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El Paso Electric Photovoltaic-System Analyses

MASTER

The BDM Corporation
1801 Randolph Road SE
Albuquerque, NM 87106

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El Paso Electric Photovoltaic-System Analyses

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Albuquerque, NM 87106

For

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Sandia Contract No. 46-3065

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FOREWORD

This technical report, BDM/A-81-656-TR, has been prepared by The BDM Corporation, 1801 Randolph Road S.E. Albuquerque, New Mexico 87106, for Sandia Laboratories under contract number 46-3065. Mr. C. B. Rogers was the Sandia Technical Program Monitor. The BDM program director was G. J. Collaros. Principal investigator was T. J. Lambarski. Other major contributors to the analyses and report were E. R. Anderson, D. L. Kadlec, and G. Rimbert.

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EL PASO ELECTRIC PHOTOVOLTAIC SYSTEM ANALYSES

CHAPTER I EXECUTIVE SUMMARY

A. BACKGROUND AND PURPOSE

The analyses reported here were performed as part of the activities in the PRDA Design Assistance and Evaluation contract. The analyses were requested by the New Mexico Solar Energy Institute (NMSEI), the prime contractor on the El Paso Electric Company-Newman Power Station Photovoltaic (PV) Demonstration Project. The purpose of the analyses was to provide design assistance and evaluate design options for NMSEI and to assist Sandia in furthering the understanding of technical issues surrounding PV system applications.

Four analyses were performed on the Newman Power Station PV system. Two were performed using the Photovoltaic Transient Analysis Program (PV-TAP) and two with the SOLCEL II code. The analyses and the objectives for each are listed below.

(1) Optimum Tilt Angle and Fixed Voltage

To determine the optimum tilt angle for the array and the sensitivity of the annual energy production to variation in tilt angle.

To determine a) the annual energy loss in employing a fixed voltage rather than a peak power tracking system, b) the optimum fixed voltage, and c) the sensitivity of the annual energy production to the choice of fixed voltage.

(2) Short Circuit Current Variation

To assess the power loss due to cell-to-cell variations in short circuit current and the degree of improvement attainable by sorting cells and matching modules.

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(3) Reverse Bias Cell Temperature

To quantify the magnitude and frequency of occurrence of high cell temperatures due to reverse bias caused by shadowing.

(4) Lightning and Switching Transients

To assess the adequacy of transient protection devices on the d.c. power lines to transients produced by array switching and lightning. To estimate the electromagnetic coupling due to lightning into a typical PV power system.

To ensure timely response, the results were initially reported in briefings and informal communications, and the first analysis was originally transmitted in a letter report. It has been reproduced intact in chapter V of this report.

B. RESULTS AND CONCLUSIONS

The analyses and their results are presented in detail in the subsequent chapters. Results and conclusions are also summarized below.

(1) Optimum Tilt Angle and Fixed Voltage

The optimum tilt angle is 28° . Variations of $\pm 2^\circ$ produce losses of only 0.06 percent in the annual energy production, but losses increase to about 1 percent if tilt angle is more than $8-9^\circ$ from the optimum angle.

The reduction in annual energy output is 2.6 percent when the module is operated at 15.4 V. Operating at ± 0.5 V from the optimum increases losses to only 3.3 percent, but at ± 1.0 V from optimum, the losses are almost 6 percent and increase rapidly beyond this.

(2) Short-Circuit Current Variation

Typical distributions on short circuit current (I_{SC}) can cause losses of about 9.5 to 11 percent in peak array power.

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Sorting cells into four bins prior to module assembly can reduce the losses to about 6-8 percent.

Using modules from the same cell bins in building series strings can reduce the losses to about 4.5-6 percent.

Results are nearly the same if the array is operated at a fixed voltage equal to the peak power voltage of an ideal module multiplied by the number of modules connected in series.

(3) Reverse-Biased Cell Temperature

Cell temperatures achieved in reverse bias are higher for cells with larger shunt resistance (R_{SH}).

For cells with $R_{SH} = 1000 \Omega$, cell temperatures for a partially shadowed cell in an 18-cell bypass group can read 113°C with perhaps 100 hourly occurrences of 105°C or more. Daily temperature cycling can be as great as $95\text{-}100^{\circ}\text{C}$.

For cells with $R_{SH} = 25 \Omega$, cell temperatures for the same conditions can reach 105°C with perhaps 50 hourly occurrences of 100°C or more. Daily temperature cycling can be up to $75\text{-}80^{\circ}\text{C}$.

(4) Lightning and Switching Transients

The large surge capacitors on the d.c. power line effectively limit voltage excursions at the array and at the control room due to lightning.

Lightning can induce voltages of 100 V and currents of 5000 A on the d.c. power lines. Coupling into the wiring harnesses of the array could not be determined accurately without detailed field measurements but could induce voltages of over 1000 V.

Currents greater than 1000 A can be induced for short time periods in the surge capacitors when the array is shorted, but exact modeling was not possible due to a lack of configuration information and equipment parameter data.

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Without insertion of series resistors, the current may be limited only by cable and switch impedances, and all elements could be severely stressed. The currents in the capacitors during switching should be measured.

Differences in the system between the design evaluated and the one which was implemented in the final construction design do not significantly affect the results and conclusions of the analyses. The changes in the design, however, should provide some additional transient protection for the system.

CHAPTER II
SHORT CIRCUIT CURRENT VARIATION ANALYSIS

A. INTRODUCTION

Short circuit currents (I_{SC}) can vary by greater than ± 10 percent from cell to cell, even for a well-controlled process line. When these cells are assembled into modules and placed in sunlight, test data indicate the variations can be increased to ± 15 percent or more. This distribution will cause most cells to operate off peak power and may force the cells with the lowest I_{SC} values into reverse bias, producing power outputs from modules that are lower than the sum of the cell peak powers. Sorting of cells into bins by short circuit current and use of cells from only one bin within a given module can improve the peak power output of the modules, but mismatch between module I_{SC} values within a series string can dilute the module improvements. Using modules from the same I_{SC} bins in building the series string will improve the output of the strings. This analysis assesses the effectiveness of this sorting and matching technique. First, a brief overview of the conditions which compound the problem of I_{SC} variation is presented, followed by a discussion of the formulation of the analysis, and implementation with the Photovoltaic Transient Analysis Program (PV-TAP) (reference II-1, II-2). Finally, a comparison of the effectiveness of the sorting and matching techniques is made.

