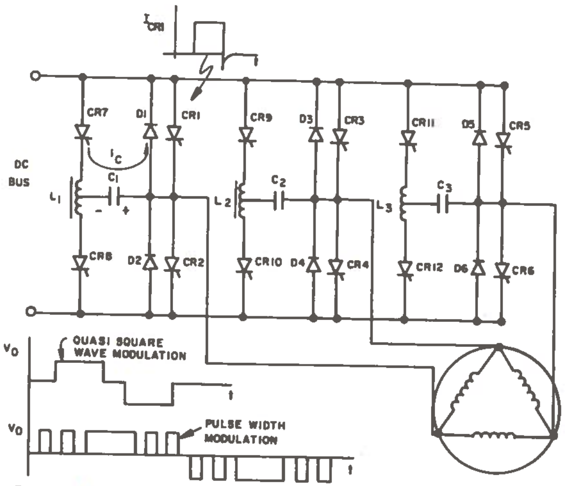
Figure 4.- Simplified Block Diagram of a Power Conditioner

The forced commutated thyristor circuit, sometimes referred to as the parallel capacitor inverter, makes use of auxiliary circuits to accomplish commutation. The mode of operation of these circuits is based on the forced interruption of thyristor switch current as part of the cyclic operation of the circuit. Several types of thyristor circuits are being developed with the major differences being in the implementation of the commutation. Examples of the forced commutated thyristor power amplifier are shown in Figure 5, where a three-phase motor drive and a dc/dc converter are illustrated. This power circuit is commonly referred to as an impulse commutated circuit, on the McMurray-Bedford inverter (ref. 4).

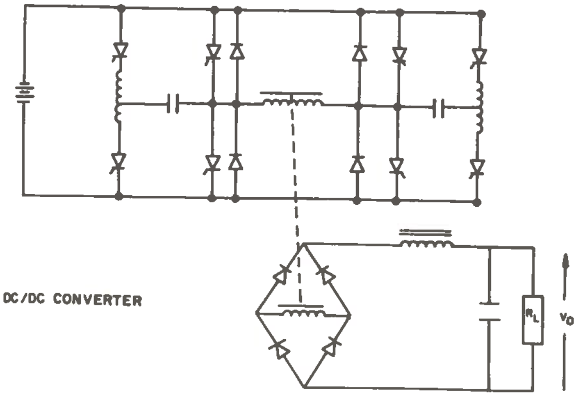
Referring to the motor drive circuit, Figure 5a, the circuit operation is as follows. The main power switches are CR1-CR6, and the commutating switches are CR7-CR12. The inductors L1-L3 and capacitors C1-C3 are part of the commutating networks. Rectifiers D1-D6 are for the reactive power and for the regenerative power mode. Assume that CR1 is conducting and that the charge is as shown only on C1 from the previous operating cycle. To commutate CR1, controlled rectifier CR7 is fired. A pulse current flows through CR1 in reverse and in CR7, L and C1. This current builds to a value in excess of the load current through CR1 such that the net current in CR1 is reduced to zero. The excess of the commutating impulse current, $I_C$, over the load current, Il, then flows through the feedback rectifier D1. After reaching a peak, the commutating current starts to decay, and a charge of reversed polarity builds up on capacitor C1. During the time that rectifier D1 is carrying current, the forward drop of D1 appears as an inverse voltage across CR1, and it turns off. The circuit is now ready for its next cycle of operation, namely the firing of CR2 and its commutation. A typical power switch current waveform is also shown in Figure 5.

Two methods for control of the forced commutated thyristor power amplifier are possible. These methods are the quasi-square and the pulse-width-modulated techniques. Sample output voltage waveforms of each of these techniques are also shown in Figure 5a.

The natural commutated thyristor circuit, sometimes referred to as the series capacitor inverter, operates with the commutation circuits as an integral part of the power circuit. The mode of operation of these inverters is based on the natural turn-off of these circuits as part of the normal cyclic operation, where the commutation networks are in series with the power switches. The common series inverter suffers from two major limitations: (1) it cannot be controlled, and (2) it is load sensitive. However, Schwarz (ref. 5) has shown that these limitations are overcome when pulse frequency modulation is employed. Examples of the natural commutated thyristor power amplifier are shown in Figure 6, where a three-phase motor drive (ref. 6) and a dc/dc converter (ref. 5) are illustrated.

