most PV generators will be interconnected with electric utilities, the Kansas Electric Utilities Research Program commissioned a study of utilities' experience with PV generation as part of a project to prepare Kansas utilities for the time when PV generation becomes feasible.

This paper presents the results of this review. Central-station and smaller commerical and residential system experience is reviewed. Design and operational difficulties and their solutions are included. The information here is a first step in letting an interested utility know what is involved in PV generation, and how past problems can be avoided.

Not all utility-interactive PV systems now in operation are covered in this paper. The projects included, however, represent the range of experience that electric utilities have had with PV generation. The information came from published articles and reports, unpublished internal reports, and discussions with utility personnel responsible for the individual PV generators.

This paper is intended to complement two previous papers [2, 3], which outline the history of PV generation and review recent literature on PV. This paper presents information on a number of residential and commercial PV systems that has not appeared in the Power Engineering Society Transactions.

PV generation is a fully commercial technology. A standard single-crystal silicon cell system can be quickly installed and can be expected to operate reliably and as rated with very little maintenance. While a utility should certainly keep the problems outlined in this report in mind as it designs a system, almost all of them have been solved. If a utility today wishes to install a standard PV system with commercially-available equipment, it should be for the experience it will gain from designing, installing, and operating the system, and not as a test of PV system technology.

As new technologies do emerge, such as amorphous cells and EPRI's point-contact cells, there will be systems installed to test these technologies. Technology-specific problems will likely be encountered, and solutions will be sought. There is therefore still experimental work to be done.

Utility-interactive power conditioning units (PCUs) are commercially available that will operate safely and reliably with high power quality. A problem with high-frequency harmonics interfering with a Carolina Power and Light distribution line carrier system raised questions about PCU power quality, but the problem was easily resolved with a simple filter. The protection incorporated into these inverters has been demonstrated safe and effective, and should be accepted by utilities.

The cost of a PV system now depends greatly on the design of the system. Costs of the PV generators discussed in this report varied widely. Much was learned from these and other projects. Design help is available from the Sandia National Laboratory Design Assistance Center, which now has some of the most experienced PV designers in the world. Any utility considering PV generation should take advantage of this service before proceeding.

References

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Microprocessor Control of Double Output Induction Generator, Part I: Inverter Firing Circuit

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Abstract—This paper investigates the design and implementation of a firing scheme using the INTEL 8086 microprocessor to control the inverter firing angle of the Variable Speed Constant Frequency Double Output Induction Generator (VSCF-DOIG).

The INTEL 8086 microprocessor is used to control the firing angle of the DC-linked inverter of the VSCF-DOIG. In this system, the microprocessor computes the voltage signals from a reference voltage pot and then outputs the calculated firing angle shifting time (as opposed to deriving it from a table look-up method) to the interface timer. This gives full range control of the firing angle between 0° and 180°, and updates the phase shifting timer in each cycle based on the values of the past three cycles. The control circuit is designed for multi-tasked purpose.

The hardware, software, interface, I/O, and experimental results are presented in this paper.

Control Scheme

The VSCF-DOIG includes a wind turbine, a wound-roter induction generator, an uncontrolled rectifier, a smoothing inductor, and a controlled rectifier (Figure 1). The INTEL 8086 microprocessor is employed in this paper to control the phase shift of the DC-linked inverter.

The control scheme is described in several functional subsystems (Figure 2). The Zero Crossing Generator generates six pulses from digitized reference signals taken from a power system and then feeds the six synchronizing pulses to the Firing Pulse Generator and the Interrupt Control Circuit. The potentiometer (pot) is used to simulate a feedback transducer. The A/D concerter converts a 0-5V signal from the pot to a digital signal and then passes the data into a block of the Random Access Memory (RAM) via a Direct Memory Access (DMA) technique. Cycle Stealing DMA is employed in this system. It transfers data to RAM directly instead of the usual read-write cycle of the microprocessor.

The Interrupt Control Circuit generates an interrupt (INT) pulse to ask the 8086 action once a cycle. After the 8086 received the INT signal, the microprocessor to take the input data pre-stored in RAM, compute the firing pulse shifting time, and then program the Firing Pulse Generator. Then the Firing Pulse Generator generates six sets of firing pulses to trigger the SCRs.

Software

The processor algorithm which implements the phase shifting control scheme is divided into two main parts. The system Initial program starts executing at the beginning of the power on or after resetting system. The interrupt service routine is used to calculate the input reference voltage signals and gets the value of clock delay.

Experimental Results and Discussion

This system was run according to the control method which was mentioned before. The machine operates smoothly in the motor mode and in the generator mode, in the speed range from 0 to twice the synchronous speed without any problem when crossing the synchronous speed which presents zero supply voltage.

