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MASTER

DC TO AC POWER CONDITIONING FOR PHOTOVOLTAIC ARRAYS AND UTILITY INTERFACING

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1. Introduction

The key to widespread usage of photovoltaic power systems in all but remote systems is the availability of efficient, low-cost DC to AC power conversion equipment over a wide range of power levels. The development of this equipment is based on technology already existing in products such as uninterruptable power systems, regenerative motor drives, high voltage DC power transmission equipment, and others. The modifications required to adopt the equipment for use with photovoltaic sources can sometimes be extensive and presently, very little equipment is available which has been developed strictly for use in photovoltaic systems. In order for the photovoltaic system designer to adequately assess the requirements and trade-offs imposed on the system design by the power conditioning equipment, it is necessary that he have a working knowledge of DC to AC power conversion. The purpose of this paper is to help impart that working knowledge.

For the purposes of discussion herein, two definitions are made. Power conditioning is the process of transforming the raw DC power from a photovoltaic array into power of the quality required by the load. An inverter is an element of power conditioning whose purpose is to change DC power to AC power. Thus a photovoltaic power conditioning unit (for conversion from DC to AC) includes not only an inverter but other necessary control and power handling subsystems as well.

2. DC-AC Conversion Techniques

The most straight forward approach to DC-AC power conversion is simply to mechanically couple a DC motor to an AC generator. The efficiencies of rotating machines range from approximately 75 percent at the one KW level to approximately 95 percent at the 500 KW level. Thus the combined efficiencies of motor-generators will range between 56 percent and 90 percent at these power levels. The relatively high cost of photovoltaic electricity imposes a requirement for high efficiency in the power conditioning. In the lower power ranges, solid state inverters can easily exceed the efficiency of motor-generator combinations albeit at somewhat higher costs. At higher power levels, the differences between efficiencies and costs of rotating machinery and solid state inverters are not as large proportionally but the scales are still tipped in favor of the solid state devices.

The basic solid state, or static, inverter circuit and its output waveform are shown in Figure 1. As can be seen, the output is a square wave when the appropriate switches are alternately switched at the same rate. The process of reversing the polarity at the output by switching is termed commutation. In practice, the switches are either transistors or silicon controlled rectifiers (SCR's, sometimes called thyristors). Either an inductor or capacitor is required on the DC input to isolate the array from the alternating voltages generated by the switching action. Also, if a raw square wave is not a suitable form of AC output, then some filtering must be included. A transformer may or may not be necessary at the output. Finally, a logic subsystem must be included which controls the on-off cycling of the switching elements.

Transistors are ideal elements for the switching functions necessary in DC-AC inversion but their application is limited to low-power designs because of their power dissipation capability. They are being used today in single phase systems up to 10 KW and three