B. PROBLEMS ASSOCIATED WITH SORTING AND MATCHING

Cell I_{SC} variations can be reduced from ± 10 percent to ± 2.5 percent by sorting into four bins. Once the cells are assembled into modules, however, I_{SC} distributions will be increased due to 1) encapsulation which causes variable increases in I_{SC} , 2) spectral mismatch which can increase or decrease I_{SC} due to variable response to the solar spectrum, and 3) initial exposure which produces a change in I_{SC} due to sunlight-induced optical changes. Table II-1 illustrates typical spreading for

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4-inch-diameter flat plate cells with a typical I_{SC} of 2 A such as used in the Solar Power modules. The ± 2.5 percent bins used by Solar Power are based on the nominal value of 2 A and do not vary 2.5 percent about the center of each bin. The limits on I_{SC} for the original ± 2.5 percent distributions for each bin are shown in the left column. The middle and right columns present the I_{SC} limits for typical spreadings of ± 7.5 and ± 10 percent, respectively, for cells in modules. Thus, bin 1 may increase from its original 0.1 A spread (1.8-1.9 A) to a 0.3 A (1.7-2.0 A) or a 0.4 A (1.65-2.05 A) spread. This represents an overall spread of cell I_{SC} to approximately ± 15 and ± 17.5 percent, respectively.

TABLE II-1. BIN DISTRIBUTIONS

Bin No.	Original $\pm 2.5\%$ Bins*	± 7.5 Distribution*	$\pm 10\%$ Distribution*
1	1.8 - 1.9 A	1.7 - 2.0 A	1.65 - 2.05 A
2	1.9 - 2.0 A	1.8 - 2.1 A	1.75 - 2.15 A
3	2.0 - 2.1 A	1.9 - 2.2 A	1.85 - 2.25 A
4	2.1 - 2.2 A	2.0 - 2.3 A	1.95 - 2.35 A
Overall Distribution	$\pm 10\%$	$\pm 15\%$	$\pm 17.5\%$

*Bin distributions are only approximate and are based on 2 A for simplicity.

If the modules to be connected into a series string are randomly chosen without regard to the bins from which they were obtained, some of the improvements in module peak power will be lost because the modules from the lower bins will limit the current from the string. Matching modules within a series string will improve the peak power of the string; however, the improvement must be weighed against the increased cost of obtaining matched modules from the manufacturer or matching modules in the field.

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C. ANALYSIS APPROACH

To assess the effects of I_{SC} variations and the effectiveness of cell sorting and module matching, an analysis was performed using PV-TAP. Runs were formulated to assess 1) power loss due to I_{SC} variations without sorting and matching, 2) power improvement due to cell sorting into bins and use of one bin per module, and 3) power improvement due to selecting modules from the same bin in building a series string. Runs were made to assess the effects with both the ± 7.5 percent and the ± 10 percent distributions within modules. A matrix of the analyses is shown in table II-2. The first run was implemented with identical 2 A cells to indicate the ideal case in which the array power is the sum of all cell peak powers. Next, ± 15 percent and ± 17.5 percent variations over the whole array were run to produce the case of no sorting or matching. Runs numbered 3 chose cells from the same bin to produce a module, but did not match modules within a string. Runs numbered 4 used modules representing the same bin within a string, but mixed strings randomly in paralleling 60 strings. The final system configuration actually contains 64 strings; therefore, the system outputs will be higher than those obtained from this analysis, but the loss percentages should be the same.

TABLE II-2. MATRIX OF ANALYSES

Run No.	Conditions	Distribution	
		Run A	Run B
1	All Cells in Array Identical	None	N/A
2	Random I_{SC} Variation in Array	$\pm 15\%$	$\pm 17.5\%$
3	I_{SC} Variation in Module due to Binning Modules in String Selected Randomly	$\pm 7.5\%$ 4 Bins/ String	$\pm 10\%$ 4 Bins/ String
4	I_{SC} Variation in Module due to Binning Modules in Strings Selected by Bin Strings in Array Selected Randomly	$\pm 7.5\%$ 1 Bin/ String 4 Bins/ Array	$\pm 10\%$ 1 Bin/ String 4 Bins/ Array

D. IMPLEMENTATION USING PV-TAP

The PV cell model used in PV-TAP is based on the Ebers-Moll diode model, as shown in figure II-1.

Figure II-1. PV Cell Model and Equations

The photo-induced current, I_p , is given as a function of insolation, temperature, and response time. The standard diode junction current, I_D , is given in two terms. The first term represents the normal diode exponential current, the second term models the reverse breakdown region. The junction capacitance, C_J , is a combination of the depletion and diffusion capacitances, but is not used in steady-state analyses such as this. The series resistance, R_S , represents the bulk material and causes the output voltage, V_{PV} , to deviate from the junction voltage, V_D , at high photocurrents. The shunt resistance, R_{SH} , accounts for the leakage current of the PV cell. Parameters used to describe the cells in this analysis were derived from typical I-V curves for a 4-inch-diameter Solar Power cell. Figure II-2 contains the I-V curves used for the data reduction and lists the parameters obtained.

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Figure II-2. Solar Power Corporation Measured I-V Characteristic

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When analyzing PV cell arrays, specifying many individual cells to the computer program can be time-consuming and costly. Therefore, the PV aggregate model is generally used. The PV aggregate model builds modules and arrays from PV cells arranged in regular series-parallel wiring configurations by statistically combining individual model parameters. All the PV cell model features are included in the aggregate model.

The method for aggregating cells is based on methods for combining individual elements in series and parallel (reference II-3). That is, for cells in parallel, capacitors add, and resistors combine as $1/R$; and so forth. Some typical aggregation techniques are illustrated in table II-3. R_A is the aggregate resistance; R_i represents individual resistances.

Elements such as photocurrent may be specified with statistical distributions on their parameters. The program statistically generates parameter values for all the individual elements of the aggregate and then combines them into the aggregate PV cell before performing the network response calculations.

TABLE II-3. TYPICAL AGGREGATION EQUATIONS

RESISTANCE	SERIES $R_A = \Sigma R_i$	PARALLEL $R_A = \frac{1}{\Sigma \frac{1}{R_i}}$
CAPACITANCE	$C_A = \frac{1}{\Sigma \frac{1}{C_i}}$	$C_A = \Sigma C_i$
PHOTOCURRENT	$I_{PA} = \text{MIN} (I_{pi})$	$I_{PA} = \Sigma I_{pi}$
SATURATION CURRENT	$I_{SA} = \frac{\Sigma I_{Si}}{n}$	$I_{SA} = \Sigma I_{Si}$
EMISSION CONSTANT	$M_A = \Sigma M_i$	$M_A = \frac{\Sigma i}{n}$

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For this analysis, statistical distributions were placed on the photocurrent, I_p , to simulate the short circuit current, I_{SC} , variations, previously described. In determining the distributions for PV-TAP, the original I_p distribution of ± 10 percent was considered to be Gaussian with 3σ points at the upper and lower 10 percent points. Figure II-3 illustrates how this distribution was divided into four bins. The first bin is truncated at 1.8 A. No cells with I_{SC} less than 1.8 A are used. The fourth bin contains all cells with I_{SC} greater than 2.1 A, including those above 2.2 A. Since the number of cells with I_{SC} less than 1.8 A would be very small for this distribution, these cells would not be expected to contribute significantly to the power loss. Therefore, to facilitate implementing the distributions in PV-TAP, this asymmetry due to truncation was not considered. This simplification will result in slightly lower outputs.

