LOAD MANAGEMENT IN PHOTOVOLTAIC-UTILITY INTERACTIVE RESIDENTIAL SYSTEMS

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ABSTRACT

Load management is an important problem for hybrid energy systems. In this paper, an interactive model of photovoltaic system (PV) with utility system is used to supply electrical energy to residential applications. The usage and performance of the PV system are measured according to some factors like load power factor, system safety, delivered power quality and maximization of the generated ac energy. Two examples are presented; one for a typical cloudy day in the winter season and the other for a clear sky shinny day in the summer season.

Key words: Renewable energy systems, PV system, PWM Inverters, Load management.

Notation

S_{ref}	Reference irradiance.
S	Value of irradiance.
T	Cell temperature (°C).
T_a	Ambient temperature (°C).
T_{ref}	Reference temperature (°C).
ΔT	Change in cell temperature (°C).
V_{dc}	Module voltage (volts).
V_{ref}	Module reference voltage (volts).
α	Current change temperature coefficient at reference isolation (Amps/°C).
β	Voltage change temperature coefficient at reference isolation (Volts/°C).
n_v	Number of series modules.
n_i	Number of parallel modules.
I_{sc}	Module short circuit current (Amps).
M_a	Modulation index.
A_n	Amplitude of dominant harmonics.
f_o, f_c	Output and carrier frequencies (Hz).
THD_v	Total Harmonic distortion of the output voltage.
THD_i	Total Harmonic distortion of the output current.
V_{in}	Inverter output voltage (Volts).
V_{on}	Amplitude of the *nth* harmonic of the output voltage (Volts).
I_{on}	Amplitude of the *nth* harmonic of the output current (Amps).
I_o	Average output current (Amps).
H_n	Transfer function of the filter and load at the *nth* harmonic component.
Z_n	The output impedance seen by the inverter at the *nth* harmonic component (Ω).
L_f, C_f	Elements of the output filter.
R, L	Load resistance and inductance (Ω).
ω_o	Output angular frequency (rad/sec).

1. INTRODUCTION

During the past decade, a growing interest in renewable energy sources applications has been observed [1-3]. These sources are non-polluting, free in their availability and continuous. These advantages make these alternative sources quite attractive for many applications specially in sites far from conventional power system. This paper describes the characteristics that are important for selecting and designing a solar system for a residential-connected PV system. Since PV modules generate d-c electrical energy and most of the residential load operates from a-c electrical energy, an inverter should be included with the PV systems. Properly designed inverter insures the safety of the system, maximizes the a-c generated energy consistent with the array operating at the maximum power point, ensures high conversion efficiency and delivers high quality power. The system which is modeled in this paper consists of 10kW photovoltaics and it is schematically shown in Figure (1). The average load is considered constant at 8kW with variable power factor. The study here is focused on the load management and the use factor (UF) of the PV system. No attempts have been made to detail the theory of operation of this system and the inverter control circuit.

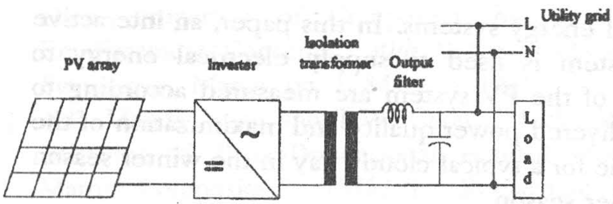

Figure 1. Schematic diagram of the hybrid PV/Utility electrical system.

2. SYSTEM IDENTIFICATION

Traditionally, PV arrays have been used to supply electrical energy to motors in irrigation or ventilation systems [3]. Most of these PV array-powered drive systems use d-c motors because of their d-c operation mode. However, most of low-power domestic appliances need ac electrical energy. Therefore, a d-c/a-c power conversion stage is required as shown in Figure (1). This can normally be achieved by an inverter which is preferably controlled by pulse width modulation (PWM) techniques with constant frequency output voltage and, at the same time, provides sinusoidal output voltage synchronized with the utility voltage [4]. The load is connected to the system through an isolation transformer which could be a step-up one.

