Gemini Synchronous Inverter Systems

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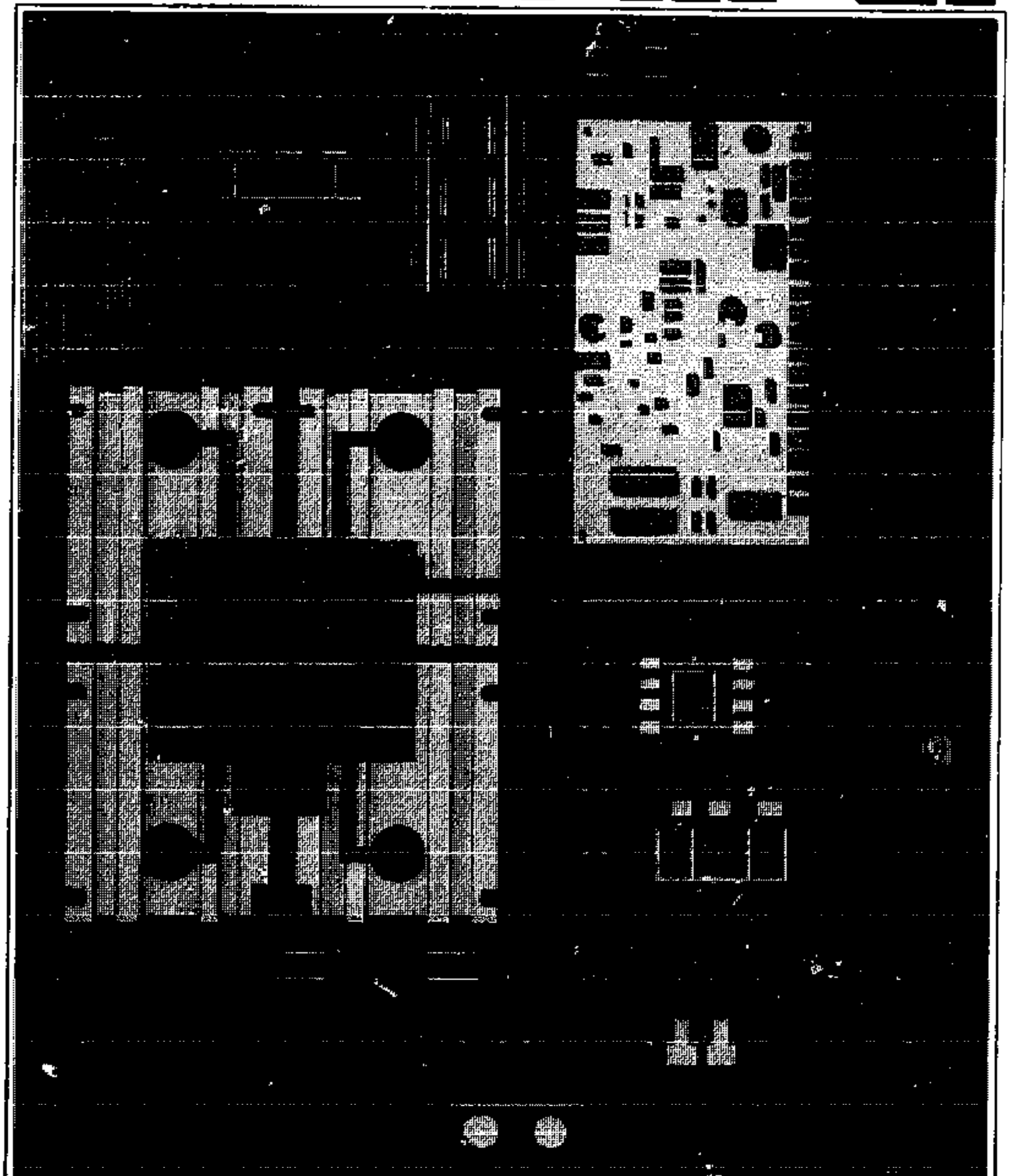
GEMINI



SYNCHRONOUS INVERTER SYSTEMS

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GEMINI

The Gemini Synchronous Inverter is a line-commutated, line-feeding inverter which when interposed between a variable voltage DC power source and an AC power source, converts the DC power to AC at standard line voltages and frequencies.

In operation, all the available DC power is converted to AC. If more power is available from the DC source than is required by the load, the excess flows into the AC lines, where it can be used by other consumers connected to the same AC system. If less power is available than required by the load, the difference is provided by the AC lines in the normal fashion.

For variable or intermittent power sources such as wind turbines, solar photovoltaic arrays, solar thermal electric systems, small hydroelectric installations, and certain industrial processes, the use of a Gemini Synchronous Inverter allows simple, safe, and inexpensive interfacing with conventional AC electrical power systems such as utility grids and engine-generator sets.

By interfacing the alternate source with conventional power lines, the need for storage is eliminated, as well as the need for separate circuits and special loads capable of functioning with the unregulated or DC power. The energy produced by the alternate source allows a corresponding reduction in the fuel requirements at the point of AC generation.

The nature of the Gemini control circuitry permits each unit to be individually programmed for optimum extraction of energy from the alternate source. Voltage, current, and current slope controls allow selection of the point at which power conversion begins, the rate of conversion, and the maximum quantity to be converted.

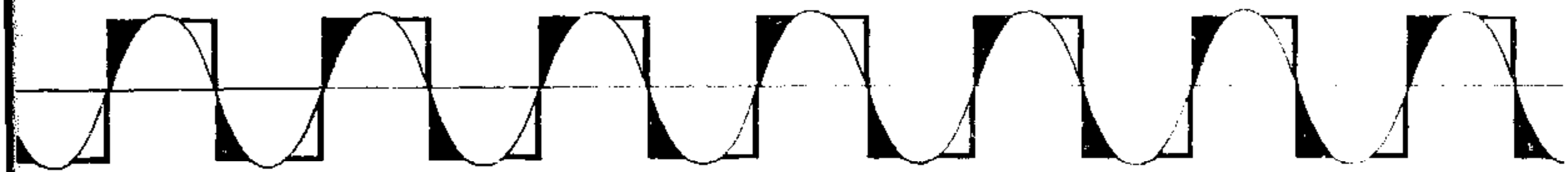
For sources such as photovoltaic arrays, where the maximum power output is not a function of a single variable, automatic tracking circuitry has been developed which continuously seeks the highest output by incrementally varying the loading of the array while monitoring the power output. This tracking circuitry adjusts the Gemini to convert DC to AC at the rate which will result in the maximum output for a given condition.

Thermal, chemical or electrical energy storage may be added to the system, if desired. When storage is used, or when the elimination of power feed back to the AC lines can be economically justified, controls are available that permit monitoring the net consumption of power from the AC lines, so that any surplus energy which would otherwise be fed back to the AC lines can be directed to either a storage system or to some other "non-critical" load such as an auxiliary water heater or a pre-heater for a standard hot water heating system.