Figure II-3. Dividing Gaussian Distribution into Four Bins

To account for the resultant spreading due to module buildup, each bin was modeled with a Gaussian distribution; the average value was at the center of the bin, and the 3σ points correspond to the limits for each bin listed in table II-1.

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Determining exact distributions for the bin photocurrents after module construction instead of using the Gaussian approximation was not within the scope of the effort because it would require a massive test program. The sensitivity of the analysis to bin distribution shape was assessed by performing run number 3A with both Gaussian and triangular distributions. The peak powers obtained were 13.97 kW with the Gaussian and 13.83 kW with the triangular. The variation from the Gaussian produced power was 1.1 percent. The triangular distribution produces higher probabilities near the limit currents as shown in figure II-4, and thus produces more conservative results.

Figure II-4. Comparison of Gaussian and Triangular Distribution Shapes

The Solar Power modules in the analysis consisted of 36 series-connected PV cells with 2 bypass diodes per module (1 per 18 cells). For the purpose of this analysis, the array was considered to consist of 9 series-connected modules by 60 parallel-connected series strings with a nominal output of 14.8 kW. The insolation was 1 sun and the cell temperature was 46°C. A resistive load was swept from short circuit to open circuit conditions to determine peak power output.

E. RESULTS AND CONCLUSIONS

The outputs for the various cases analyzed are summarized graphically in figure II-5 and presented as reduction and improvement

POWER PRODUCED BY EACH CASE

Figure II-5. Comparison of Output Powers

percentages in tables II-4 and II-5. Run 1 represents the best possible output assuming all cells are identical. In runs 2A and 2B, the effects of ± 15 and ± 17.5 percent distributions with no bin sorting is seen. As seen in table II-4, the peak powers are reduced by 9.5 and 11.2 percent, respectively. In runs 3A and 3B, sorting into four bins is seen to reduce peak power losses to only 5.9 and 7.7 percent, respectively. In runs 4A and 4B, selecting modules from the same bin to produce series strings is seen to reduce peak power losses to only 4.5 and 6.1 percent, respectively, for total savings from runs 2A and 2B to runs 4A and 4B of 5.0 and 5.1 percent, respectively, more than half of what was lost from run 1 to runs 2A and 2B.

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TABLE II-4. RESULTS EXPRESSED IN TERMS OF PERCENT REDUCTIONS FROM THE IDEAL CASE

RUN NO.	POWER (kW)	% REDUCTIONS
1	14.85	<p>9.5%</p> <p>5.93%</p> <p>4.51%</p> <p>5% SAVING</p>
2A	13.44	
3A	13.97	
4A	14.18	
1	14.85	<p>11.2%</p> <p>7.7%</p> <p>6.1%</p> <p>5.1% SAVING</p>
2B	13.19	
3B	13.71	
4B	13.94	

In table II-5, the results are presented from a different viewpoint. Here, the cases in which the cell distributions in the array are random (2A and 2B) are taken as the baselines. Thus, overall improvements are 3.9 percent each for cell sorting and 5.5 and 5.7 percent, respectively, for module matching.

The intent of the analysis was to obtain an indication of the approximate losses due to I_{SC} variations and improvements due to cell sorting and module matching. Since the distributions were only approximations, the conditions represented by runs 2, 3, and 4 might produce different powers in the actual array. Actual losses and improvements will also differ for different initial distributions and sorting techniques. It is clear, however, that the greater the overall variation in I_{SC} , the more effective is the use of sorting and matching techniques.

Since the matching within strings was based on cell bins, further improvements may be possible if modules were binned; i.e., sorted according to module I_{SC} instead of cell I_{SC} .

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TABLE II-5. RESULTS EXPRESSED IN TERMS OF PERCENT IMPROVEMENTS

RUN NO.	POWER (kW)	% CHANGES
2A	13.44	<p>3.9% IMPROVEMENT</p> <p>5.5% IMPROVEMENT</p>
3A	13.97	
4A	14.18	
2B	13.19	<p>3.9% IMPROVEMENT</p> <p>5.7% IMPROVEMENT</p>
3B	13.71	
4B	13.94	

It should also be noted that distributions on open circuit voltage, shunt resistance, and series resistance could produce further power losses. However, the sensitivity is greatest to I_{SC} variations since peak power in a cell is directly in proportion to I_{SC} .

Several manufacturers such as Solar Power are employing cell sorting techniques to improve module output. The question of module matching must be answered by the purchaser in terms of comparing increased output versus increased cost of field sorting unless module production becomes sufficiently high to induce manufacturers to sell modules by bin grades.

The Newman Station array is operated at a fixed voltage of approximately 139 V which approximates the peak power point. Since the voltage of the peak power point varies with variations in the I_{SC} distribution, the power losses should be assessed at the fixed voltage to ensure applicability to the Newman Station array. In comparing the powers obtained at 139 V to the peak powers for each case, however, the differences occurred in the fourth significant figure and were no greater than 0.3 percent in any single case. Therefore, the results presented at peak power are well within the accuracy of the modeling and apply equally well to the fixed voltage conditions.

CHAPTER III
REVERSED-BIASED CELL TEMPERATURE ANALYSIS

A. INTRODUCTION

The impetus for this analysis derived from the results of the Mt. Laguna Cell Failure Analysis previously reported by BDM under this contract (reference III-1). In this analysis, it was shown that cell temperatures could reach 130°C or more due to reverse bias caused by partial shadowing in Solar Power M401 modules which contain 40 series-connected cells with one bypass diode. The Newman Station array uses Solar Power PRDA-38 modules containing 36 series-connected cells in two bypass groups of 18 cells each. With the smaller series groups, cell temperatures due to reverse bias should not be as great, but could still exceed 100°C under the proper conditions. Since partial shadowing of a cell could occur due to dust accumulation, animal tracks, weathering or such, many cells could be partially shadowed. This might lead one to wonder how often shadowed cells would experience high temperatures and to what degree. More specifically, the question was phrased as "What is the distribution of cell temperatures for a shadowed cell during the course of a year?" This analysis sought to answer this question by determining the temperature of the cell at every hour of the year. The results have been summarized as histograms of temperature occurrence and plots of high and low temperatures for each day.

B. APPROACH AND MODELING

The approach to the solution of the problem involved three steps: 1) modification of the results of the Mt. Laguna analysis to apply to the Newman Power Station modules, 2) modification of the SOLCEL computer code (reference III-2) to determine reverse biased cell temperature, and 3) computer runs made with the modified SOLCEL program.