PWM techniques are usually preferred over square-wave control techniques in order to reduce the harmonic content in the output voltage and therefore reduce eddy current loss, acoustic noise and overheat at the transformer. Also, due to the non-linearity of the voltage-current characteristic of the PV array, a maximum power point tracker (MPPT) is usually incorporated in the array control stage in order to extract the maximum possible power.

The total harmonic distortion (THD) of the overall output voltage and current are considered as the deciding factors of whether the inverter will be turned-on or -off. The battery bank in this case has the effect of continuing the operation of the inverter in the cases of over- and under- voltages when the array voltage goes beyond the boundaries of the inverter operating voltage.

If we consider the average irradiance levels during the day for both summer and winter are shown in the histograms of Figure (2).

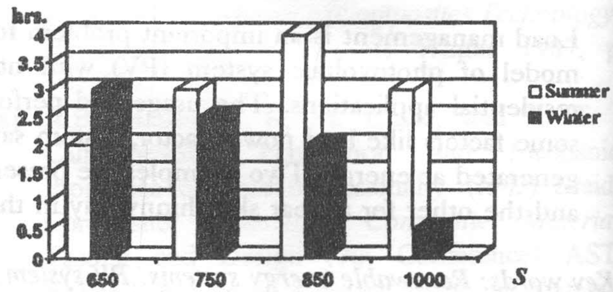

Figure 2. Average daily summer and winter irradiance levels.

3. SYSTEM SIMULATION

The performance characteristics that distinguish ac power supplies based on PV arrays from other static ac power supplies include [5]:

- Constant amplitude and frequency for the load voltage while the array voltage may vary from 10% above to 20% below its rated value.
- Load voltage and current with minimum harmonic distortion.
- Sinusoidal output voltage regardless of the load.
- High efficiency with minimum power conversion stages.
- Isolation at low weight and cost.
- High reliability.

PWM inverters are suited to meet these requirements, since they allow the implementation of effective voltage and harmonic control techniques while employing a minimum number of active and passive components [4]. The number of PWM voltage and harmonic control techniques that can be implemented is theoretically infinite. However, each technique requires a specific number of switching transitions per cycle and produces an inverter output voltage with a specific harmonic profile [5]. Also, the reduction of the size, and hence cost, of the output filter should be taken into consideration by increasing the carrier frequency of the PWM technique. However, it is emphasized that the higher the number of switching instants per cycle, the higher the switching loss and consequently the lower the inverter efficiency. Similarly, the larger the amplitude of the low-order harmonics in the inverter output voltage, the larger the size and the lower the efficiency of the load filter. The choice of the carrier frequency, and therefore the switching frequency, mainly depends on the power rating of the inverter. Performance characteristics of an inverter power conversion scheme largely depends on the choice of the particular PWM strategy employed.

To achieve the required characteristics, the sinusoidal PWM (SPWM) control technique with variable modulation ratio was chosen for the inverter and it is illustrated in Figure (3). The amplitude and the frequency of the carrier triangle wave are kept constant while the amplitude and phase of the reference sine waves can be adjusted in order to synchronize the PV output voltage with the utility (load) voltage. The theory and design of the control circuit are not included in this study.

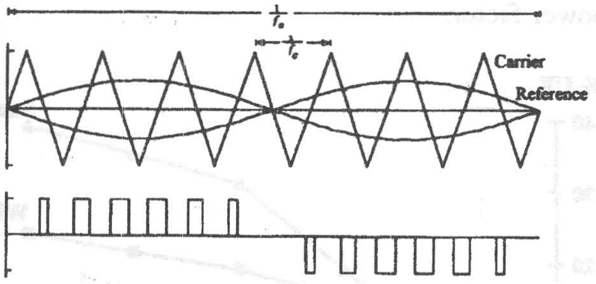

Figure 3. The SPWM control technique of the inverter.