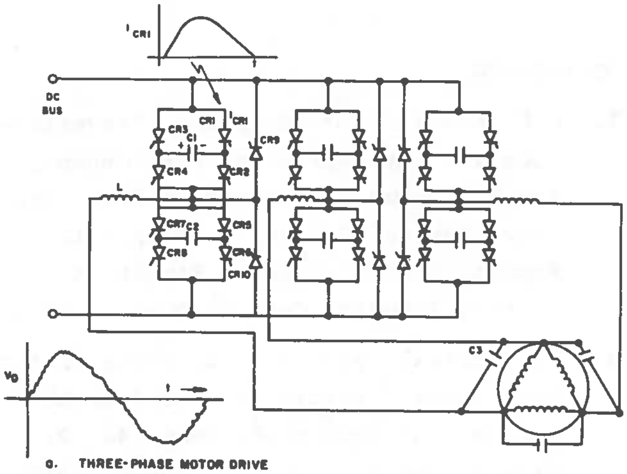


a THREE-PHASE MOTOR DRIVE

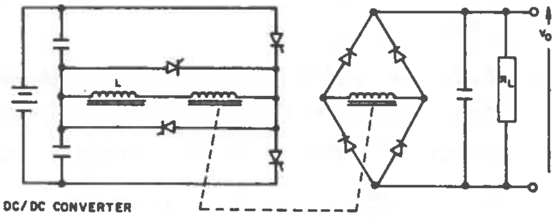


b. DC/DC CONVERTER

Figure 5.- Examples of Forced Commutated Thyristor Power Amplifiers



a. THREE-PHASE MOTOR DRIVE



b. DC/DC CONVERTER

Figure 6.- Examples of Natural Commutated Thyristor Power Amplifiers

Referring to the motor drive circuit, Figure 6a, the circuit operation is as follows. Looking at one phase, the power switch sequences are CR1-CR4, CR3-CR2 for positive current, and CR5-CR8, CR7-CR6 for negative current. Each time a set of power switches fire, a resonant circuit consisting of alternatively of LC1 or LC2 is connected in series. Controlled rectifiers CR9-CR10 are for reactive power flow, for regenerative power flow, and as a clamp for the capacitor voltage. Capacitor C3 in conjunction with inductor L forms a low-pass filter for blocking the high-frequency switching component of the power switches. To examine one cycle of operation, assume that CR1-CR4 are fired and capacitor C1 is charged, as shown. A sinusoidal pulse of current flows through C1. As this current flows to zero, CR1-CR4 are naturally commutated and the polarity across capacitor C1 has reversed, thus reverse biasing CR1-CR4. One cycle of high-frequency operation has been completed. Next, CR3-CR2 are fired and the cycle proceeds as described. Several high-frequency cycles are required to form one half-cycle of current through the motor. To form a negative half cycle of current through the motor switches, CR5-CR8 and CR7-CR6 are cycled several times. Typical thyristor power switch current and output voltage waveforms are also shown in the figure. Note that the output voltage waveform is synthesized from a series of high-frequency pulses. This waveform can be further filtered by increasing capacitor C3.

In comparing these two classes of thyristor power amplifiers, one finds basic philosophical differences in their operation. The formed commutated circuit, by its operation of forced interruption of current, causes large peak-to-average stresses on the circuit components. The stored energy required to accomplish commutation is a function of the switch current. One must guarantee commutation, since failure to commutate usually results in a catastrophic event. The natural commutated circuit, because of its quasi-sinusoidal current, automatically achieves commutation as the switch current approaches zero, and the shape of the current waveform is nearly independent of the external load. However, component stresses also occur with this circuit because of the underdamped nature of the series resonant LC circuit. Also, one must guarantee that the capacitor voltage remains bounded.

The forced commutated thyristor amplifier is at an advanced development stage. Many models have been built for non-flight vehicle applications. The controlled natural commutated thyristor amplifier only recently has achieved technical feasibility (ref. 5), and experimental development of inverters and converters is in process.

## CONCLUSIONS

Power conditioners are capable of providing all of the required matching interfaces between a high-voltage dc bus and the load demands that can be anticipated for any flight vehicle. The transistor power conditioner is immediately available for the moderately low dc distribution system, and for the moderately low power levels. Transistor power conditions will offer very limited application to the higher bus voltages and power levels that are anticipated for large vehicles.

The thyristor power conditioner offers capability for operation with the higher distribution bus voltages, and with significant power capacity. The technology of thyristor power conditioners must be advanced so that light weight and high performance can be achieved. The two classes of thyristor power conditioners discussed in this paper are applicable to the flight vehicle power conditioner requirement, although they have significant differences in design philosophy. As the development of these power amplifiers progress, a preferred configuration may become evident.

## REFERENCES

1. C.H. Lee and J.J. Brandner, "Investigation and Development of New Concepts for Improvement of Aircraft Electrical Power Systems," Interim Technical Report, NASA Contractor Report, Electronics Research Center, August, 1969.
2. "Electrical Systems Study Using Static Components," Volume II, Solid-State Devices and Equipment, Nobs 94S 42, Naval Ships Engineering Center, July 1968.
3. F.W. Gutzwiller, "Thyristor and Rectifier Diodes - The Semiconductor Workhorses," IEEE Spectrum, August 1967.
4. B.D. Bedford and R.G. Hoft, *Principles of Inverter Circuits*, New York, Wiley & Sons, 1964.
5. F.C. Schwarz, "A Series Capacitor Inverter-Converter for Multikilowatt Power Conversion," NASA TR R-336, April 1970.
6. J.J. Wawzonek, "Series Commutation for Variable Frequency Thyristor Inverters," Proceedings 24th Annual Power Sources Conference, May 1970.