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The necessary modification was in the reverse voltage of the shadowed cell. In the Mt. Laguna analysis, the highest temperatures were obtained when the shadow caused a reverse bias of about 85 percent of the maximum voltage attainable. The maximum voltage is given by the equation:

$$V_{RMax} = -(N_{BP}-1) V_{OC} - V_{BP}$$

where N_{BP} = number of cells in bypass group

V_{OC} = open circuit voltage of one cell and

V_{BP} = forward voltage of bypass diode.

The open circuit voltage (V_{OC}) of a cell can be found by the equation:

$$V_{OC} = V_{OCM}/N_M$$

where V_{OCM} = open circuit voltage of the module

N_M = number of cells in the module

For the Mt. Laguna module, $V_{OCM} = 22$ V and $N_M = 40$. For the PRDA-38 module, $N_{BP} = 18$. Using $V_{BP} = 1.0$ V and combining equations, we obtain:

$$V_{RMax} = - (N_{BP}-1) V_{OCM}/N_M - V_{BP}$$

$$= - \frac{17}{40} (22 \text{ V}) - 1.0 \text{ V}$$

$$V_{RMax} = - 10.4 \text{ V}$$

The worst case reverse bias is then:

$$V_R = 0.85 V_{RMax}$$

$$V_R \approx -9 \text{ V}$$

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SOLCEL was modified to calculate cell temperature (T_C) resulting from reverse bias with the following equation:

$$T_C = T_A + R_{TS} S A (1-f_s) - R_{TE} I_R V_R$$

where T_A = ambient temperature ($^{\circ}\text{C}$)

R_{TS} = rate of temperature increase with insolation ($^{\circ}\text{C}/\text{W}$)

S = insolation in (W/m^2)

A = cell area in m^2

f_s = fraction of cell shadowed

R_{TE} = rate of temperature increase with electrical power dissipation ($^{\circ}\text{C}/\text{W}$)

V_R = reverse bias (V)

I_R = reverse bias current (A)

I_R , in turn, can be expressed as

$$I_R = I_{P0} S (1-f_s) - V_R/R_{SH}$$

where I_{P0} = photocurrent generation constant ($\text{A}\cdot\text{m}^2/\text{W}$)

R_{SH} = cell shunt resistance (Ω)

Combining these equations, we obtain:

$$T_C = T_A + S [R_{TS} A (1-f_s) - R_{TE} I_{P0} (1-f_s) V_R] + R_{TE} V_R^2/R_{SH}$$

$$T_C = T_A + K_1 S + K_2$$

The parameters summarized in table III-1 were obtained from the Mt. Laguna analysis. It was determined from tests that $R_{TS} = 4.35^{\circ}\text{C}/\text{W}$ and $R_{TE} = 3.0^{\circ}\text{C}/\text{W}$ for Solar Power modules. For the solar power cells (4-inch diameter), $A = 78.54 \text{ E-4 } \text{m}^2$ and $I_{P0} = 2.0 \text{ E-3 } \text{A}\cdot\text{m}^2/\text{W}$. In the Mt. Laguna analysis, two values for R_{SH} were considered (1000Ω and

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TABLE III-1. PARAMETERS USED IN SOLCEL REVERSE BIAS
TEMPERATURE EQUATION

PARAMETER	RUN 1	RUN 2
$R_{TS} (^{\circ}\text{C}/\text{W})$	4.35	4.35
$R_{TE} (^{\circ}\text{C}/\text{W})$	3.0	3.0
$A (\text{m}^2)$	78.54E-4	78.54E-4
$I_{PO} (\text{A}-\text{m}^2/\text{W})$	2.0E-3	2.0E-3
$V_R (\text{V})$	-9	-9
$R_{SH} (\Omega)$	1000	25
f_S	0.208	0.385
$K_1 (^{\circ}\text{C}-\text{m}^2/\text{W})$	0.070	0.054
$K_2 (^{\circ}\text{C})$	0.243	9.72

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25 Ω). The worst case f_s varies with R_{SH} . For 1000 Ω , $f_s = 0.208$ and for 25 Ω , $f_s = 0.385$. Thus, the final equations implemented in SOLCEL were

$$T_C = T_A + 0.070 S + 0.243$$

for $R_{SH} = 1000 \Omega$ and

$$T_C = T_A + 0.054 S + 9.72$$

for $R_{SH} = 25 \Omega$.

The runs were made with the Typical Meteorological Year (TMY) data for El Paso, Texas. The TMY data provides hourly insolation, ambient temperature, and wind speed. Cell temperature was corrected for wind speed in SOLCEL using a rate of 1.00C-s/m. The array was considered to be tilted at 26°.

C. RESULTS

The results of the SOLCEL runs are summarized in figures III-1 through III-5 for $R_{SH} = 1000$ ohms and in figures III-6 through III-10 for $R_{SH} = 25 \Omega$. In figures III-1 to III-4, the high and low cell temperatures in °C for each day throughout the year are plotted for the cell with $R_{SH} = 1000 \Omega$ and 20.8 percent shadowing. Note that the temperatures increase in summer and decrease in winter.

A histogram presenting the number of hourly occurrences of each cell temperature experienced is presented in figure III-5 for $R_{SH} = 1000 \Omega$. The horizontal axis represents temperature from 0 to 115°C in 10°C steps. Fractional values were truncated to the lower integer. The vertical axis represents number of occurrences and is graduated in steps of two. Odd numbers of occurrences were plotted on the next lower line. Thus, single occurrences are plotted on the zero line. Zero occurrences were not plotted. Thus, there are single occurrences of 111, 112, and 113°C but

III-6

Figure III-1. Daily High and Low Cell Temperatures with $R_{SH} = 1000 \Omega$

Figure III-2. Daily High and Low Cell Temperatures with $R_{SH} = 1000 \Omega$ (Continued)

Figure III-3. Daily High and Low Cell Temperatures with $R_{SH} = 1000 \Omega$ (Continued)

Figure III-4. Daily High and Low Cell Temperatures with $R_{SH} = 1000 \Omega$ (Concluded)

Figure III-6. Daily High and Low Cell Temperatures with $R_{SH} = 25 \Omega$

Figure III-7. Daily High and Low Cell Temperatures with $R_{SH} = 25 \Omega$ (Continued)

III-13

Figure III-8. Daily High and Low Cell Temperatures with $R_{SH} = 25 \Omega$ (Continued)

Figure III-9. Daily High and Low Cell Temperatures with $R_{SH} = 25 \Omega$ (Concluded)

Figure III-10. Histogram of Cell Temperature Occurrence with $R_{SH} = 25 \Omega$

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no occurrences of 114 or 115°C. The maximum cell temperature experienced was 113.3°C. There were seven occurrences of temperatures $\geq 110^\circ\text{C}$ with many more between 100 and 110°C. There are two occurrences of temperatures less than zero (-3.1 and -1.2°C) which were not plotted due to insufficient space, and there were three occurrences of 0°C which have been inked into the plot due to an error in the plotting setup.