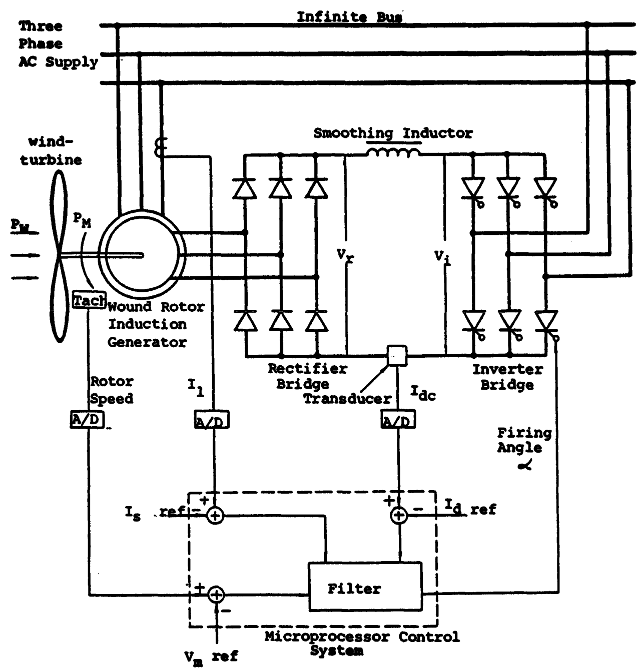

Fig. 1. System schematic diagram.

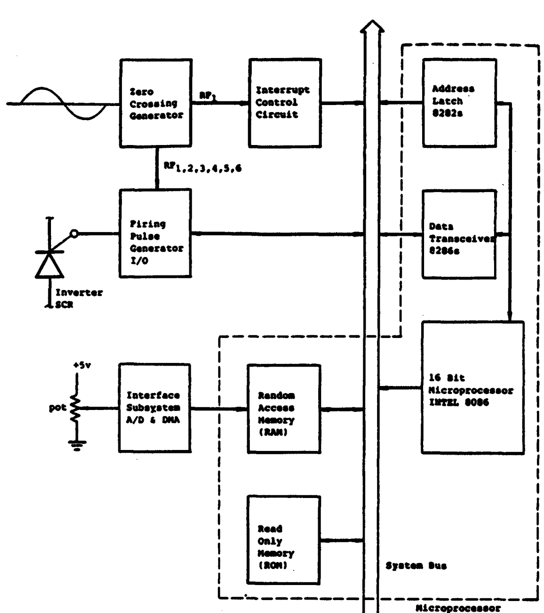

Fig. 2. Control system block diagram.

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Simulation Studies of Islanded Behavior of Grid-Connected Photovoltaic Systems

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"Islanding" or isolated operation usually refers to the continued generation from grid-connected photo-voltaic systems following the interruption of utility power. A special case known as a "run-on" condition involves the operation of a single PV system-load combination when the power conditioning subsystem is designed to operate only in a utility interactive mode. Such islanding or run-on conditions may pose a safety hazard to utility personnel or endanger the integrity of protective and other utility equipment. Live crew personnel, working to repair a fault occurring on the grid, may mistakenly consider the load side of the line to be inactive; in fact, islanding PV sources may be feeding power back to the utility grid through power conditioning units which are normally designed to shut down when such events occur. Also, depending upon the duration of an islanding condition, automatic reconnection of the PV system may present severe resynchronization problems with consequent detrimental effects upon the integrity of utility equipment.

Experimental evidence of islanding or run-on with commercial PV systems has been provided by a number of investigators. Hybrid and complex digital computer programs have been developed to study a variety of islanding configurations. The models require considerable skill and computational power for their implementation and lack portability.

This work is concerned with the development of simplified analytical models of those features of the interconnected PV system-utility grid that affect significantly its isolated operation.

The study focuses on two power conditioning subsystems available commercially for residential PV applications. The control philosophy adopted by most PCS manufacturers is intended to provide optimum conversion while adequately handling the variable electrical conditions and safeguarding the integrity of the interconnection. A utility-interactive self-commutated, voltage-sourced inverter based on high-frequency isolation has been developed by TESLACO to provide a photovoltaic to utility interface at the residential power level of 4 kW. Figure 1 is a block diagram of the TESLACO T-4 kW-A power stage and control circuitry. The dc power from the solar array is converted to a full wave rectified sinusoidal waveform through the push-pull buck stage converter. In the second stage of the inverter, alternate half sine waves are inverted by unfolding to form the complete output sine wave that is matched to the 240 volt ac line.

The most crucial control component responsible for shutting down the transistor bridge in the event of a utility disconnect is the line lock phase-locked loop (PLL). A reference rectified sine wave voltage is generated internally and locked to the line by use of the digital PLL circuitry. Current delivered to the line is automaticaly in phase with the voltage, once it is brought into synchronization with the line through the PLL circuitry. A phase discrepancy between the line and reference signal is used to destabilize the loop upon line disconnection resulting ultimately in inverter shutdown.

For a simplified representation of the PV system-utility grid under islanded conditions, attention is focused upon the dynamic behavior of the PLL circuitry responsible for the regenerative phase difference instability, one one hand, and the determination of the initial phase difference between the internal reference waveform and the terminal voltage upon disconnection of the utility line. The simplified model was tested with a variety of input data. Figure 2 shows typical waveforms obtained when the load power is 3996.27 watts and 178.64 vars. The run-on time is estimated in this case to