The technological base for the Gemini is derived from solid state industrial drive circuitry which has been developed and put to widespread use over the past 20 years. Conservatively estimated, some 1500 megawatts of regenerative and 6000 megawatts of non-regenerative solid state drives have been put on-line in the last 10 years. A regenerative drive takes energy from the AC lines to energize a piece of equipment or machinery. Alternately, for control or braking purposes, it can extract energy from the machinery and return it to the AC lines. Even though the drive may at times supply power to the AC lines, it is still a net energy consumer. This characteristic distinguishes solid state drive equipment from synchronous inverter systems which are net energy producers. Additionally, drive equipment is almost always associated with mechanical motion, while a synchronous inverter operates equally well with rotating and non-rotating sources.

Issues that must be considered when interfacing two power sources include safety, power quality, and rate structures.

Safety is of concern in that there is a possibility for power to flow from one source to the other even if the other



source has been de-energized. Energy fed into a downed power line could jeopardize the safety of a serviceman who has failed to take the usual precautions to insure a dead line. The Gemini has features built in to minimize risks of this type. The very nature of line commutated inverters makes it impossible to produce AC in the absence of AC voltage from the lines, and a line voltage activated contactor disconnects the DC source from the Gemini and the AC lines whenever the line voltage drops 20% or more. Fusing is provided at both the DC and AC sides of the Gemini to protect against fire and damage under fault conditions.

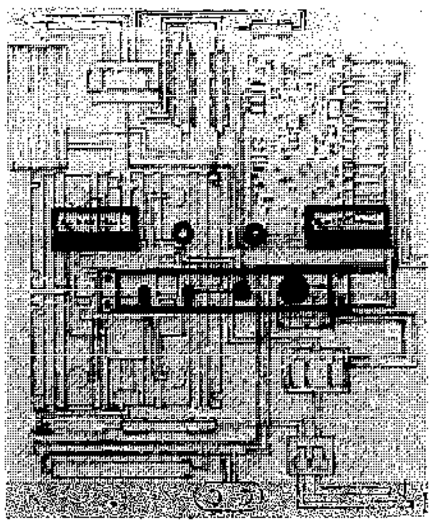
Gemini power quality falls well within the range of values found for other typical household and industrial loads and is identical to that of solid state drive equipment. The Gemini represents an inductive load to the AC lines, similar to that of an induction motor. Field tests indicate that electromagnetic interference is well within standards established by the Federal Communications Commission. Where justified, power quality can be improved using the same techniques which have been developed to improve power quality in industrial applications.

Rate structure becomes important when the AC and DC power sources are not owned by the same entity, such as the case when tying an alternate energy system to a utility grid. A further distinction can be made between installations where the prime interest is to decrease the consumption of AC power as opposed to those installations where the desire is to feed back significant quantities of energy and to be reimbursed for it. The first type of installation is referred to as "supplemental" and generally requires very little modification of the rate structure, since its net effect of being "on-line" is no different than a simple reduction in loading of the AC power source. The second type of installation, where significant energy is fed back to the AC lines, is often referred to as "co-generation", and generally requires a specific agreement with the utility company involved.

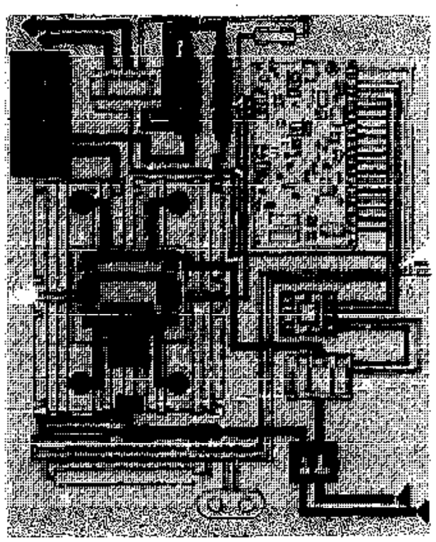
The simple circuitry employed in the Gemini provides high reliability and high efficiency at the lowest cost per kilowatt of any DC to AC power conditioning equipment.

BASIC SUBSYSTEMS

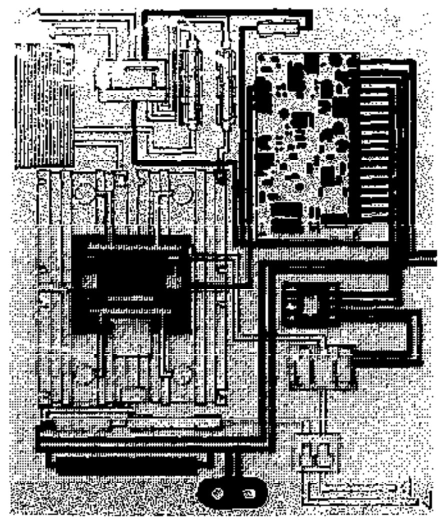
The METERING CIRCUITRY consists of the panel meters, the current sensing shunt, and the selector switch test circuitry on the regulator board. The metering circuitry is used in programming the Gemini for specific load demand curves while during normal operation it permits monitoring of the system's performance.



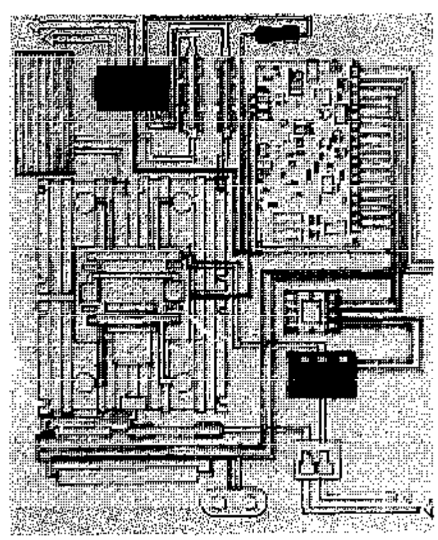
The POWER ELECTRONICS are comprised of the SCR (silicon controlled rectifier) bridge assembly with associated heat sinks, the optical firing circuit board mounted on the heat sinks, the air-core reactor filter, and the AC and DC fusing. The power electronics provide the transfer of power from the DC source to the AC source in a manner regulated by the control electronics.



