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ALL-PURPOSE BIDIRECTIONAL FOUR-QUADRANT CONTROLLER

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The basic conventions for defining power flow are illustrated in figure 1. The circuit in the upper left of figure 1 defines a positive voltage source and positive current flow. When the current and voltage are plotted as on the upper right, they define positive power flow to the load and fall in the first quadrant. With a negative voltage source and a negative current flow, as shown in the lower left of figure 1, the power flow to the load is still positive, but it falls in the third quadrant as shown in the lower right. Thus positive power, or power flowing to the load, falls in either the first or third quadrant. The other two quadrants are obviously negative power (+I x -E or -I x +E) and represent power flowing from the load. In the second and fourth quadrants the load is acting as a power source.

Figure 2 shows an example of a bidirectional load. With the switch in the position shown, the battery is powering the motor, which in turn is driving a flywheel. When the switch connects the motor to the resistor, the only source of energy in the circuit is the rotating motor and flywheel. Assuming an ideal motor with no inductance and proper excitation, the motor would act as a capacitor. The voltage would remain constant, but the current would reverse and flow from the motor, now in a generating mode, to the resistor. This is illustrated on the plot in the lower half of figure 2 by the arrows pointing downward from the point in the first quadrant to the point in the fourth quadrant. Since with actual motors inductance would be present, the trajectory would be more like the other path of arrows with the current remaining constant and the voltage decreasing and even going negative before reaching the point in the fourth quadrant. In this example the energy flow is bidirectional and several quadrants are involved in the transition of energy from one point to the other. The purpose of the bidirectional four-quadrant controller is to control the flow of energy between the various quadrants.

Figure 3 is a Lissajous pattern showing the locus of operating points for a load. With a sinusoidal voltage and current, and with some phase angle between them, the locus of operating points forms an ellipse as plotted in the figure. If the load were purely resistive, the ellipse would collapse into a line lying in the first and third quadrants only. That is because a pure resistance operates only as a load and not as a source. However, with a load containing both resistance and reactance, energy is stored and released as well as dissipated and the locus extends into all four quadrants. Again, reviewing the basic definition, the load is dissipative in the first and third quadrants and is a source in the second and fourth quadrants.

A resonant circuit, since it has both resistance and reactance, operates in all four quadrants. This means that it can either deliver or accept power; hence it is bidirectional. There will be limits on the voltage and current as shown in figure 4. The circuit will not support a voltage above the line labeled voltage limit nor accept a current above the line labeled current limit. If the resonant circuit is connected to a source each time the locus occupies the first quadrant (or the third quadrant with inversion), the load presented to the source will be a steady dc load. The load voltage and current will always be the same value each time the switch is closed. This illustrates how a resonant circuit can accept dc power. If a point on the locus were chosen in the second or fourth quadrant, the resonant circuit would act as a dc source instead of a load. Alternating-current operation is a bit more complicated since the switch must be closed and inverted at different times rather than for one fixed quadrant. However, if the switch closure is controlled, frecuencies lower than the resonant frequency can be synthesized either for loads or sources. Therefore, through the proper use of resonant circuits and connecting switches, bidirectional four-quadrant ac and/or dc power controllers can be implemented.

Figure 5 shows a bidirectional controller with associated plots for both terminal sets. The plot shown for terminal set 1 indicates that it is accepting power, in this case a dc input. This is the same as the example discussed previously, where the controller is acting as a dc load. The dashed lines on the terminal 2 plot indicate the constant power limit at the output. Because of the law of conservation of energy the output power cannot be greater than the input. However, the output can operate in either the second or fourth quadrants and can provide either dc or ac. The controller can also be operated in an ac-to-ac mode. In that case the controller can be used to provide power factor correction. However, the amount of correction possible is limited by the available reactive power.

The upper half of figure 6 shows a half-bridge transistorized series-resonant dc-to-ac converter. When one transistor is switched on, the current from the dc source flows through the inductor, the transformer, and one capacitor. The current is initially limited by the inductance, gradually increases, and then starts to be limited by the capacitor charging. The result is a quasi sine wave. The transistor is opened when the current goes through zero, and some current flows in the opposite direction through the bypass diode (causing the small bump in the waveform). The second transistor is then turned on, and the current flows in a direction opposite to that of the first transistor (causing an ac output). One very important point is that the transistors are switched off when the current passes through zero. This eliminates second breakdown, which is one of the major causes of transistor failure in converter and inverter circuits. As a result, the series-resonant converter is considerably more reliable than conventional converters, and the transistors can be operated at both high power levels and higher frequencies. The output of this converter is a high-frequency sinusoid that has lower harmonics and slower risetimes than conventional square-wave converters. As a result, the electromagnetic interference (EMI) is much less for this design. The particular circuit configuration shown in figure 6 acts as a current source at the output. This can be very desirable for operating loads such as motors, particularly during startup. When a current-limited source is used, only the frequency needs to be controlled instead of having to maintain a constant voltage-to-frequency V/F ratio as is done with voltage sources. This circuit can also be reconfigured to act as a voltage source by taking the output from the capacitors. Both types of configurations have been demonstrated.