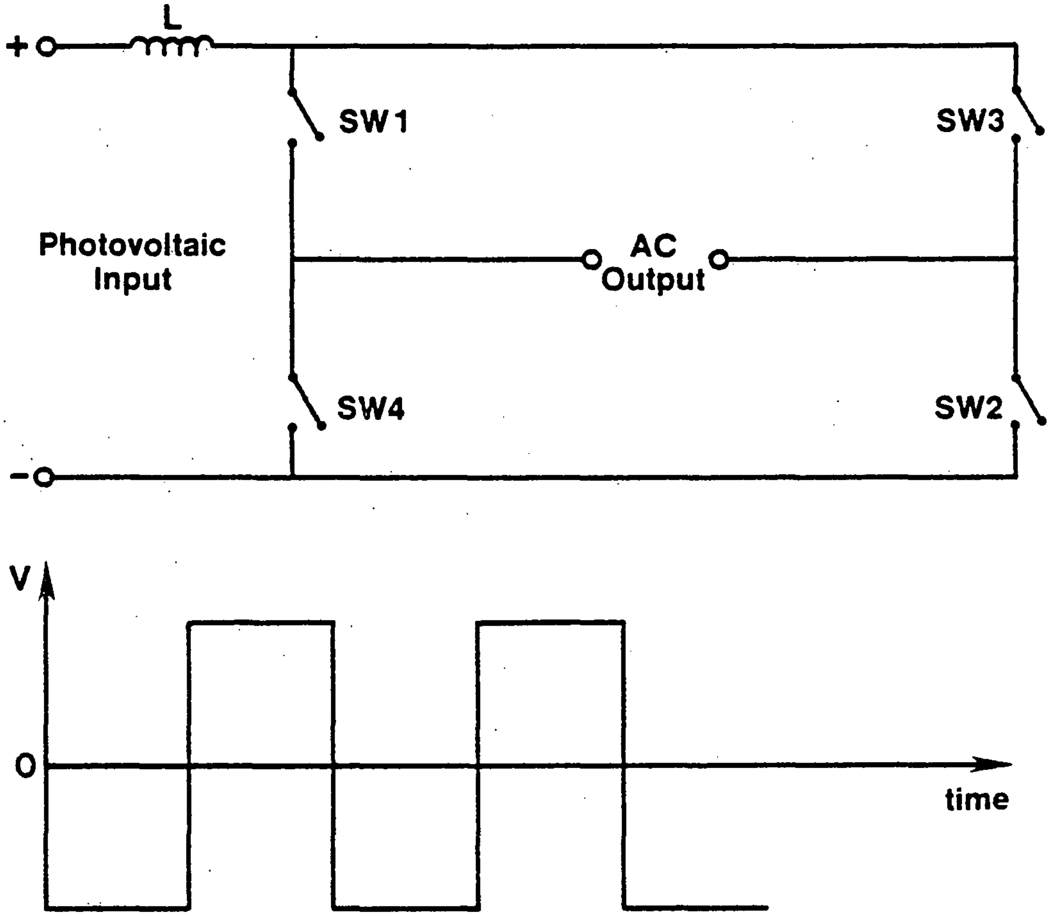

Figure 1. Basic inverter circuit and output waveform

phase systems up to 30 KW. However, advances in power semiconductor development are constantly raising the power handling capability of these devices. Some higher power units have been built with many transistors operating in parallel, but the circuitry becomes very complex: it is impossible to force transistors in parallel to share the load during the inactive switch-off mode of operation and difficult to force them to share the load in the conducting state. Transistors have two major advantages over SCR's: 1) they are easily turned on and off and, 2) they can be switched at relatively high frequencies. However, they will always be more costly than SCR's of the same power handling capability.

Silicon controlled rectifiers, on the other hand, have successfully been used as switching elements in high power inverters and related applications and are currently operating in series-parallel arrangements in high-voltage DC transmission line terminals at power levels of hundreds of megawatts. Unlike transistors, SCR's cannot be turned off by a control signal. To turn an SCR completely off, the current through it must be reduced to zero for a specified length of time. The energy to accomplish this turn-off may be supplied either internally from energy storage circuit elements such as capacitors or externally by connecting the inverter to an AC power source. New types of devices (for example, the gate turnoff SCR which can be turned off by a gate pulse) are beginning to emerge from the laboratory but presently the current handling capability and cost of such devices precludes their application in power inverters.

The method used to turn off the SCR's leads to the classification of inverters as line commutated when the energy is supplied by an external AC source and self-commutated when energy storage circuit elements within the inverter supply the commutation energy. Note that inverters utilizing transistors as switching elements are naturally self-commutating. Also, only self-commutating units can be used in stand-alone applications. The choice of self-or line-commutation is the most significant factor effecting the design and operation of the inverter.

3. Line-Commutation

Figure 2 shows the basic line-commutated inverter circuit. This circuit is a controlled full-wave rectifier with the DC polarity reversed. Also shown in Figure 2 is the sinusoidal waveform that is present (supplied by the utility) at output terminals a and b of the inverter. At point A on the curve, SCR3 and SCR4 are triggered connecting the positive side of the DC source to output terminal b and the negative side to terminal a. The current temporarily stored in the input inductor is forced into the AC system until the AC voltage rises to such a level as to effectively stop the current flow through the SCR's which turns them off. At point B, SCR1 and SCR2 are triggered connecting the positive and negative DC terminals to output terminals a and b respectively and a similar current flow occurs.