Figures III-6 to III-9 show the daily high and low cell temperatures for the cell with $R_{SH} = 25 \Omega$ and 38.5 percent shadowing, and figure III-10 contains the histogram of cell temperature occurrences for $R_{SH} = 25 \Omega$. The maximum cell temperature experienced was 104.9°C as contrasted with 113.3°C for $R_{SH} = 1000 \Omega$. There are also much fewer occurrences of cell temperatures greater than 100°C than there were for the $R_{SH} = 1000 \Omega$ case. Higher R_{SH} will produce maximum reverse bias at lower amounts of shadowing, therefore, producing higher temperatures. This can be seen from the equation for T_C . The temperature increase $T_C - T_A$ for a typical insolation, S , of 1000 W/m² would be

$$T_C - T_A = 0.070 (1000) + 0.243 = 70.243^\circ\text{C}$$

for $R_{SH} = 1000$ ohms but only

$$T_C - T_A = 0.054 (1000) + 9.72 = 63.72^\circ\text{C}$$

for $R_{SH} = 25 \Omega$.

The analysis was formulated to produce worst case (highest) cell temperatures for any given ambient temperature. This can occur only if a single cell in a bypass group is shadowed at the optimum shadow fraction. For multiple cell shadowing or different shadow fractions, the cell temperature will be lower. In addition, periodic array cleaning will prevent any single cell from experiencing the frequency of occurrence of high temperatures demonstrated in this analysis. Therefore, it should not be expected that any cell would experience higher temperatures than seen here or a more stressful history except in the case of weathering

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effects and/or occurrence of extremely high ambient temperatures with little or no wind. Thus, the analysis provides a practical upper limit on the temperatures which cells in this array may experience. The analysis also provides an appreciation for the frequency of this temperature stress and the degree of temperature cycling which may be experienced by the cells.

CHAPTER IV
LIGHTNING AND SWITCHING TRANSIENTS ANALYSES

A. INTRODUCTION

1. Purpose

The Newman Power Station of the El Paso Electric Company has been selected as one of the sites to support the Department of Energy (DOE) in advancing solar PV technology through the Photovoltaic Applications Experiments Program. A PV system helps supply power for an Uninterruptible Power Supply (UPS) at the station. The purpose of the project described within this report was to investigate potential upset and/or damage to the UPS and PV system due to both: 1) the array being switched on or off line and 2) lightning discharges coupling into the system.

2. Scope

This particular analytical effort is intended to be a preliminary assessment of the likelihood of upset or damage to the array and UPS system from transients associated with programmed array switching or lightning discharges from the overhead protective lightning wire. A high confidence assessment was beyond the scope of the project resources and was not attempted. Rather, the objective was to determine whether or not upset and damage are likely, based on the magnitude of the calculated responses and whether further, more accurate assessments of this likelihood are warranted.

The analysis is based on the system as described in the referenced documents (IV-1, IV-2). The final design implemented differs in many respects. Assessments of the effects of these differences are provided in this report where appropriate.

3. System Definition

At the Newman Station, a 20 kW PV array interfaces through an overvoltage/overcurrent protection subsystem to the station UPS. A pictorial illustration of the Newman Station is shown in figure IV-1. The PV array is on the left. An overhead lightning wire, near the array,

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was designed to protect the array from a direct lightning hit. A d.c. power cable connects the array to the d.c. switchboard in the Visitors Center located just across the arroyo. The d.c. cable then connects to the UPS contained in the Control Room located on the right side of the drawing.

Figure IV-1. 20 kW Photovoltaic Array at El Paso Electric's Newman Station

A block diagram of the system is shown in figure IV-2. The a.c. inputs to the battery chargers are produced by three separate generators of the Westinghouse Pace 260 generating system. The battery chargers convert the a.c. power to d.c. power to supply d.c. power to the system loads. The PV array also supplies d.c. power to the UPS system when its output is above the set threshold of the system controller (during daylight hours). The array is designed to operate at constant

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voltage (set by the battery chargers) by designing its output level below the d.c. load power requirement. The difference between the load requirement level and the d.c. array output is supplied by the battery chargers. The array is automatically switched off-line when its output is below threshold (during non-daylight hours). The battery chargers then supply all the load requirements.

Figure IV-2. 20 kW Solar Photovoltaic Array Flat Panel Power System/Uninterruptible Power Supply Load

The d.c. loads of the system are two inverters and various d.c. motors and relays. Power to supply the UPS application(s) comes from the inverter outputs or from a backup a.c. power line.

The system has many redundancies as is evident in figure IV-2. The d.c. inputs to the inverters are triply redundant (not including the

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array). Any of the three battery chargers can supply all of the power required by the d.c. loads. Since each battery has 70 kWh of storage, any of the three batteries can supply the d.c. load.

Under normal operating conditions, the battery chargers equally share in supplying d.c. power. The inverters equally share in supplying a.c. power.

The Newman Station d.c. load is fairly constant at 22 kW. The d.c. load uses 135 V and draws 165 A. The two inverters require 130 A and the various d.c. motors and relays require 35 A. The 135 V d.c. system is actually a ± 67.5 V system with an earth neutral. The UPS is operated 24 hours a day, every day of the year. Further detail on the array, UPS design or operation can be found in reference IV-1.

4. Approach

The approach to this project was divided into four tasks. The tasks are as follows:

Task 1 - System Definition

Task 2 - Subsystem/Component Modeling

Task 3 - Lightning Source Definition

Task 4 - Computer Analysis

Task one was to determine the overall system, how it fits together, and how it operates. The subsystems to be evaluated were determined during this task. The system definition is presented in the Introduction under System Definition (section A-3).

Task two involved determining each subsystem function and then modeling it using components that the computer code PV-TAP (reference IV-3) could evaluate. Information gathering was the most intense aspect of this task. Information to base the models on came from reference IV-1, reference IV-2, information received from manufacturers when available, and any other sources possible. Notes were made of component specifications and upset and damage criteria. The results of task two are given in Subsystem/Component Modeling (section B).

The lightning source definition and calculation of discharge levels to the underground power cable from the overhead lightning wire

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and the modeling of this coupling for use in PV-TAP computer analysis were performed as task three. The lightning source definition is included in Subsystem/Component Modeling (section B-6).

Task four encompassed the actual computer analysis. Once the models of the system were determined for both the turn-on and turn-off analysis and the lightning analysis, they were evaluated using PV-TAP. PV-TAP runs were performed for the array being switched on-line, the array being switched off-line, and the lightning analysis using four different lightning source cases. The results of this task are given in PV-TAP Analyses (section C).

Conclusions and recommendations were gathered throughout the evaluation. These are presented in Conclusions and Recommendations (section D).