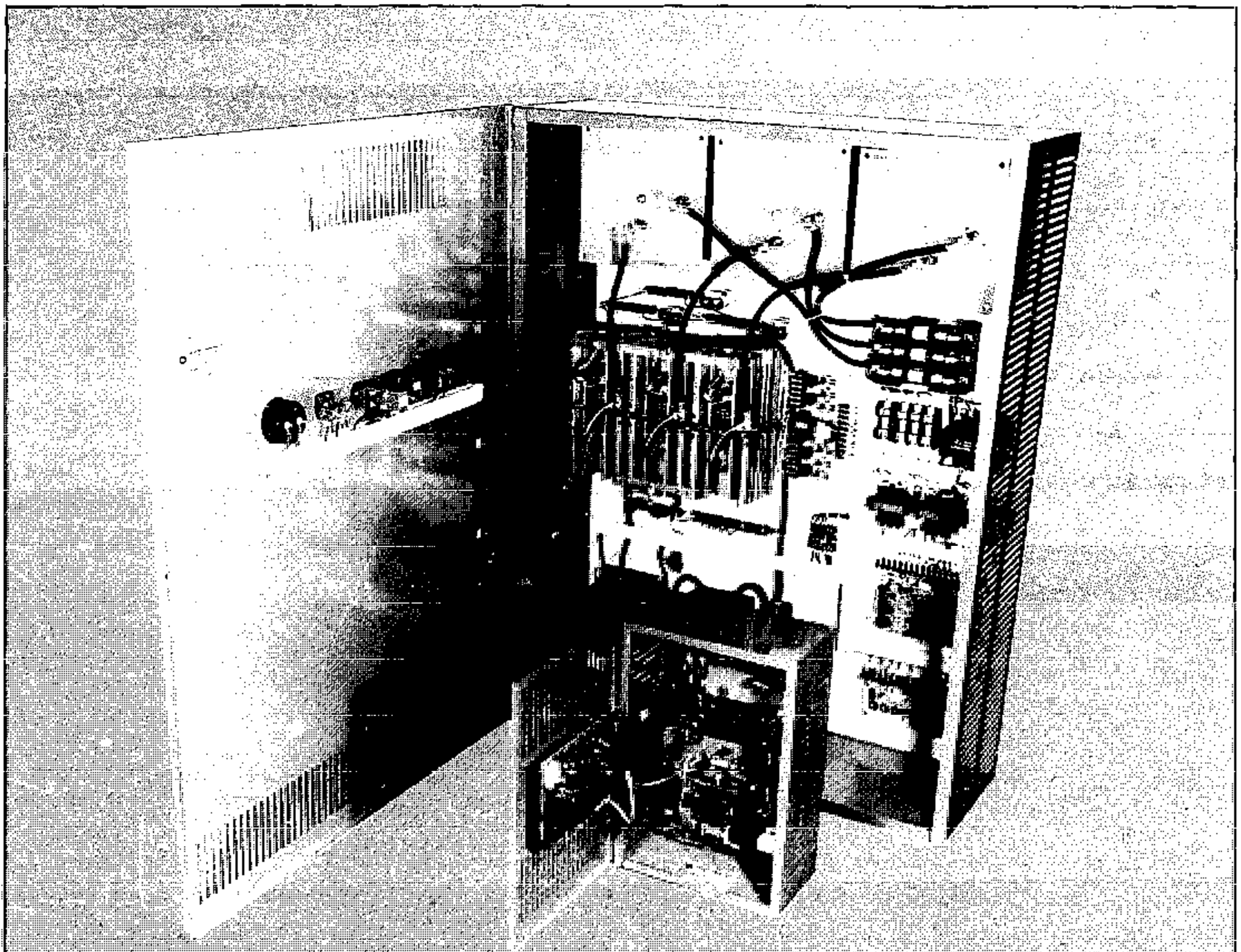
The CONTROL ELECTRONICS are contained in the regulator printed circuit board mounted in the cabinet. This circuitry controls the firing of the SCR's with respect to some variable, such as DC output voltage, and in accordance with user-programmed values for voltage cut-in, rate of loading and maximum current to be converted.



The MAGNETIC CONTROL is comprised of the DC contactor and the on/off switch on the front of the cabinet. The magnetic control functions to connect the DC source to the Gemini during normal operation. In the event of an AC power failure, the contactor automatically drops out, regardless of the position of the switch, thereby disconnecting the DC source from the AC lines.



GEMINI*



4 KW Single Phase Gemini
20 KW Three Phase Gemini

SPECIFICATIONS

SINGLE PHASE GEMINI				
Model	Power Capacity (kw)	Input Voltage (VDC)	Maximum Amperage (Amps)	Output Voltage (VAC)
PCU-40-1	2 4	0-100 0-200	20 20	120 240
PCU-80-1	4 8	0-100 0-200	40 40	120 240
PCU-150-1	15	0-200	75	240

THREE PHASE GEMINI				
Model	Power Capacity (kw)	Input Voltage (VDC)	Maximum Amperage (Amps)	Output Voltage (VAC)
PCU-200-3	20 20	250 500	80 40	240 480
PCU-400-3	40 40	250 500	160 80	240 480
PCU-500-3	50 50	250 500	200 100	240 480
PCU-1000-3	100 100	250 500	400 200	240 480

* U.S. patent Nos. 3,946,242 and 4,059,772

Specifications for inverters with capacities up to 1.5 megawatts available on request.

FEATURES

* Voltage, current and current slope controls permit matching the load demand to the power available from the source, thereby maximizing the energy extracted. For example, in a wind system the power available from the wind varies with the cube of the wind speed. The Gemini controls permit loading the wind system to extract the available energy to within a few percent of what could be extracted under ideal conditions.
* Inverter efficiency at rated output is 96% for single phase systems and 98% for 3 phase systems (exclusive of optional filters and transformers).
* The no-load power draw for the inverters is typically less than 1/2 of 1% of rated capacity, thereby maximizing the net energy production of the power source.
* A DC contactor energized by the AC lines automatically disconnects the DC source from the AC lines during utility outages and automatically reconnects it when the AC power is restored. This feature insures the safety of a utility lineman while servicing a downed line to which the Gemini is interfaced.
* Input and output fuses are installed in all Gemini Synchronous Inverters to protect internal wiring, the DC source and the AC lines from severe overload conditions.
* Inverters rated at 40 amps or less may be installed by plugging into a standard electric range outlet of suitable rating.
* All units have a DC ammeter and voltmeter, AC and DC power indicator lights, and an AC power switch externally mounted for convenience and safety.
* Test circuitry is built into the Gemini controls to facilitate programming of the unit and for use in troubleshooting.
* All units are housed in wall or floor mounted steel cabinets.

OPTIONS

* **Interface Filters:** When the DC source is of low impedance the use of an inductive or an inductive/capacitive filter may be required. Optimally sized air core reactors and electrolytic capacitors are used to fabricate interface filters for photovoltaic arrays, wind systems which employ alternators or low impedance generators, battery storage applications, and other low impedance sources. For experimental installations, multiple-tap air core reactors and multi-valued capacitors can be supplied to permit determination of the filter configuration which results in optimum system performance.
* **Maximum Power Trackers:** Automatic power tracking circuitry is available for use with concentrating and non-concentrating photovoltaic arrays. The tracker continuously seeks that operating level which results in the maximum power conversion for a given climatic condition. A wattmeter circuit monitors power output to provide information to a power tracker circuit which varies the loading conditions seen by the array. This nearly instantaneous variation of load permits optimization of the energy output at very little additional cost and with essentially no increase in circuitry losses.
* **Isolation Transformers:** For applications in which the DC source voltage is too high or too low with respect to the AC line voltage for optimum performance and for applications requiring grounding of the DC source for testing or precautionary reasons, isolation transformers of appropriate rating can be provided.
* **DC Field Supplies:** For systems requiring the use of shunt wound generators, the field supply can be built into and controlled by the Gemini. When the DC source is not in operation the field is deenergized to minimize losses. Field excitation can be either fixed or variable for optimum system performance.
* **Starting Circuit:** For Darrieus wind systems a starting circuit has been developed which permits utilizing AC power to accelerate the turbine. When generating speed is reached, a reversing contactor permits the Gemini to extract power in the normal fashion. The starting sequence may be initiated by a timer, a wind signal input, or manual control.