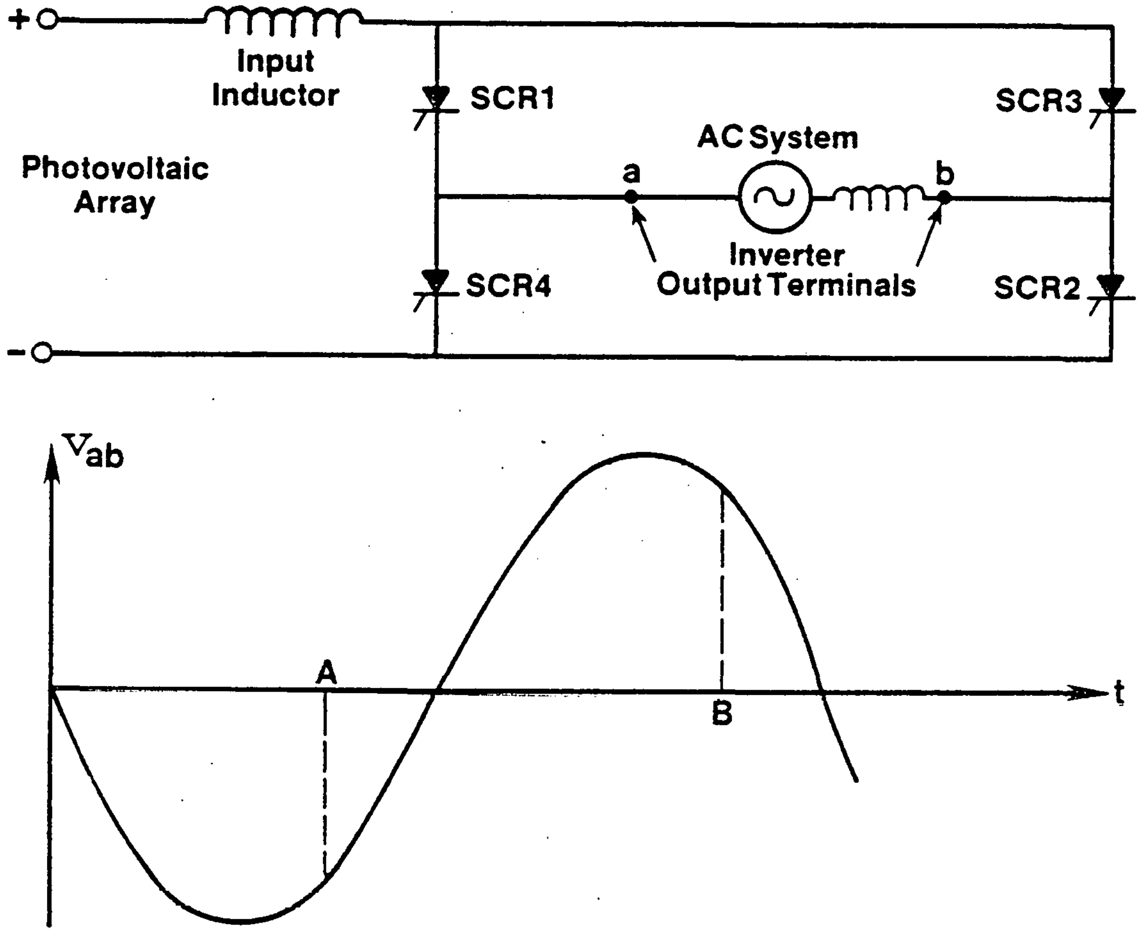

Figure 2. Line-commutated inverter circuit and utility voltage waveform

The amount of power returned to the AC system is a function of the time in the cycle at which the SCR's are triggered, (called the firing angle), that is the position of points A & B. Note that the line commutated inverter presents a lagging power factor to the utility. This power factor is a linear function of the ratio of the DC voltage level to the AC rms voltage. For single phase systems, the power factor ranges from 0.0 to 0.90 as the DC voltage ranges from 0 to a maximum 89 percent of the AC rms line voltage. For three phase systems, the power factor ranges from 0.0 to 0.95 as the DC voltage ranges from 0 to a maximum of 135% of the AC rms line voltage. A transformer may be used to match the DC source to the appropriate AC rms voltage and power factor correction may be used. It is important that the DC voltage not be allowed to increase above the maximum levels given above because the SCR's would then be unable to switch off resulting in current over loading (short circuiting the DC source).