B. SUBSYSTEM/COMPONENT MODELING

1. Photovoltaic (PV) Array

The PV array is divided into three main subsystems. They are the array subsystem, the electrical and control subsystem, and the monitoring and instrumentation subsystem. Each of the subsystems will be discussed individually in the following pages. The section ends with the overall model used for the PV array system.

a. Array Subsystem

For this analysis the main concern in the array modeling is its d.c. output. A detailed model of the PV array was not necessary. Since the array cannot supply currents or voltages in excess of 20 percent above nominal values, the array is not a significant source of transients. The main transients will be supplied by the large capacitors during the turn-off analysis and by the lightning source during the lightning analysis. The array configuration described in reference IV-1 indicates that the modules are connected in series and parallel to produce 154 A and 135 V d.c. from normal daylight illumination. The array model is shown in figure IV-3. For the analysis the resistance was set at a conservatively high value of 100 Ω to model the array as a nearly constant current source. This model simulates the array by producing the same d.c. output.

Figure IV-3. Array Model

The current and voltage in the final system constructed are slightly different than those shown above, but do not represent a significant difference for this analysis.

b. Electrical and Control Subsystem

The electrical and control subsystem is composed of three main areas of concern for this analysis. The first area is the systems design for constant voltage operation. The second area contains the protective devices for the array. The third area is the control subsystem's responsibility for opening and closing the switches that bring the array on- or off-line.

As long as the load demands more power than the array produces (which is always the case under normal circumstances) the PV system will operate at its determined constant voltage. A simplified block diagram of the interface scheme is given in figure IV-4. The array voltage is the load voltage plus the voltage drops due to the diodes and the line resistance. The rest of the power the load demands is made up by the battery chargers.

Also included in the electrical and control subsystem are the protective devices for the array on the d.c. line between the array and d.c. switchboard. Adding these elements of figure IV-4 produces the block diagram shown in figure IV-5. The protective devices consist of d.c. surge capacitors, an overvoltage limiter, a bus interface, and various contactors and fuses.

Figure IV-4. Constant Voltage Interface Scheme

Figure IV-5. Protective Devices

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There are three d.c. surge capacitors of 4 F, each connected from the plus line to ground and three connected from the negative line to ground at the PV array. One d.c. surge capacitor is connected in the same configuration from each line to ground in the circuitry at the d.c. switchboard. These are General Electric capacitors, model 18L4NH, and are rated 0 to 750 V d.c. These capacitors are used to arrest large voltage spikes (even those that can occur from lightning discharges) in the circuitry near them.

The array overvoltage limiter is designed to limit the voltage attainable out of the array in the case of a load loss or break in the lines connecting to the utility system. The voltage is limited by grounding the array. The contactor is a General Electric #IC2801AD201H and is rated at 300 A.

The d.c. bus interface is simply an electrical contactor to enable disconnection of the array and two diodes (d_1 and d_2) to prevent reverse current flow into the array. The contactor is a General Electric #IC2801AD211AB and is rated at 300 A.

The two blocking diodes are rated at 300 A and 200 V d.c. They are General Electric #A19015BH1AD2.

Not included in the electrical and control subsystem, but provided for PV array protection, is an overhead lightning wire. This lightning wire is placed near the array to protect the array from a direct lightning strike.

There are various contactors and fuses on the d.c. line between the array and d.c. switchboard. These parts are not included in the model because they are assumed to be in their normal operating state either opened or shorted. Their ratings are, however, considered as upset criteria. Each of the six subarrays has a shorting switch, a fuse, and an in-line non-automatic circuit breaker. These six shorting switches and fuses are all rated at 250 VDC and 60 A. Between the array and the visitor center is a non-automatic circuit breaker rated at 250 VDC and 400 A. It is a General Electric #TFJ226Y225. The in-line non-automatic circuit breaker will open the circuit, disconnecting the array from the UPS. It is a General Electric #TJJ426Y400.

At the d.c. switchboard, there is an in-line non-automatic circuit breaker on each line on either side of the blocking diodes, d_1 and d_2 . These circuit breakers are for the same purpose as the in-line circuit breaker at the array. The model number and ratings are the same. Between the blocking diodes and the UPS is a fuse. It is rated at 250 VDC and 200 A. The contactors, switches, and fuses are for extra protection of the array or UPS from high voltages or currents.

The system controller controls the overvoltage limiter switch S_1 and the bus interface switch S_2 . The system controller connects and disconnects the array and UPS at the d.c. switchboard. At night, when the array produces little or no output, the array is off-line. Switch S_1 is closed and switch S_2 is open (See figure IV-5). As the sun rises, the array output increases. When the output reaches a predetermined level, the system controller first closes switch S_2 and two seconds later opens switch S_1 . As the sun goes down, the array output decreases, and when it reaches a predetermined level the controller will command switch S_1 to close and then switch S_2 to open. The system controller will close switch S_1 if the array voltage rises too high or will close switch S_2 if current is detected flowing into the array from the UPS. (In the system which was eventually constructed, the delay between switches was 0.4 sec instead of 2.0 sec. The effects of this change are discussed in section D.)

The main elements of concern in the electrical and control subsystem for this analysis are the d.c. surge capacitors, switch S_1 of the overvoltage limiter, and switch S_2 and blocking diodes d_1 and d_2 of the bus interface. As mentioned previously, the other contactors, switches, and fuses can be considered to be in their normal state, either shorted or opened so the array is operating normally. However, these contactors and fuses will be kept in mind when looking at the results to make sure currents or voltage do not exceed their maximum ratings.

The main protection elements of concern are those used in the model. The capacitors at the array are lumped together as 12 F since the actual configuration of the array is not relevant to this analysis.

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The switches S_1 and S_2 are modeled as switches in PV-TAP. Their value is dependent on time, thereby allowing them to open or close as the system controller commands. The switches are connected between two nodes. There is a short between the two nodes when the switch is closed and the circuit is open between the two nodes when the switch is opened. The diodes are modeled as zener diodes so that the PV-TAP output waveforms would clearly indicate if one is in a breakdown region.

c. Monitoring and Instrumentation Subsystem

The monitoring and instrumentation subsystem monitors the array output. It detects system malfunctions and provides the DOE and contractor with needed data. Due to its complexity, this subsystem could not be modeled within the constraints of this contract. However, upset or damage due to array switching transients or lightning transients may be more probable to equipment of this subsystem than to equipment or components of the power subsystems.

d. Photovoltaic (PV) Array Model

The PV array system d.c. output is fed directly into the inverters and other loads. The array operates at constant voltage and will never supply more power than the application can use. Combining the models of each subsystem modeled gives the overall PV array model. This model is shown in figure IV-6.

Figure IV-6. Photovoltaic Model

2. Battery Charger

There are three battery chargers on the UPS system for redundancy purposes. Any one or all of the chargers can supply the required power to the UPS loads when the PV array is disconnected from the UPS system. When the array is connected and supplying power to the UPS loads, the battery chargers (any or all) supply the difference of what the UPS loads require and what the array can provide. While in use, the battery chargers keep the batteries on the line charged.