To provide the final controlled output, the high-frequency sinusoidal power of the resonant converter is fed into the circuit shown on the bottom of figure 6. The switches are closed in pairs (synchronous rectification) to connect the transformer to the output momentarily. The synthesized waveform illustrated is a sinusoidal ac of much lower frequency than the carrier. Direct current of either polarity can be synthesized by closing the switches to maintain one output terminal at the same polarity.

Figure 7 shows a fully bidirectional resonant controller with resonant bridges on both ends. This arrangement allows either port to be used as the input accepting either ac or dc power. With this circuit arrangement one full wave bridge is at the source end, the other is at the load end, and the transmission line between operates at the carrier frequency. The capacitance of the line is made a part of the resonant circuit. This reduces the parts count and makes use of the line capacitance that would be present in any case. Systems of this configuration have been tested at 20 kHz with line lengths of 50 m, which is typical of the line length in a large transport aircraft. The line loss was quite small.

Figure 8 illustrates an ac distribution system configured for bidirectional resonant power conversion. The distribution bus at the top of the figure is the high-frequency transmission line as shown on the previous figure. However, instead of just having an input/output circuit at either end of the line, several loads or sources are paralleled on the line. The first bidirectional converter on the left provides dc power to a storage device such as a battery. If the power failed on the main ac bus, the storage device would feed power back to the bus. The second converter is shown as an interface for ground power. Any appropriate type of power (dc, 60 Hz, or 400 Hz) could be used to power other equipment connected to the main bus or even to start the engines. Power could also be fed from the airplane to perform such tasks as starting the engines of another aircraft. The next power converter shown is provided to power various loads on the aircraft. An aircraft system would have a number of these dedicated converters.

The basic purpose of this paper is to provide some information regarding bidirectional four-quadrant resonant power conversion and describe possible applications to aircraft electrical systems. As this technology has been developed sufficiently to demonstrate its feasibility, this is an appropriate time to evaluate the benefits of its application to aircraft electrical systems.

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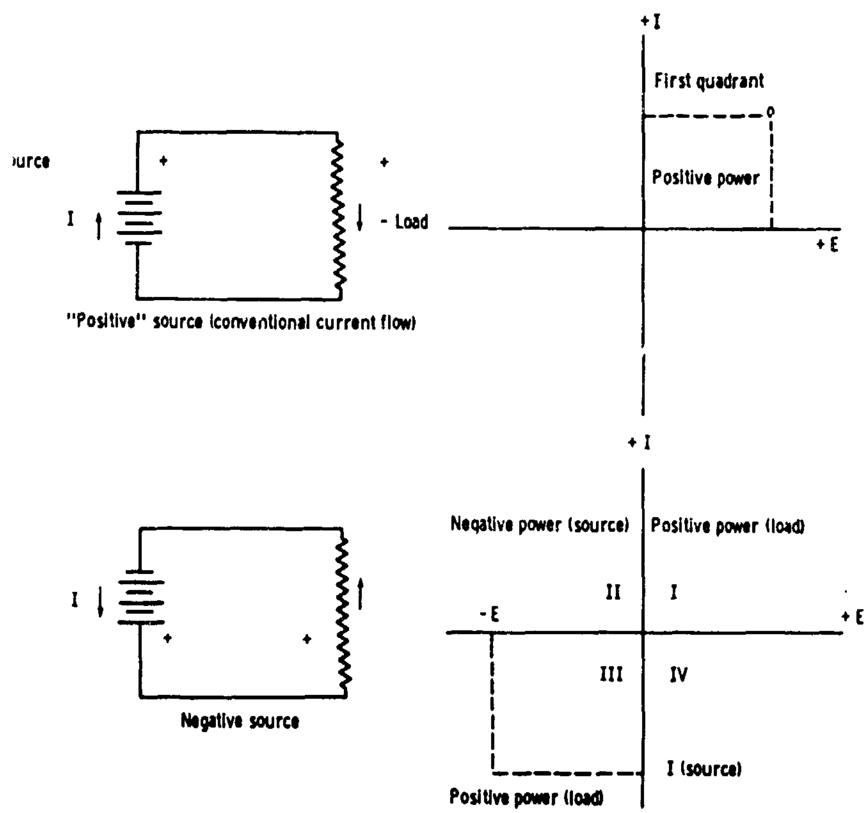

Figure 1. - Basic definitions of four-quadrant controller.