NEW PRODUCTS

AC/DC wattmeters, watt-hour meters, and VAR meters will be available soon for various power ratings. The patented circuitry samples amperage and voltage 15,000 times per second, multiplies and integrates to determine power. A timing circuit is added to provide watt-hours and a phase displacement is effected to provide volts-amps reactive. The meters will be available with analog or digital readouts and with an isolated analog signal output for use with recording equipment. Meter error is less than 1% of full scale for frequencies up to 1000 Hz.

Load management hardware is under development which has the capability of optimizing the use of energy produced by the DC source. AC dumping circuitry detects any surplus generation which would otherwise be fed back to the AC source and shunts this energy to a variable load such as a hot water storage system. DC dumping circuitry, used when battery storage is added to the system, also detects any surplus generation but in this case regulates the Gemini to convert only that amount of energy necessary to null out consumption from the AC source. Surplus energy goes to the battery. See Load Management, Page 7, for a further description of these circuits.

A Gemini computer-controlled loader is being developed for performance testing and determination of optimum loading characteristics for a particular source. The loader imposes various load conditions on the DC source in response to manual or computer control. Operation at constant voltage, current, torque power or RPM (for rotating sources) can all be readily accomplished.

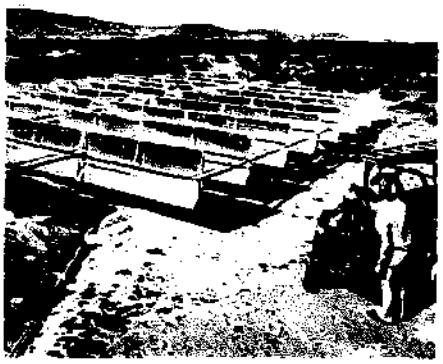
SERVICES

* Engineering and design services are available for adaptation and optimization of the Gemini circuitry for use with specific AC and DC sources. Start-up assistance is available for new installations.
* Gemini Synchronous Inverters with capacities up to 1.5 megawatts can be supplied on a custom basis.
* Start-up assistance is available for new and experimental installations.

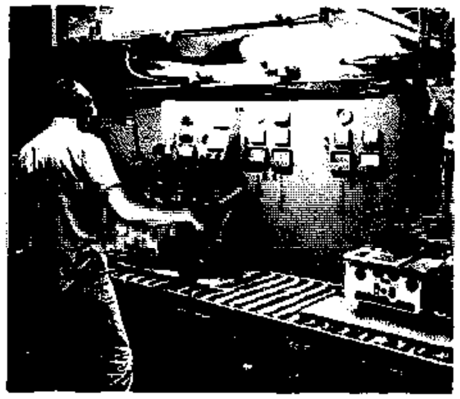
WARRANTY

Gemini Synchronous Inverters are warranted to be free from defects in material and workmanship for a period of one year from date of purchase. Components which have become defective will be repaired or replaced when delivered prepaid to the factory or an authorized service station. This warranty does not apply to components which, in the opinion of the manufacturer, have been subjected to overload, mechanical abuse, improper installation, or use with an unsuitable source of DC power. No other warranty is expressed or implied. No liability is assumed for consequential damages.

REPRESENTATIVE APPLICATIONS



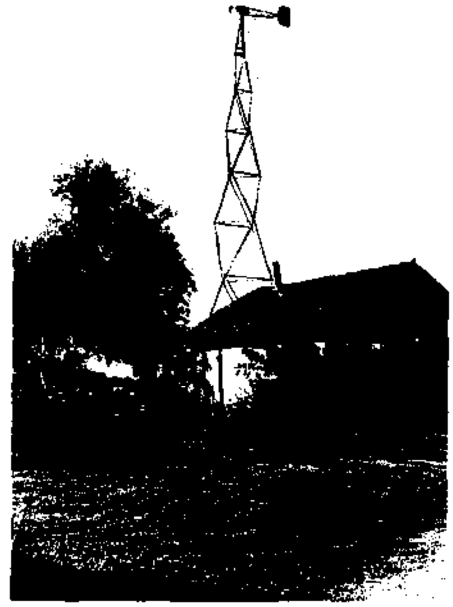
SOLAR THERMAL ELECTRIC research is being carried out on both large and small installations. Shown here is a 4 KW capacity array of concentrator collectors which heat a fluid that drives a turbine generator. The variable output of the array is fed into the AC service of the laboratory through a Gemini Synchronous Inverter. The future looks promising for solar thermal electric installations where insolation levels are high as is typical of the Southwest part of this country.



ENGINE TESTING is an industrial application in which the Gemini can be used to recover significant amounts of energy which would otherwise be wasted.

Typically today, engines undergoing testing or break-in are loaded with an hydraulic pump or a generator where energy is dumped in the form of heat. The use of a Gemini Synchronous Inverter in this application allows recovery of anywhere from 25-75% of this energy. Other similar applications, such as the testing of rotary inverters, motors and generators, can benefit from the use of the Gemini in the same fashion.

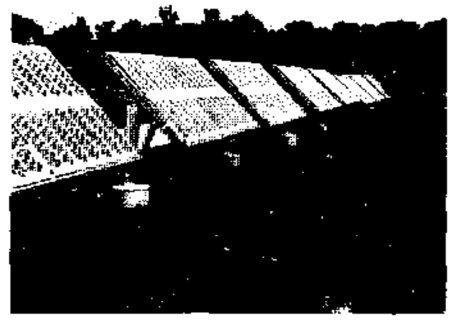
The programable circuitry of the Gemini allows manual or computer control of the load imposed on the equipment being tested. The Gemini's ability to accept a variable input makes it possible to conduct tests over a wide range of operating conditions.



WIND ENERGY is the nearest term, most cost-effective solar electric energy source presently under development in this country. Department of Energy estimates suggest that 2-5% of the nation's electrical energy needs can be supplied by wind systems by the year 2000. It is conceivable that as much as half of this capacity will be supplied by small residential size wind systems interfaced with local utility grids while the other half will come from large utility owned and operated systems. The Gemini Synchronous Inverter provides an economical and fail-safe means of interconnecting small wind systems with existing AC circuitry, thereby eliminating the need for redundant circuitry, specialized appliances or battery storage. Shown above is a 2 KW Jacobs Wind Generator supplying a residence.