A.C. power comes into a charger from the steam and diesel generators at the Newman Station. It is then rectified, filtered, and sent as d.c. output to the UPS loads. A feedback loop is used to regulate the output voltage.

The battery chargers are made by Exide. They are 480 VAC, 3 phase, 60 cycle, 66.7 a.c. A, and 250 d.c. A. The charger was designed such that the voltage shall be maintained at $\pm\frac{1}{2}$ percent from 0 to 100 percent of the charger capacity rating, with an a.c. line voltage variation of ± 10 percent and a frequency variation of ± 5 percent at 60 cycles. The model number is USF-130-3-250. The circuit paths which are important for this analysis are on the d.c. side of the battery charger, since the analysis is evaluating the d.c. power parts of the UPS system. The most important parts are the filter, the rectifier, and the feedback loop, for they perform the critical functions of the battery charger. Values for the elements at the d.c. side of the charger were obtained by telephone from Exide. The elements determined to be significant are shown in table IV-1 with their values. Other elements on the schematic, but of low or no significance, were determined as such by their low series impedance, high shunt impedance, or location in the circuit away from the d.c. power. The schematic and values of the feedback module were unavailable.

The model of the battery charger was based on the circuitry considered significant to this analysis. It is shown in figure IV-7. The elements of table IV-1 and their corresponding values were modeled in the same configuration as they are in the circuit schematic. The rectifier is modeled by a d.c. constant voltage source. The feedback module model had to be completely derived by the analysts since the schematic of this module was unavailable.

Figure IV-7. Battery Charger Model

TABLE IV-1. SIGNIFICANT BATTERY CHARGER ELEMENTS AND THEIR VALUES

<u>DESCRIPTION</u>	<u>VALUE</u>
Charge Ammeter Shunt	0.17 mΩ
Filter Choke	1. mh
Filter Choke	1. mh
Filter Capacitor	5500. μF
Current Sensing Resistor	0.01 Ω
Filter Diode	V _{BD} = 600 V

The feedback loop is used to regulate the battery charger output. When the PV-array is switched on-line supplying most of the required power, the battery charger drops the amount of power it supplies to keep the positive and negative lines at approximately +67.5 V and -67.5 V, respectively. This system function was modeled using an opposing voltage source to the battery charger voltage supply. The opposing source is dependent upon a fraction of the positive and negative line voltages. The voltage across a zener diode with a breakdown voltage of

one tenth the system d.c. voltage is compared to the voltage inside a resistive voltage divider. When the voltage at the voltage divider becomes greater than the voltage across the zener, that voltage difference times a proportionality factor is subtracted from the battery charger supply. The proportionality factor was chosen as 50 to give a 0.25 percent voltage change at the charger outputs due to array load switching. (Specification load regulation equals 0.5 percent maximum).

The voltage source for the battery charger was set at an even number of 140 V. It was estimated that this would produce approximately ± 67.5 V on the d.c. lines. The ± 67.5 V is a circuit guideline, the actual circuit may not be operating at exactly this value. The results are evaluated for circuit voltages or currents that exceed component or upset specifications. A small increase in voltage should not bring a device above its rated level.

Two more blocking diodes were added to the model in series with the voltage supplies in case the circuit would ever be run using an a.c. instead of a d.c. voltage source resulting in the final battery charger model shown in figure IV-7. Since the system contains three battery chargers, three battery charger models were also used in parallel for the analysis.

3. Batteries

One battery is connected to each of the three d.c. lines across the battery chargers. The batteries are charged by the battery chargers. Each battery has 70 kWh of storage and can therefore supply all the power the inverters and other d.c. loads require for several hours.

Since a transient analysis is being performed on the system, the batteries were modeled using the transient battery response model from PHOTOVOLTAIC TRANSIENT ANALYSIS PROGRAM USER'S GUIDE, Volume II (reference IV-3). The transient response model simulates only the impedance characteristics of the battery and does not model the energy storage function. The model is valid for transients at a specified frequency. The element parameters do not have a physical significance but merely act to present the proper complex impedance to transient signals.

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To determine the element values of the model, first the ampere-hours must be determined. Since the storage is 70 kWh, the storage is divided by the 135 V of the d.c. line to obtain the capacity of 518.5 Ah. The inductance, L , may now be determined from the curve in figure IV-8. L is found to be 0.13 microhenries. The transient capacitance, C , the series resistance, R_{SERIES} , and the shunt resistance, R_{SHUNT} , are found from the following equations:

$$C = \frac{(3.65) Q_0}{(f^{0.77})} \quad (\text{farads})$$

$$R_{\text{SERIES}} = \frac{0.272}{(f^{0.90}) Q_0} \quad (\text{ohms})$$

$$R_{\text{SHUNT}} = 0.20 Q_0 \quad (\text{ohms})$$

where

$Q_0 = 518.5 \text{ Ah}$, the battery capacity

$f = 60 \text{ Hz}$

The above methodology for determining the transient response element values for a battery is explained in more detail in reference IV-3.

Figure IV-8. Inductance Versus Battery Capacity

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To reference the UPS system to ground, the system was designed with a $10\text{ k}\Omega$ resistor connected from the positive line to ground and a $10\text{ k}\Omega$ resistor connected from the negative line to ground. The complete battery model is shown in figure IV-9.

Figure IV-9. Battery and Circuit Reference to Ground Model

4. Inverters

The two inverters used at the Newman Station invert their d.c. power inputs into a.c. power to provide an a.c. UPS system. The inverters are Cyberex 4th Generation Inverters. The inverter design is based on high frequency switching. Rectifiers and SCRs are used. The model number is 120/25Ib1. They are 60 Hz, single phase, 120 VAC static inverters. The inverters require 130 A of the 165 A available. The d.c. input transient protection is 4000 V for 100 s and $40\text{ }\Omega$ of dynamic source impedance. Inverter schematics are not shown here because they were proprietary and could not be obtained. Therefore, information about the inverter was requested from Cyberex. Cyberex stated the d.c. input appears capacitive. The resistance of the inverter could be determined by knowing the system voltage and the current required by the inverter.

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The capacitance was said to consist of 36 capacitors, of 5400 μF each, connected in parallel; therefore, giving a total capacitance of 0.1944 F. The resistance is found by dividing the system voltage of 135 V by the current each inverter requires, 65 A. This gives approximately 2 Ω . The capacitance and resistance of the inverter were the only information available to model the inverter. The model is shown in figure IV-10.

Figure IV-10. Inverter Model

5. Power Cabling

A d.c. line power cable connects the PV array to the d.c. switchboard in the Visitor Center. It is then routed to the Control Room to supply power to the inverters. Since this cable is fairly long, its impedance characteristics should be included in the UPS model. A diagram showing the d.c. power cable layout is shown in figure IV-11. The angles and distances are approximations determined from the FLGM (reference IV-2) drawing package dated 3/20/80.