This SPWM control technique is simulated on the computer with a variable modulation ratio, the following results were obtained:

1. In the range of $1 \geq M_a \geq 0$, the normalized fundamental component of the output voltage varies linearly and it is independent of the value of the normalized carrier frequency.
2. The value of M_a must be changed in response to the variation of the input dc array voltage in order to maintain a constant load voltage.
3. The order of the dominant harmonics is shifted at twice the carrier frequency and hence the size and cost of the output filter can be reduced.

The PV array output voltage and current can be calculated as function of irradiance level and temperature as follows [6]:

$$T = T_a + 0.02S \tag{1}$$

$$\Delta T = T - T_{ref} \tag{2}$$

$$V_{dc} = \left(-\beta \Delta T + V_{ref}\frac{S}{S_{ref}}\right) n_v \tag{3}$$

$$I_o = \left\{(\alpha \Delta T + I_{sc})\frac{S}{S_{ref}}\right\} n_i \tag{4}$$

The inverter output voltage can be expressed as:

$$V_{in} = V_{dc}\left\{M_a \sin \omega_o t + \sum_{n=3}^{\infty} A_n \sin n\omega_o t\right\} \tag{5}$$

For a given output filter configuration, the combined transfer function of the filter and the load and overall input impedance at each harmonic frequency are obtained. The harmonic amplitudes of the overall output voltage and current are given by:

$$V_{on} = V_{in} H_n \tag{6}$$

$$I_{on} = \frac{V_{on}}{Z_n} \tag{7}$$

For an L-type output filter, the combined filter and load transfer function is given by:

$$H_n = \frac{-J(R + J\omega L)}{-J(R + J\omega L) + \omega^2 C_f^2 L_f + J\omega^2 L_f C_f (R + J\omega L)} \tag{8}$$

and, the output impedance seen by the inverter is given by:

$$Z_n = Jn\omega L_f - J\frac{1}{n\omega C_f} \cdot \frac{R + Jn\omega L}{R + J\left(n\omega L - \frac{1}{n\omega C_f}\right)} \tag{9}$$

The total harmonic distortion of the output voltage and that of the output current are given by:

$$THD_v = \left[\sum_{n=3}^{\infty}\left(\frac{V_{on}}{V_{ol}}\right)^2\right]^{1/2} \quad (10)$$

$$THD_i = \left[\sum_{n=3}^{\infty}\left(\frac{I_{on}}{I_{ol}}\right)^2\right]^{1/2} \quad (11)$$

where, V_{ol} and I_{ol} are the fundamental components of the output voltage and current respectively. If the $THD_v > 5\%$ or the $THD_i > 3\%$, then the inverter is required to turn-off.

4. SIMULATION RESULTS

Since the carrier frequency of the PWM control technique is 1kHz, the output filter should be designed to eliminate the associated range of output harmonics which exist at 2kHz. An L-type output filter comprises an inductor of 10mH and a capacitor of 200μF was found quite effective to suppress this band of harmonics [7].

The described system is simulated on the computer using the overmentioned equations and the following PV system parameters:
T_{ref} = 25°C, T_a = 15°C for winter and 27°C for summer, α =0.00267 Amps/°C, β =0.0024 Volts/°C, V_{ref}=400V,I_{sc}=5.4Amps,S_{ref}=400,n_i =5,n_v =8.

The irradiance level is taken as shown in Figure (2) and the load power factor (pf) is varied from 0.5 to unity. The inverter, and therefore the whole PV system, is assumed to be turned-off either when the THD of the output voltage or current is less than 5% and 3% respectively. Since the load power is assumed constant at 8kW, the required load current is calculated for each pf. The percentage load share of the PV system at different irradiance levels and load pf are shown in Figure (4) provided that the overall output voltage and current distortions below the specified limits. The utility grid has to supply the remainder of the load. It has been found that the ambient temperature has a minor effect at high power applications (> 5kW). On the other hand both S and load pf mainly decide the PV system share of load power as can be clearly seen in Figure (4). The percentage UF of the PV system as function of load pf for both summer and winter are shown in Fig.5 where the UF is defined as:

$$UF = \frac{\text{All day PV system output energy}}{\text{Average all day load energy}} \quad (12)$$

where the nominator can be calculated from the summation: $\sum_{i=1}^{n} V_o I_{oi} \cos\phi.\tau_i$ where τ_i is the time of each irradiance level whose output current is I_{oi}.