BATTERY MANUFACTURING: In the manufacturing of stationary lead acid batteries it is often necessary to charge and discharge the cells several times to condition the surfaces of the plates. This is typically accomplished today by using rectified power from the utility for charging and connecting the batteries to a resistor bank for discharging. Simple modifications to the basic Gemini circuitry permit charging the batteries from the utility lines in much the same fashion a battery charger would. Discharging is accomplished by feeding the stored energy back into the AC lines. Energy requirements are typically reduced 50-60% by using this approach.

HYDROELECTRIC applications, while geographically dispersed, are typically ideal energy sources due to their relatively constant nature and high energy density. Many low capacity hydroelectric sites exist in this country, however, which have not been developed or are no longer in use due to the difficulty in regulating the power output or due to the complexities of getting on and off line when interfaced with a utility. The Gemini provides a ready solution to these problems where conventional AC sources of power are available for interconnection. Government programs are presently being initiated to encourage greater use of this valuable energy source.

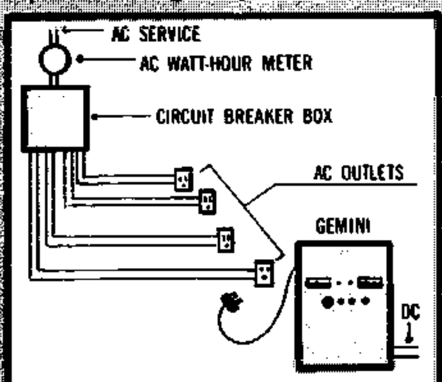


SOLAR PHOTOVOLTAIC: A significant research effort is being put into the development of concentrating and non-concentrating photovoltaic arrays for residential, commercial and industrial applications. Shown above is an array capable of supplying a peak output of 8 kw undergoing testing at the NASA-Lewis Research Center in Cleveland, Ohio. The Gemini power conditioning hardware developed for this installation includes maximum power tracking circuitry which permits extracting the greatest amount of energy under varying temperature and insolation conditions. The dramatic reduction in the cost of photovoltaic cells in the past several years and the anticipated cost reductions in the near future could make this source cost-effective for residential applications by the mid 1980's.

APPLICATION CONSIDERATIONS

INSTALLATION

The installation of a Gemini Synchronous Inverter is accomplished by wiring the unit in parallel with the AC source. For single phase units of 40 amp capacity or less, this can be accomplished by simply plugging the unit into a standard electrical range outlet (see diagram 1). This is a particularly convenient approach in that it provides for a positive disconnect anytime servicing is required.



Three phase units can be wired in permanently to the circuit breaker box serving the AC loads or facility in question. For both single phase and three phase applications the Gemini should be isolated on its own circuit and circuit breaker. Power from the DC source is then fed through the Gemini to the circuit breaker box where it is automatically distributed to any AC loads or fed back to the AC source.

Before operating the system, the Gemini must be programed to load the DC source for maximum extraction of energy. Three variables must be specified to accomplish the programming: the voltage cut-in, that point at which the unit begins converting DC to AC; the current slope, the rate at which the unit converts power as a function of some variable; and the current limit, the maximum current to be converted in normal operation.

Standard Gemini control circuitry requires feedback of a key system parameter to accomplish the variable loading. Typically for small wind systems this variable is DC terminal voltage which is generally proportional to rotor speed. Some other signal such as RPM or wind speed can be used where it enhances the overall system performance.

SAFETY

A synchronous inverter that takes advantage of the line voltage for commutation of its switching devices cannot function without the line voltage present and must automatically disconnect when the line fails. If it does not, the thyristors may cause a fault at the DC source and the power lines on the secondary side of the service transformer could possibly have DC voltages that would be dangerous to personnel working on the lines.

Care has been taken in the design of the Gemini to avoid these problems by using a contactor to isolate the DC source from the inverter and, hence, from the line in the event of power failure. The contactor coil is energized by the AC lines so that loss of power will cause the contactor to open.

Further care has been taken to fuse both the AC and DC sides of the Gemini. In the extremely unlikely event that the contactor should fail in the closed position, the DC resistance of the secondary of the distribution transformer or a pair of thyristors would act as a virtual short circuit to the DC source causing the AC or DC fusing in the Gemini to open and again provide protection.

The fusing of the input and output also serves to protect the DC source, the internal wiring, and the AC lines from overload conditions.

The nature of a line-commutated inverter results in the DC source being connected to first one side and then the other side of the AC service. In that the utility service is tied to ground it is very important that neither side of the DC source be tied to ground to avoid a fault condition.

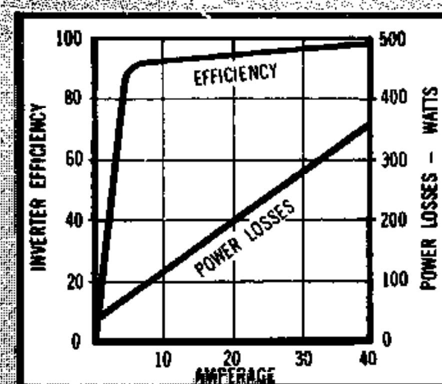
Under normal conditions, this approach is acceptable and is the most economical. When special testing is taking place or when the particular nature of the DC source requires grounding of one leg of the DC circuit, isolation transformers may be used.

An AC power switch and AC and DC power indicator lights are located on the exterior of Gemini Synchronous Inverters to inform the user of the operating condition of the unit. A DC ammeter and voltmeter are also externally mounted to enable monitoring of the system performance and to permit easy programming of the control circuitry.

PERFORMANCE

The losses in a line-commutated inverter are essentially proportional to the current being converted. The power output, on the other hand, is a function of both current and voltage. The losses incurred during operation can therefore be minimized by running at the highest possible voltage for a given power level.

Shown below is a typical efficiency curve for an 8 kw Gemini tied to a wind system employing a shunt wound DC generator.



In addition to minimizing system losses associated with current level, operating at higher voltages results in a minimum VAR load imposed on the AC lines.

Data collected in tests conducted by Wisconsin Electric Power Company on a single phase Gemini at various power loadings and for various AC loads is shown below. The performance of three phase systems is significantly better than that of single phase systems in that higher DC input voltages may be achieved.

GEMINI SYNCHRONOUS INVERTER
SUPPLYING AC LINE
WITH ADDITIONAL LOADS

	Gemini Output: 2 KW			Gemini Output: 6 KW		
	No Load	Res Load	Res Cap Load	No Load	Res Load	Res Cap Load
Line						
AC Volts	235	232	233	238	235	235
AC Amps	14.3	14.3	7.5	37.5	28.3	20.0
KVA	3.36	3.25	1.75	8.93	6.65	4.70
KW	– 2.035	1.925	1.935	– 5.93	– 1.90	– 1.90
KVAR	2.84	2.709	0.125	6.559	6.231	3.612
Load						
KW	0	3.927	4.00	0	4.015	4.015
Gemini						
DC Volts Input	190.8	190.5	190.6	180.0	180.6	180.4
DC Amps Input	12.2	12.2	12.2	35.5	35.5	35.5
Output KW	2.03	2.047	2.057	6.0	6.0	6.0

POWER QUALITY

Power quality is an issue of general concern for any load tied to common AC lines, whether positive or negative with respect to the direction of power flow. When the impedance of the DC source has been properly determined relative to the impedance of the AC line, the power quality characteristics of line-commutated inverters are well within the range of typical loads on utility lines today.