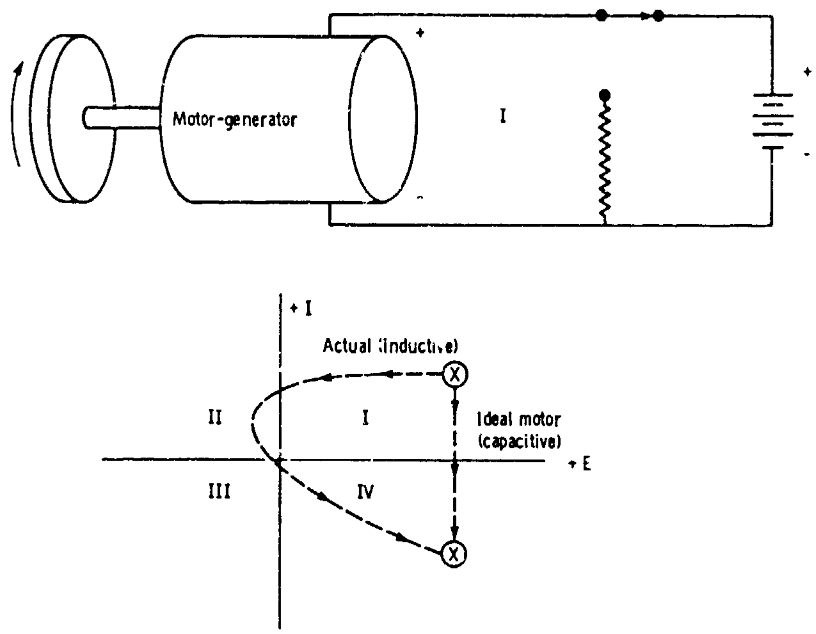

Figure 2. - Bidirectional energy flow.

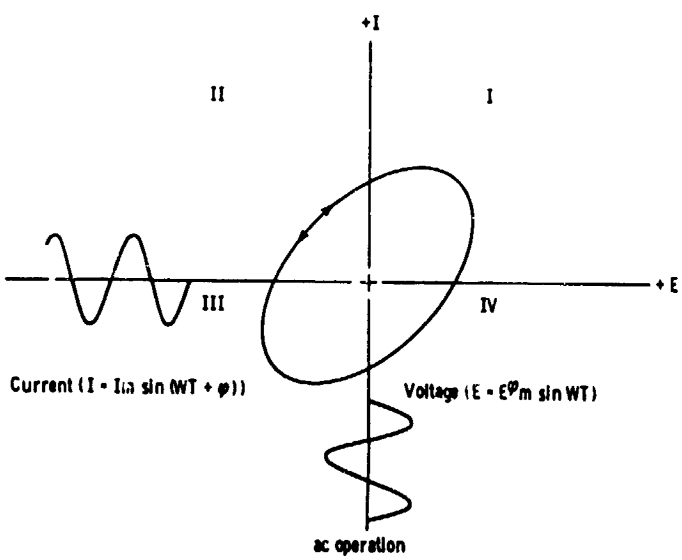

Figure 3. - Loci of operation points depending on magnitude and phase of load (Lissajous pattern).

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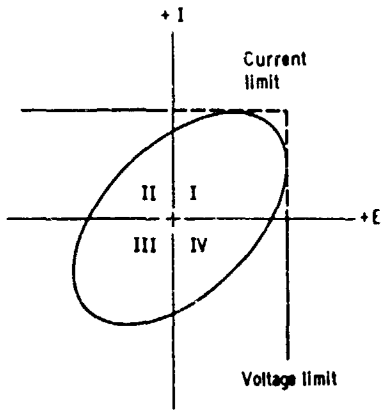

Figure 4. - Resonant circuit.

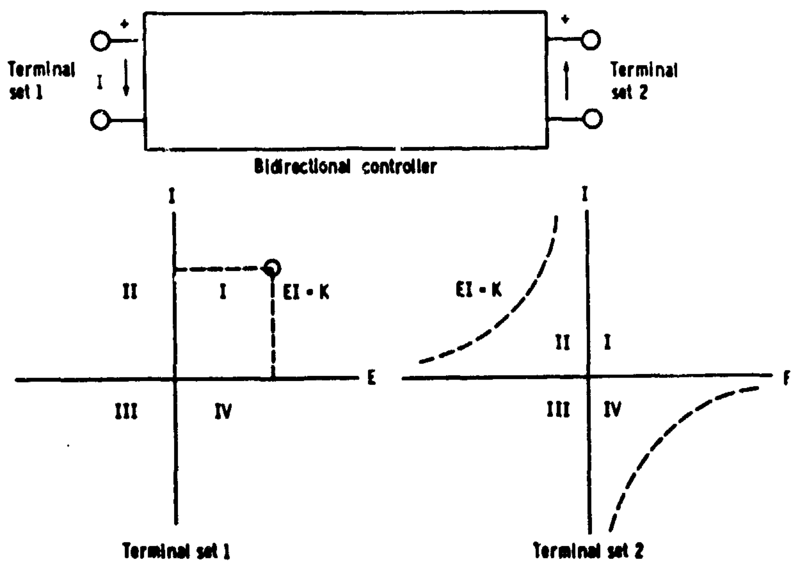

Figure 5. - Conservation of energy - a problem with bidirectional converters.