In addition to the power factor and DC voltage restrictions on the line-commutated inverter, it also injects significant current harmonics into the AC system. The current contribution in the odd harmonics can reach levels as high as 30 percent of the fundamental current. Thus it is important to have adequate characterization of the AC system to which the line commutated inverter will be connected. Specifically, the DC source impedence must be many times greater than the AC source impedence in order to prevent the unfiltered output of the inverter from effecting the AC power quality. Alternatively, filters (harmonic traps) may be used to "clean up" the line-commutated inverter's output although such filters may seriously effect power conditioning cost and efficiency.

The primary advantage enjoyed by line-commutated inverters are their inherent simplicity. The theory and technology used in regenerative AC motor drives and in high voltage DC power transmission is directly applicable. Also, the simplicity and low parts count imply low cost.

4. Self-Commutation

In self-commutated inverters, the AC output is generated within the inverter independent of any utility interaction. Thus self-commutated inverters can operate in the stand-alone mode. Initially, let us assume that only stand-alone operation is of interest. Thus the inverter must supply AC power of suitable quality for a specific load. The inverter must respond to increasing load requirements without major fluctuations in AC voltage or frequency.

Generally, there are three methods for the synthesis of the sinusoidal output from the inverter. The first is the square wave as shown and produced by the circuit in Figure 1. An inverter of this type is relatively simple, reliable, and efficient. However, the harmonic content of the output is high; a square wave contains all odd harmonics in inverse proportion to the number of the harmonic so that the ratio of the third harmonic to the fundamental is 0.333, the fifth is 0.20, etc. To obtain a low-harmonic sine wave requires substantial filtering thus adding cost and reducing overall efficiency. A trade-off can be made, however, based on the quality of the power required by the load and the cost and efficiency of the required filtering. Thus it is conceivable that a square wave generator with minimal filtering might be the optimal inverter for some applications.

There are three popular methods for controlling the output voltage of a square wave generator. The first method employs a DC voltage regulator between the DC source and the inverter section. In this way, the inverter always operates at a specific input voltage and the regulator operation can be controlled automatically with a feedback loop. The disadvantage of this method is that the power must be handled twice: once through the regulator and again through the inverter which will cause the overall efficiency to drop. In an effort to avoid this drawback, two square wave generators can be operated in parallel from the same DC source with a variable phase shift between them. When they are operated 180, out of phase, no power is delivered to the load and when operated in phase, maximum power is delivered to the load. The disadvantage to this method of voltage control is that harmonic filtering requirements become more severe. This is because at some relative phase angles, the harmonics of the two square wave generators add in-phase and become a much higher percentage of the fundamental frequency. By far the least complex method of voltage control is obtained by using a ferroresonant transformer on the output of the square wave generator. This will provide voltage regulation, harmonic suppression, and overload protection in a single circuit. Because of the transformer's large leakage reactance, the square wave in the primary circuit is not transformed into the secondary. Instead, the impulse from the primary activates a tuned, saturating magnetic circuit and AC capacitor combination. At a constant frequency, this tuned circuit provides a constant voltage to the load. The harmonic content of the ferroresonant transformer output is satisfactory for most applications. The square-wave ferroresonant transformer inverter provides a constant voltage and constant frequency that are not field adjustable. The overall efficiency runs from 70-85 percent depending on power level.

The second common method for the generation of sinusoidal output from an inverter is a step-wave approach. With this technique, several square wave generators are controlled in phase and amplitude to make a step-wave as shown in Figure 3. Usually, the steps are evenly spaced across 360, and the height of each step is selected to eliminate low order harmonics. Most popular are 12 and 24 step waves. In practice, step-wave synthesis is usually not employed in single phase systems because it greatly increases switching circuit complexity; more square wave generators are required. For three phase systems, however, positive and negative half-cycle symmetry can be used to generate three phases with a single set of components thus power sharing.

Voltage control with the step approach is similar to that of the single square wave generator. A separate voltage regulator (with its inefficient double handling of power) is one approach. A phase shifter that moves a second complete set of steps with respect to the first is most often used in large SCR uninterruptable power systems.

Finally, the third method of sine wave synthesis has been made possible largely by the introduction of inexpensive large scale integrated circuits and higher power switching transistors. With this method, the sine wave is digitally synthesized by switching the transistors at rates significantly higher than the fundamental. Unfiltered digitally synthesized sine waves are shown in Figure 3. The advantage of this method is that the pulse pattern can be tailored such that all harmonic distortion is in the higher order harmonics which are much easier to filter. The digital synthesizer regulates voltage by increasing the amount of time the pulse pattern stays at zero as the DC voltage increases. At least two methods of digital sine wave synthesis for power inversion have been developed to commercial hardware. The first uses a programmable read-only memory to store the pulse pattern and the second generates the pulse pattern dynamically by modulating a high frequency square wave generator with a reference sine wave signal.