Shown below is representative data from a current harmonic analysis performed at NASA-Lewis Research Center. Although higher order current harmonics exist, and are as high as 11% as in the case of the 3rd harmonic, the first harmonic contributed on the average approximately 98% of the total power.

HARMONIC CONTENT OF LINE CURRENT
GEMINI SYNCHRONOUS INVERTER
SUPPLIED BY FILTERED DC POWER SUPPLY
WITH 10 MHY OUTPUT INDUCTANCE

A RMS Line Current

A	33 5	29 2	35 8	32 6	37.8	
	Percent Harmonic (RMS)					Ave
1st	98 94	98 76	99 09	98 57	99 51	98 97
2nd	2 26	2 11	2 15	2 23	2 47	2 24
3rd	12 31	12 85	10 69	14 33	7 52	11 54
4th	- -	- -	1 32	- -	1 25	51
5th	5 05	6 06	5 57	7 02	4 11	5 56
6th	- -	- -	1 34	- -	- -	27
7th	3 72	3 9	2 98	3 81	2 55	3 45
8th	- -	1 28	1 46	- -	- -	55
9th	2 58	2 74	2 53	2 49	1 81	2 43
10th	- -	1 09	1 26	- -	- -	47
11th	1 96	2.69	1 98	- -	1 57	1 64
12th	- -	1 10	1 62	- -	1 03	75
13th	1 69	1 87	1 60	- -	1 05	1 24
					RMS TOTAL	99.94

With respect to electromagnetic interference, data taken again at NASA-Lewis shows that the Gemini meets or exceeds standards set by the Federal Communications Commission.

Perhaps of greatest significance in maintaining high power quality, is the minimization of voltage waveform distortion, in that the operation of parallel connected loads is strictly a function of their terminal voltage and impedance. When the ratio of the DC and AC source impedances has been properly established, voltage waveform distortion for line-commutated inverters is limited to short duration notches caused by SCR's switching on and is of little consequence in normal residential and industrial applications.

UTILITY INTERFACE

Many of the regional assessments and market analyses prepared for the Department of Energy cite the high potential of distributed solar electric technologies, specifically wind and photovoltaic. It is generally agreed that if these technologies are able to impact the national need, which is the objective of the federal program, they will do so as supplemental sources interfaced with the utility grid.

Rate structure becomes an important issue when the AC and DC sources are not owned by the same entity. When this is the case, a distinction can be made between supplemental installations, where the objective is to decrease consumption of energy from the AC source, and cogeneration installations, where payback for energy delivered to the AC source plays a significant role in the economics of the system.

For supplemental systems, proper sizing of the source in light of the available resource and in consideration of the load demand, generally results in a very low percentage of the generated energy being fed back. The net effect of the system is a reduction in load seen by the AC source and generally requires little modification of the rate structure. For cogeneration installations, the ramifications of trading significant amounts of energy generally requires a specific contract with the utility involved.

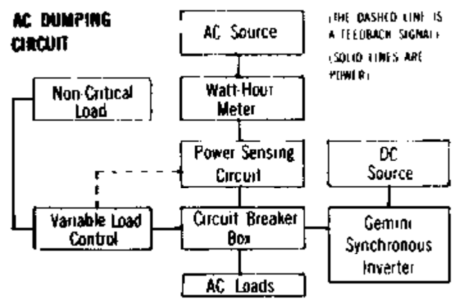
Numerous Gemini installations have been put on-line in the past several years in cooperation with various utilities. In some cases rate structures have been developed that provide for reimbursement of the customer for energy feed back, while in other cases the customer is serviced under the standard rate but with a racheted meter and no payback. Data is being collected on a majority of these installations to provide a basis for establishing equitable rate structures.

The ramifications of interfacing are complex. Technical and economic considerations vary with the generation mix and load demand of the utility, the availability of the alternate resource and the percent penetration of the alternate source in terms of generating capacity.

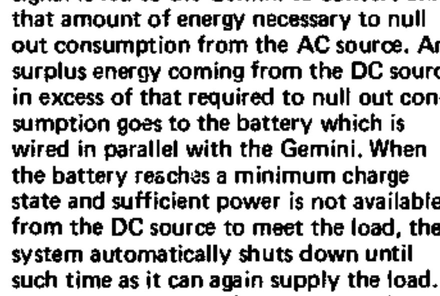
A diligent effort in the coming years will result in a significant percentage of our energy needs being supplied by renewable sources with a significant portion of that coming from small, dispersed systems.

LOAD MANAGEMENT

AC dumping circuitry is presently under development which provides for the consumption of any surplus generated power that would otherwise be fed back to the AC source. A wattmeter circuit senses the magnitude and direction of power flow between the AC loads and the AC source and provides a signal to the dumping circuitry which controls a variable load. In that the amount of surplus generated power and the time of its occurance cannot be predicted, the dumping circuit must work with non-critical loads such as secondary hot water heaters.



DC dumping circuitry is also under development which permits adding DC electrical storage to a supplemental energy system. Again the wattmeter circuit is used to sense power flow between the AC loads and the source, only in this case a signal is fed to the Gemini to convert only that amount of energy necessary to null out consumption from the AC source. Any surplus energy coming from the DC source in excess of that required to null out consumption goes to the battery which is wired in parallel with the Gemini. When the battery reaches a minimum charge state and sufficient power is not available from the DC source to meet the load, the system automatically shuts down until such time as it can again supply the load. If desired, charging of the batteries from the AC line can be accomplished with little additional circuitry.



SYNCHRONOUS INVERSION

Many industrial or commercial electric motor drive systems are connected to mechanical loads that store large quantities of kinetic energy in the form of moving or rotating mass. When such a load is accelerated to operating speed, a large amount of temporary power is required. Similarly, when the load speed is reduced to zero, the kinetic energy must be extracted from the moving mass. Again, the power involved in deceleration can be very large.

Other types of loads store energy in the form of potential energy resulting from a change in vertical location of large masses. Cranes and hoists are typical examples of this situation. In both cases, the exchange of energy with the load takes place in both directions, and very early in the history of electric drive systems it was discovered that while electrical or mechanical braking could be used to absorb the energy when necessary, undesirable heat was produced, efficiency suffered, and the process was difficult to control with any degree of precision. Regenerative drive systems were developed to minimize these problems. "Regeneration" is the process of feeding excess energy from load into conventional AC power lines.