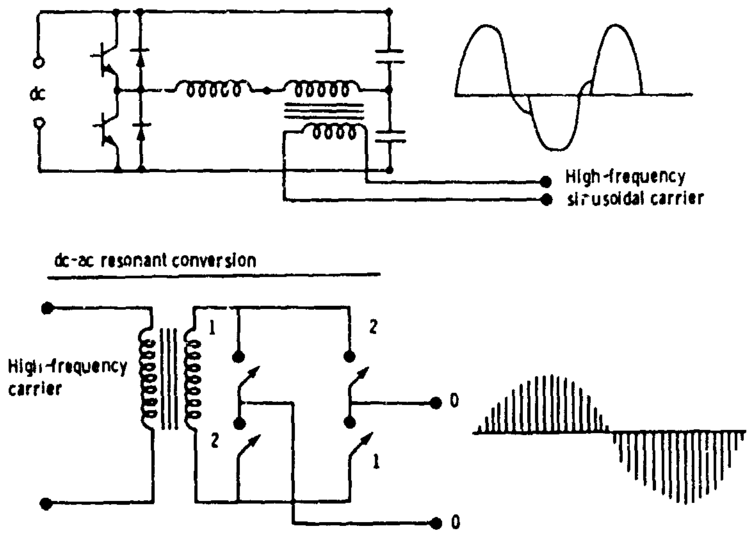

Figure 6. - Low-frequency synthesis (including bipolar dc).

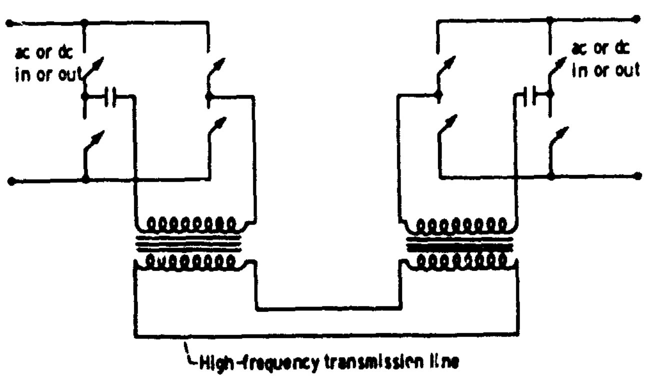

Figure 7. - Bidirectional resonant controller.

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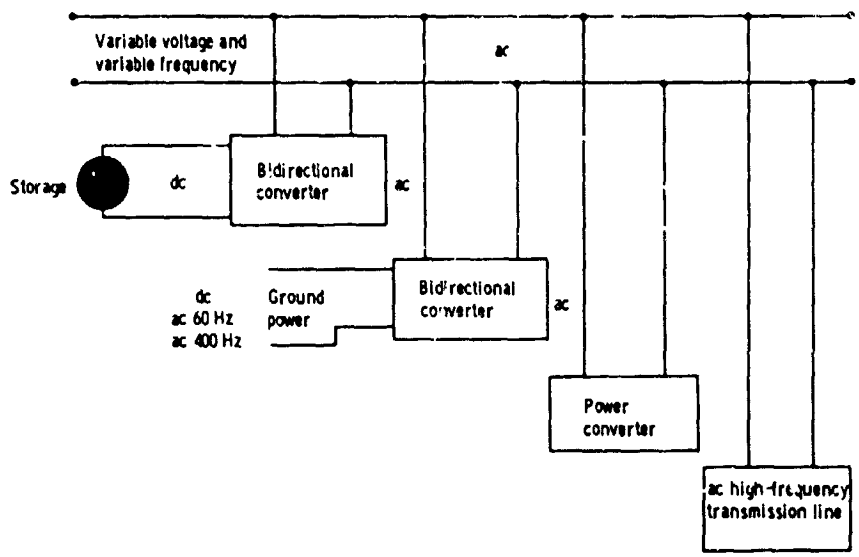

Figure 8. - Distribution system. (Power converter is dc (fixed or variable frequency), ac (variable voltage), or bidirectional if required.)