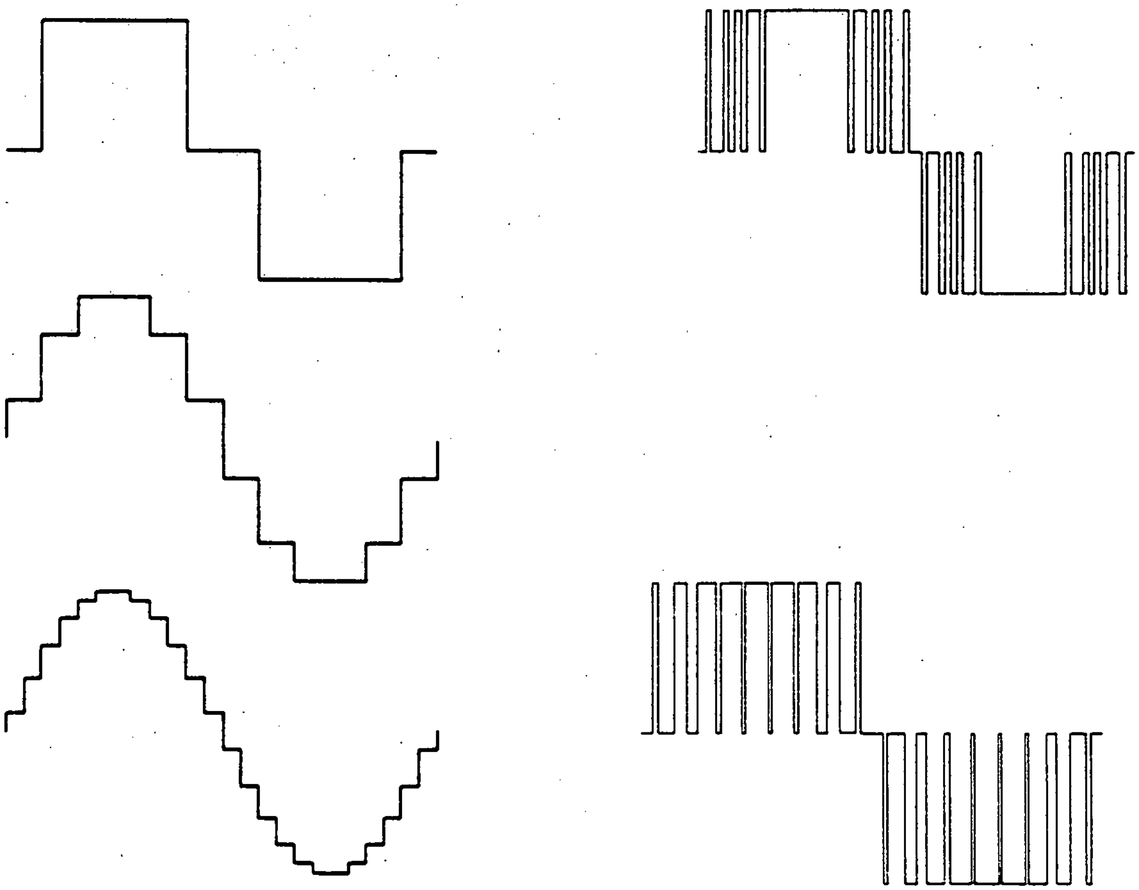

Figure 3. Step-waves and digitally synthesized approximations to sine waves

5. Utility Interconnection

In the case of line-commutated inverters, utility interconnection is already accomplished notwithstanding the concerns of harmonic injection into the AC system and power factor. For self-commutated systems, however, the problem is significantly different. In essence, a self-commutated inverter which is connected to an existing utility grid can be considered simply another generator which can be added to the utility's overall capacity. Thus, to connect a self-commutated inverter to the utility line, the inverter's output must be phase-locked to the utility system and the rms voltages must be equal. At this point, when the actual connection is made, no current (and thus no power) will flow. After the connection has been made, the inverter can then be controlled such that the phase of the inverter output leads the phase of the utility, thus transferring real power to the utility, as shown in Figure 4. The phase difference between the utility and inverter voltage waveforms is used to control the real power delivered to the AC system from the DC source. The difference in peak values of the voltage waveforms controls the reactive power exchanged between the utility and the inverter. This can be controlled (within the design limits of the inverter) to present the utility with any desired power factor, leading or lagging.