Electronic switching devices such as mercury pool tubes, thyratons, or thyristors can control power flow in either direction by instantaneously connecting the AC line to a DC motor during a selected portion of each cycle or half cycle of the AC line voltage. The variation of conduction periods is referred to as "phase control" and is also used to control power to welders, heaters, industrial arc furnaces, battery chargers, and numerous other loads. All three types of switches have one common characteristic. The turn "on" signal can be removed and the switch will continue to stay "on" until external conditions reduce the current through the switch to zero. In some cases, this occurs naturally at some time in the cycle; in other cases additional circuitry is needed to force the current to zero to turn the switch "off".

A greatly simplified explanation of how power can flow in either direction can be seen in figure 1, showing the AC voltage and current waveforms of a single phase line supplying an inductive load. Although a purely inductive load consumes no power, current flows through the load, and power is instantaneously traded back and forth with the AC lines.

During intervals marked "C", the voltage and current are in the same direction, and power flows from the line to the load. During intervals marked "D", voltage and current oppose each other, and power flows from the load to the line. If the load is a pure inductance, areas C and D are equal, and the average power is zero.

A modern DC drive system uses this relationship in combination with high speed switches to allow current to flow during one of these times, and to block the flow of current during the other time. If power is required to flow from the line to the DC motor, the switch is closed during the times marked C and opened during the times marked D. Similarly, if it is desired to extract power from the DC motor, it is connected to the line during D intervals and disconnected during C intervals.

SYNCHRONOUS INVERSION

If the basic concept of regenerative power feedback used for retreival of load energy in a DC drive is adapted for general conversion of DC power to AC, such a system can be used to efficiently take advantage of alternate energy sources. All that is required is to first convert the alternate energy to DC. If the alternate energy is mechanical, it can drive a DC generator or an alternator whose output is then rectified. Solar cells can convert sunlight directly to DC power. Other forms of energy are already DC and can be connected directly with such a system to an AC source.

In its simplest form, a single phase AC line is connected to a source of DC power through what looks like an ordinary bridge of thyristors. Notice, however, that the polarity of the DC side of the bridge is reversed when compared to a thyristor bridge intended for converting AC to controlled DC. Figure 2 shows this basic connection.

Figures 3 and 4 show two alternate paths for current flow from the DC source to the AC lines, arranged so that each path is suitable for power flow to the line in one of the half cycles during the interval that corresponds to the D area in figure 1.

Figure 5 shows waveforms of AC line voltages and the DC source for the path that is shown schematically in figure 3. While an arbitrary value of DC voltage is shown, the actual magnitude can be any value from zero to the peak of the AC wave. During the positive half cycle, there are two intervals, A and B, where the DC voltage is instantaneously more positive than the AC line voltage, and current flow from the DC source to the line will oppose line voltage, so that the flow of power is to the line. Current flow in the same direction is also possible during the negative half cycle, but since the AC voltage has reversed, current no longer opposes the line voltage, and power flow is in the wrong direction, from the line to the DC source.

Time intervals A and B have one significant difference. During interval A the difference between the AC and DC voltages is initially high and decreases to zero. This condition is useful when thyristors are used as the switches, since it automatically reduces the current in the thyristors to zero and the thyristor turns off or "commutates" naturally. In interval B, however, the voltage differential is zero initially and increases with time until it reaches a large value at the end of the interval. To operate in this time interval, a switching device must therefore have an independent means of commutating to an off state. With transistors this is relatively simple, however, thyristors require complex commutating circuitry. For this reason, when thyristors are used as the switching element, the conversion period is generally limited to time interval A, and the inverter is known as a "line-commutated inverter", since the line voltage itself provides the reduction in current that turns the device off.

While the circuit of figure 3 and the waveforms of figure 5 demonstrate the transfer of power from the DC source to the AC line, the current is of a single polarity, and the DC power it represents

FIGURE 1

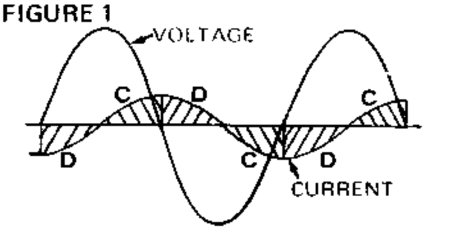


FIGURE 2

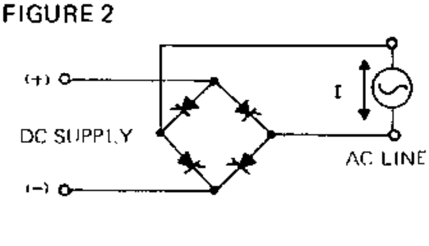


FIGURE 3

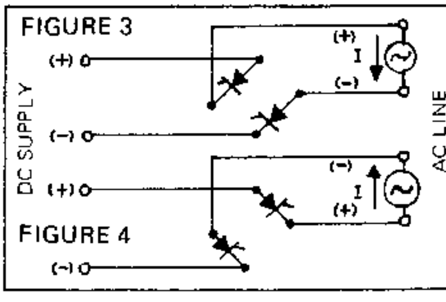


FIGURE 4

would not generally be useful, would tend to saturate transformers, and could not be transformed to distribution voltage levels. The alternative conducting path shown in figure 4 provides a reversed polarity of the DC source for conduction in a similar period of the other half cycle.

The waveforms of figure 5 now become those of figure 6, showing the effects of the reversed DC voltage in the negative half cycle. The current is now truly AC, can be readily transformed, and is compatible with ordinary AC appliances.

Figure 7 illustrates the voltage and current waveforms that result from the relationships in figure 6.

Although this description has shown single phase circuits for simplicity, the same principles apply to multiphase circuits.

QUALITY OF THE INVERTED POWER

To prevent disturbing the waveform of the AC line voltage with this type of inverter, the impedance of the DC source must be many times larger than that of the AC line, since connecting any two voltage sources together results in a terminal voltage that is divided between them in a manner porportional to their individual impedances. A relatively large DC source impedance allows the connection to the AC line to be made without changing the line waveform, and the voltage at the output terminals of the synchronous inverter is therefore the normal line voltage, both in magnitude and frequency, without distortion.

The normally inductive impedance of a DC generator fits this requirement. An inductive source, in addition, tends to spread out the conduction periods which results in lower resistive losses due to improved form factor. Any installation of a synchronous inverter of this type must be engineered for proper impedance ratios, and inductance added to the DC source, if required, to maintain line voltage integrity.

While the voltage waveform is very likely a nearly perfect sine wave, the output current of the inverter is an entirely different matter. Even though AC in nature, it is delivered in pulses, once each half cycle, and the shape of these pulses is dependent on both magnitude of the DC voltage and the total impedance in the DC and AC sources. Prediction of the shape of these waveforms is a very complex problem. Analysis of existing waveforms, however, is not as difficult, and an analysis of harmonic content of a specific installation is shown in another section.

The current of a synchronous inverter occurs with the same polarity and during the same part of the cycle as would an inductive load current. For this reason, the introduction of power in this manner is seen by the power line as an additional lagging VAR load, and the effects are generally the same.

Tests indicate that standard power factor correction techniques are as effective for inverted power as they are for normal inductive loads.