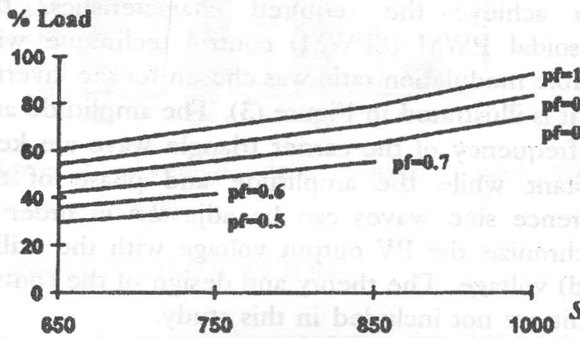

Figure 4. Percentage load share at different load power factor.

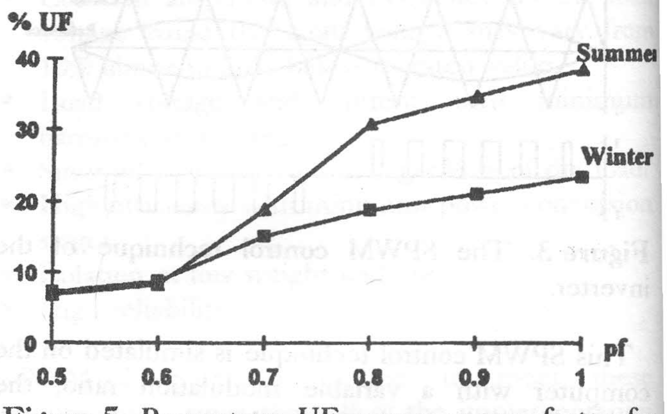

Figure 5. Percentage UF versus power factor for winter and summer.

5. CONCLUSIONS

In this paper, an interactive model comprising a PV system and utility grid is used to supply electrical energy for residential applications. The study is focused on the load management and the use factor. The effect of the load pf on the operation of the PV system is studied as when combined with the output filter affects the THD of the overall output voltage. It is found that the PV system saves about 20% of the consumed energy during a typical winter day and about 33% during a summer day both at a load pf of 0.8.

REFERENCES

[1] G.W. Hart, "Residential photovoltaic system simulation: Electrical aspects," Proc. of the 16th *IEEE Photovoltaic Specialists Conference*, San Diego, CA, 1982, pp. 281-288.

[2] M.A. Khallat, S. Rahman, "A Probabilistic approach to photovoltaic generator performance prediction," *IEEE Trans. on Energy Conversion*, vol. EC-1, No. 3, pp. 34-40, Sept. 1986.

[3] J. Appelbaum, "The operation of loads powered by separate sources or by a common source of solar cells", *IEEE Trans. on Energy Conversion*, vol. EC-4, No.3, pp. 351-357, Sept. 1989.

[4] J. Holtz, "Pulsewidth Modulation- A survey," *IEEE Trans. on Ind. Elect.*, vol. 39, No. 5, pp. 410-420, Dec. 1992.

[5] N. Mohan, T. Undeland and W. Robbins, "Power Electronics: Converters, Applications and Design," John Willy & Sons, Inc., 2nd Edition, 1995.

[6] Z. Salameh and B. Borowy, "Photovoltaic module-site matching based on the capacity factors", *IEEE Trans. on Energy Conversion,* vol. 10, No. 2, pp. 326-332, June 1995.

[7] T.H. Abdelhamid, "Single transformer HF link UPS system with microprocessor supervisory control", *Ph.D. dissertation*, Alexandria University, 1995.