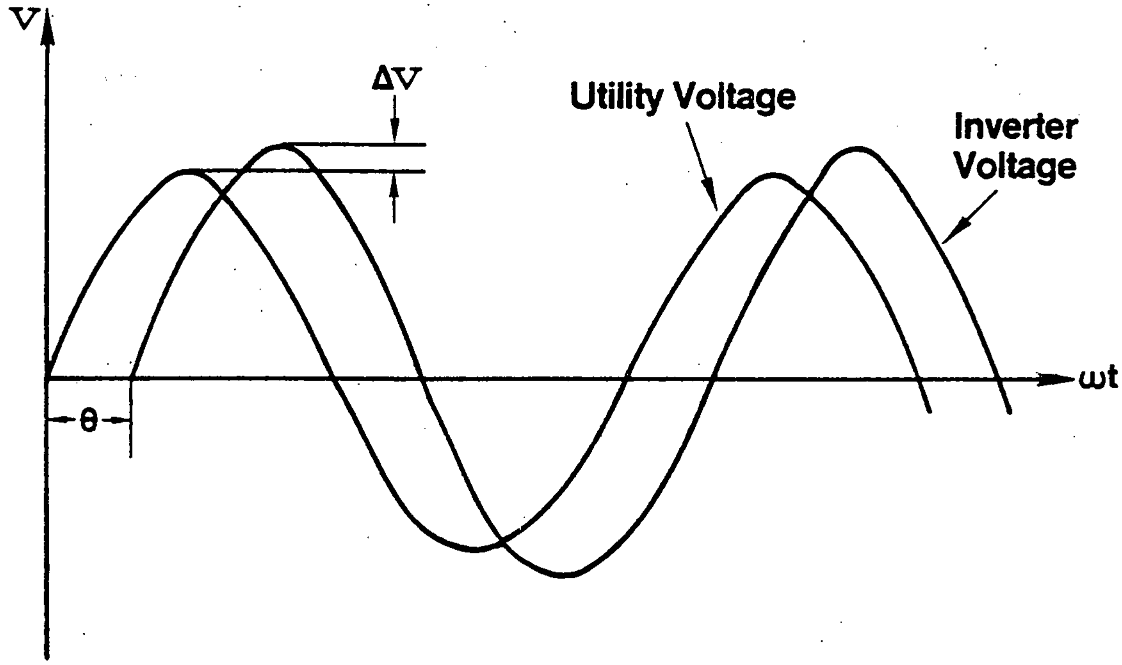

Figure 4. Relationship between Inverter voltage and Utility voltage in Self-commutated inverter operated in parallel with utility

Problems with the operation of self-commutated inverters in parallel with utility systems usually arise because of transient conditions on the utility side. The presence of significant noise on the utility line can cause phase-lock to be lost. Transient excursions in utility voltage can be severe enough that the inverter system cannot respond effectively thus causing abnormally high current flows. The severity of these problems is determined by the characteristics of the specific utility system at the point of interconnection.

6. Application Of DC To AC Conversion To Photovoltaic Systems

The nature of photovoltaics as a DC source has certain implications on the design of inverters for use in power conditioning systems. The photovoltaic source is inherently "soft", i.e., it is a high impedence source. Indeed, short circuit current from a photovoltaic array is seldom more than 125 percent of maximum power current. This fact can be used to alleviate the need for over-current protection in the inverter. However, the photovoltaic source voltage can vary significantly over normal operating ranges, making it difficult to design a highly efficient inverter which produces high quality power. Also, the current state of the art in array technology tends to preclude photovoltaics from employment in higher voltage applications. The upper limit on array voltage with today's photovoltaic technology is approximately 500 volts DC. This implies that the inverter used for power conditioning will tend to be a high current device instead of a high voltage device.