Metering accuracy of standard kilowatt hour meters has been compared to a digital meter having an accuracy of 0.1%. Even with the pulsed currents, no significant inaccuracy was found in the standard kilowatt hour meters. It is assumed that metering accuracy will be maintained as long as voltage waveforms are not distorted, since the voltage coil of the meter has a slow response which may not be able to react to the harmonic voltages as easily as the faster current measuring coils can respond to the harmonic currents.

OTHER CONSIDERATIONS

A synchronous inverter that takes advantage of the line voltage for commutation of its switching devices cannot function without the line voltage present and must be automatically disconnected when the line fails. If not, the thyristors may cause a fault at the DC source and the power lines could possibly have DC voltages that would be dangerous to personnel working on the lines.

GEMINI synchronous inverters prevent both of these problems by using a contactor to isolate the DC source from the inverter and the line in the event of power failure. The coil to this contactor is energized by the AC lines, and therefore the contactor will open immediately on loss of AC line power.

The switching action of the thyristors is quite capable of causing radio or TV interference, and filters to prevent this are part of the design. An interference filter consisting of a line reactor and a capacitor is included in the line voltage terminals at a Gemini inverter to minimize these types of interference.

COMPARISON WITH OTHER METHODS

Most other methods of adding power to the utility grid system use rotating machinery to generate the AC by direct connection to the power lines. The generators may be synchronous alternators, squirrel cage induction motors, or wound rotor induction motors.

The advantage of any of these methods over the synchronous inverter lies in the low harmonic content of the generated current. With a synchronous alternator, there are the additional advantages of controlled power factor and the ability to function as an independent source of AC in the event of a power line failure.

With either a synchronous alternator or a squirrel cage induction generator, the operating speed is either fixed or must remain within a narrow range. This constraint is not consistent with the variable nature of waste energy sources. In the case of the synchronous alternator, additional complications arise when momentary loss of source energy requires a disconnect, followed by a subsequent resynchronization.

The wound rotor induction motor can operate above synchronous speed over a fairly wide range of speeds, but control of secondary power can be complex, possibly best accommodated by the use of the versatile synchronous inverter.

Advantages of the synchronous inverter includes of handling wide voltage variations of both rotating and non-rotating sources, active and passive control for maximizing extraction of energy from the source, highly efficient operation, and low cost.

FIGURE 5

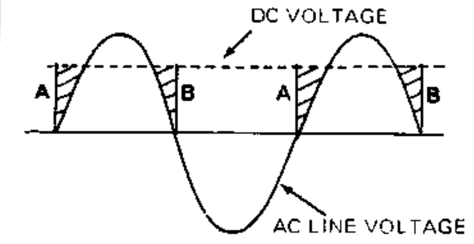


FIGURE 6

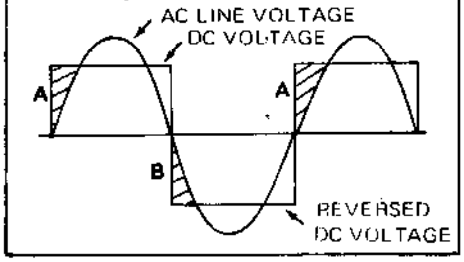
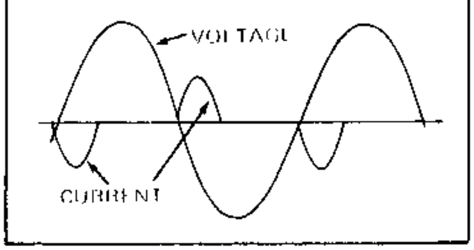
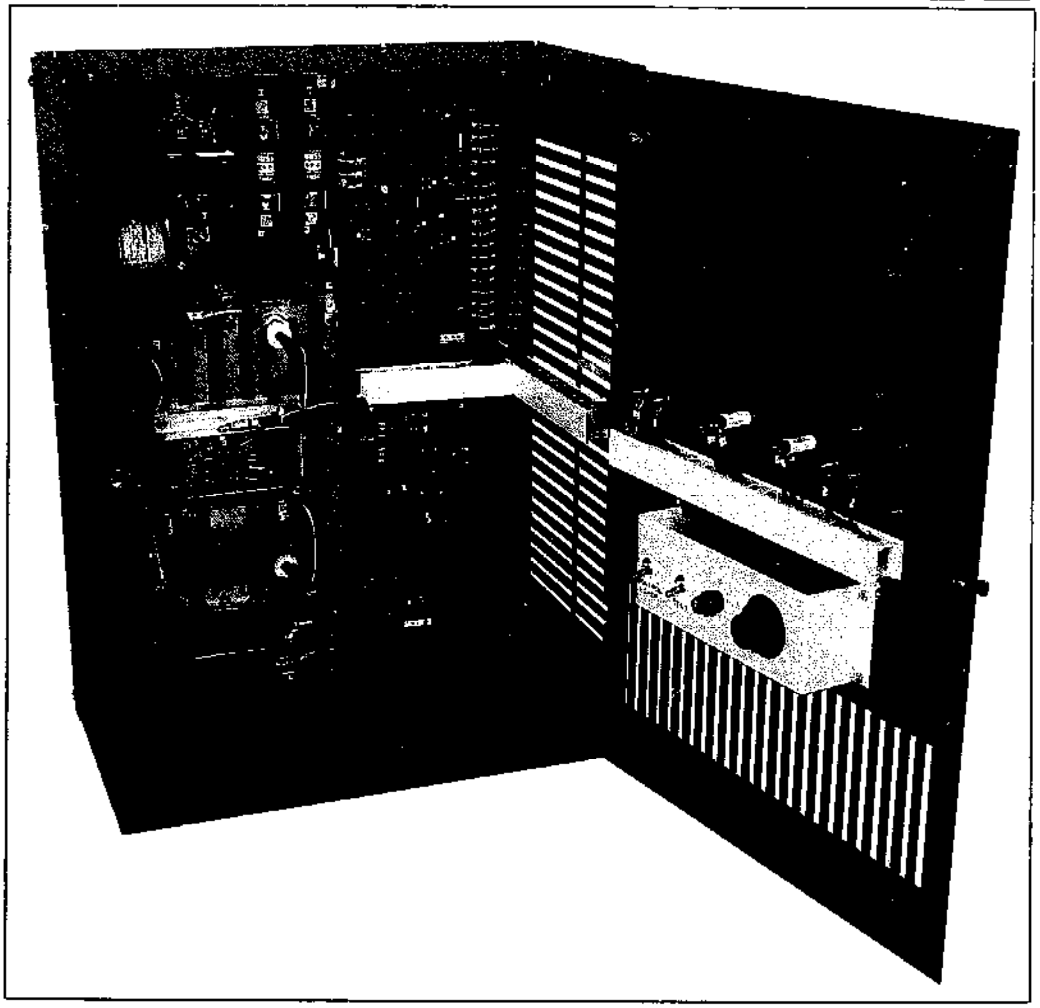


FIGURE 7



GEMINI



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