Solar photovoltaic DC sources also lead to several interesting control problems. The most obvious problem concerns itself with automatically turning the system on at sunrise and turning it off at dusk. This is most easily done by measuring the current through a resistance across the array output. When a specified threshold has been reached which insures that the array electrical output can support the internal losses in the power conditioning unit, the resistance is switched out and the system is powered up. It is sometimes difficult to design a control algorithm that adequately distinguishes between sunrise and sunset and periods of intermittant cloudiness. Periodic on-off cycling of the photovoltaic system throughout a cloudy day is usually undesireable. Other control problems include the proper action to be taken for system overload conditions, component failure, and in the case of utility interconnected systems, control sequences for various abnormal utility conditions.

There are three basic photovoltaic system configurations which have significant impact on power conditioning design. The first configuration, shown in Figure 5, is the simplest of the three. Here, all available photovoltaic output power is fed directly into the utility network. Insofar as the power conditioning is concerned, the "load" is the utility grid and the specific application is unimportant. In this configuration, it is usually advantageous to maximum power track the array. This is an automatic control mode which commands the inverter to present the photovoltaic array with the impedence necessary to extract maximum power from it at all times. This is done by varying the firing angle in line-commutated units or the phase angle between the utility voltage and the photovoltaic power system voltage in self-commutated units thus varying the power delivered. It is usually accomplished in a closed-loop feedback fashion whereby the photovoltaic system output power is measured, the firing angle or phase angle is varied (dithering), the new output power is measured, compared to the previous value, and a decision is made to either increase or decrease the firing angle or phase angle. This process is repeated continually thus extracting the maximum power from the array under varying conditions of temperature and insolation. Note that this operating mode can only be used when the load is larger than the array output. The advantages in terms of power conditioning design for this particular system configuration are 1) it is relatively simple, 2) the inverter need be designed only to handle maximum array output; load dependent requirements (such as motor starting transients) can be ignored, and 3) either line-or self-commutated units can be used. The major disadvantage of this configuration (as far as the power conditioning design is concerned) is that the inverter must be able to respond to all utility system conditions, steady-state or transient.

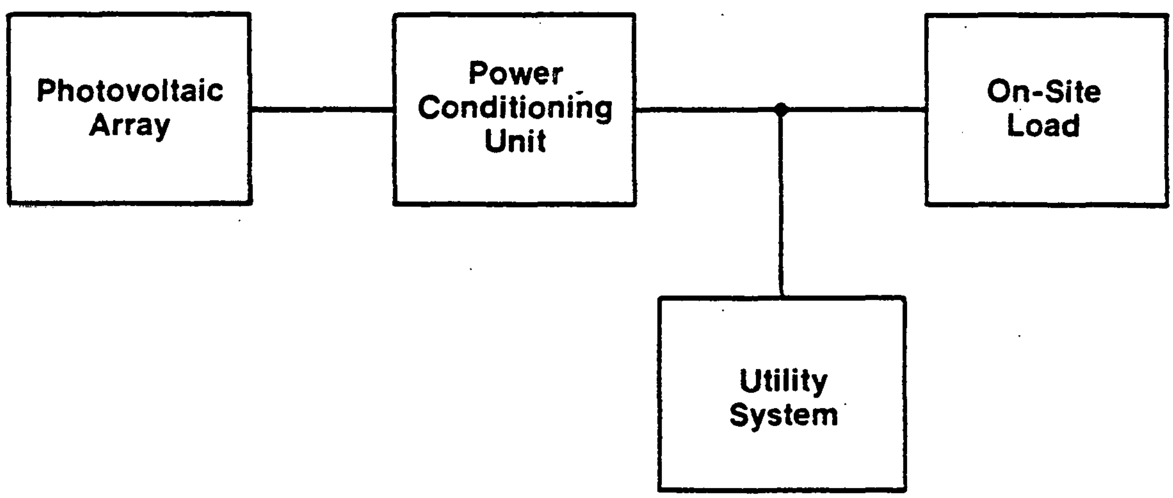

Figure 5. Basic utility interconnected photovoltaic power system

The second basic configuration, shown in Figure 6 is a stand alone system. Here, energy storage (usually a battery) is provided to meet load demands when photovoltaic output is insufficient or unavailable. In its simplest form, this configuration has the photovoltaic array connected in parallel with the battery storage subsystem allowing the battery voltage to determine the array's operating point. A more efficient configuration (although perhaps not more cost-effective) consists of a DC to DC converter between the array and the battery subsystem to present the array with an optimal impedence while providing optimal charging current for the battery. In either case, the power conditioning unit AC output is determined strictly by load demand which can place stringent requirements on inverter design. For example, when starting AC induction motors under load, in-rush current can be seven to eight times full load current. If the induction motor power requirements are near the power conditioning unit's maximum output capability, it is extremely difficult to design an inverter which can start the motor without significant voltage deviations. Also, the power quality required by the load will effect inverter design. Finally, depending on the application and the load, it is often necessary to supply some sort of back-up power system for those occasions when successive periods of poor weather render the photovoltaic power system inoperative. This back-up can take several forms; diesel-generator, utility connection, etc. Thus in terms of power conditioning design, it can be seen that this configuration requires detailed knowledge of the load characteristics. Any unique requirements of the load must be considered in the design of the power conditioning subsystem. The control problems include overcurrent, overvoltage, and undervoltage sensing and protection, battery charge control, and perhaps automatic load shedding and/or back-up power supply dispatching.

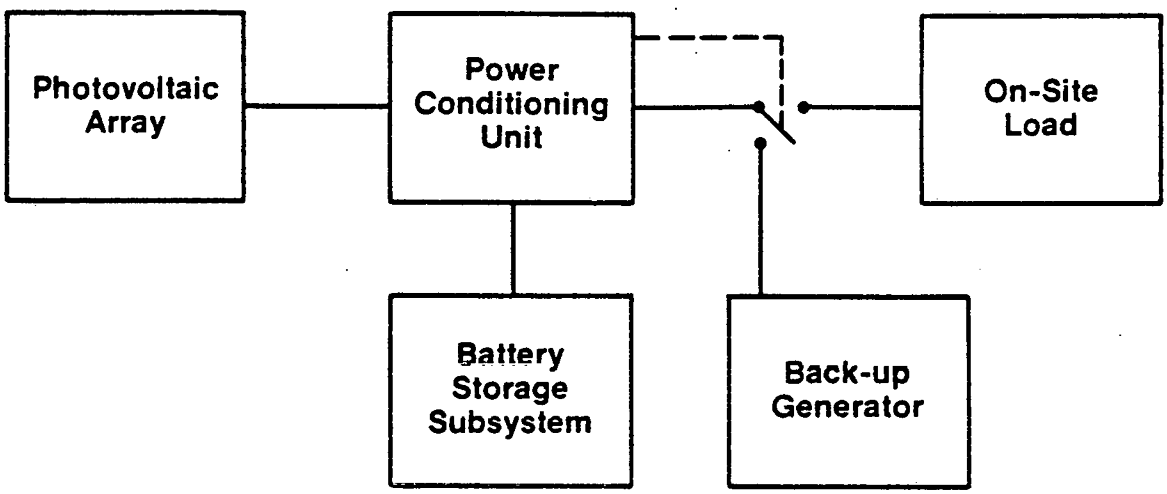

Figure 6. Stand-Alone Photovoltaic Power System

The third configuration is simply some combination of the first two in which battery storage is present and parallel utility interconnection is also required. Clearly the control options associated with this configuration are the most complex. Algorithms must be developed which determine in what combination energy is to be supplied to the load from the photovoltaic array, the battery storage subsystem, and the utility. In addition, the battery storage subsystem may be charged either from the photovoltaic array or the utility. The implications of these operational characteristics on power conditioning design are of great significance and the cost of developing a power conditioning and control subsystem with the necessary sophistication to perform these functions must be weighed against the economic need for such operational flexibility.

7. Conclusions

While the art of solid state DC to AC power conversion is well-developed, there is by no means a clear resolution of which of the conversion techniques is most appropriate for photovoltaics nor is it likely that such resolution will ever occur. The various power conditioning design options are likely to follow in some sense the variety of possible photovoltaic applications. Also, while certain well-developed industries and markets presently exist for power conversion equipment, these markets are relatively fixed. Development of power conditioning equipment for photovoltaic applications will most likely evolve from these industries but not until a market for such equipment is well established. Finally, the requirements for power conditioning for photovoltaic applications are sufficiently unique that simple adaptations of existing equipment will not support widespread useage of photovoltaic power systems.