The cable is 2 #350MCM TW-2"C. It is code grade rated 600 V, is softdraw annealed copper, thermoplastic insulated and in a galvanized rigid steel conduit, according to reference IV-1. The cable runs 1 foot 6 inches under grade except where it crosses the arroyo to the Newman Station (see figure IV-1).

The d.c. cable was modeled using a three wire transmission line configuration. The cable characteristics were determined using equations from the RADIO ENGINEERS HANDBOOK (reference IV-5), and input values from the STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS (reference IV-6). The cable dimensions and other constants needed to determine the element values of the d.c. line characteristics are shown in figure IV-12.

Figure IV-11. Newman Station Cable Layout

$$\begin{aligned} d &= .6945'' = 17.6403 \text{ mm} \\ D &= 2'' = 50.8 \text{ mm} \\ h &= d + 1/3 (D - 2d) = 22.813 \text{ mm} \\ C &= h/2 = 11.4065 \text{ mm} \\ \nu &= h/d = 1.29323 \\ \sigma &= h/D = .4491 \\ \epsilon_R &= 2.3 \text{ RELATIVE PERMITTIVITY} \\ \nu_p &= 3 \times 10^8 \text{ m/s} \end{aligned}$$

Figure IV-12. Cable Dimensions and Constants Needed to Determine d.c. Power Line Characteristics

The differential characteristic impedance is found using equation 1. This value subtracted from the Z_o^{single} term is the off-diagonal term of the characteristic impedance matrix.

$$Z_o^{\text{diff}} = \frac{276}{\sqrt{\epsilon_R}} \log_{10} \left[2\nu \frac{1-\sigma^2}{1+\sigma^2} \right] \quad (\text{Equation 1})$$

Plugging in values to equation 1, Z_o^{diff} is calculated to be 42.783.

The on-diagonal term of the characteristic impedance matrix is given by equation 2.

$$Z_o^{\text{single}} = \frac{60}{\sqrt{\epsilon_R}} \ln (u + \sqrt{u^2 - 1}) \quad (\text{Equation 2})$$

where

$$u = \frac{1}{2} \left[\frac{d}{D} + \frac{D}{d} - \frac{4C^2}{dD} \right]$$

After calculations Z_o^{single} is found to be 31.004.

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The off-diagonal term is the difference between Z_o^{diagonal} term is the difference between Z_o^{diff} and Z_o^{single} . The characteristic impedance matrix is then:

$$\underline{Z_o} = \begin{bmatrix} 31.0 & 9.61 \\ 9.61 & 31.0 \end{bmatrix}$$

The inductance matrix is found using equation 3.

$$\underline{L} = \underline{Z_o} / v_p \quad (\text{henries/meter}) \quad (\text{Equation 3})$$

The inductance matrix is:

$$\underline{L} = \begin{bmatrix} 1.033 \times 10^{-7} & 3.203 \times 10^{-8} \\ 3.203 \times 10^{-8} & 1.033 \times 10^{-7} \end{bmatrix} \frac{\text{henries}}{\text{meter}}$$

The on-diagonal terms represent the inductance per meter of each conductor line in the cable. The off-diagonal terms represent the mutual inductance per meter between the two lines inside the cable.

The capacitance matrix is found using equation 4.

$$\underline{C} = \underline{Z_o}^{-1} / v_p \quad (\text{farads/meter}) \quad (\text{Equation 4})$$

The capacitance matrix is:

$$\underline{C} = \begin{bmatrix} 1.1897 \times 10^{-10} & -3.6867 \times 10^{-11} \\ -3.6867 \times 10^{-11} & 1.189 \times 10^{-10} \end{bmatrix} \frac{\text{farads}}{\text{meter}}$$

The absolute value of the off-diagonal terms represent the capacitance per meter between the two power lines inside the cable. The addition of an on- and off-diagonal term gives the capacitance per meter of each line with respect to ground.

The resistance of #350 MCM soft draw copper is shown to be .03022 Ω per 1000 feet in the STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS (reference IV-6). The cable length from the PV array to the Visitor Center is approximately 120 feet. The length from the Visitor Center to the Control Room is approximately 70 feet. The inductance and capacitance matrices, impedance, coefficient of coupling and circuit representations of the d.c. line are shown in figure IV-13 for the line between the PV array and the Visitor Center and in figure IV-14 for the line between the Visitor Center and the Control Room.

6. Lightning Source Definition and Model

a. Lightning Source Definition

1) Introduction

Electromagnetic fields radiated from lightning strokes may couple significant energy into the PV array. Even if a direct strike is ignored (on the grounds that it would create catastrophic damage anyway), a lightning strike which attaches to the horizontal protection wire will still radiate high intensity field strengths. The purpose of this section is to scope the lightning-induced transient problem to obtain equivalent current and voltage driving sources. These were used in the PV-TAP models to predict damage and upset to the power system. Because of the lack of data on configuration, cable harness routings, and transfer impedances, approximate engineering judgements were made and realistic worst case coupling assumed.

2) Electromagnetic Fields from a Lightning Stroke

a) Current Waveform

The most common physical model of a lightning stroke discharge is the transmission line formulation. The transmission line extends from the point of discharge vertically into the atmosphere for several kilometers. A current generator, usually of the double exponential type, is used to drive the line at its base. The double exponential waveform is given by

$$i(t) = I_0 (e^{-\alpha t} - e^{-\beta t}) u(t) \quad (\text{Equation 1})$$

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$$\underline{L} = \begin{bmatrix} 3.777 \times 10^{-6} & 1.171 \times 10^{-6} \\ 1.171 \times 10^{-6} & 3.777 \times 10^{-6} \end{bmatrix} \text{ HENRIES (H)}$$

$$\underline{C} = \begin{bmatrix} 4.3499 \times 10^{-9} & -1.3480 \times 10^{-9} \\ -1.3480 \times 10^{-9} & 4.3499 \times 10^{-9} \end{bmatrix} \text{ FARADS (F)}$$

$$R = 3.6264 \times 10^{-3} \text{ ohms } (\Omega)$$

$$K = .31$$

Figure IV-13. d.c. Power Line Characteristics From PV-Array to Visitor Center

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$$\underline{L} = \begin{bmatrix} 2.203 \times 10^{-6} & 6.831 \times 10^{-7} \\ 6.831 \times 10^{-7} & 2.203 \times 10^{-6} \end{bmatrix} \text{ HENRIES (H)}$$

$$\underline{C} = \begin{bmatrix} 2.537 \times 10^{-9} & -7.863 \times 10^{-10} \\ -7.863 \times 10^{-10} & 2.537 \times 10^{-9} \end{bmatrix} \text{ FARADS (F)}$$

$$R = .002115 \text{ ohms } (\Omega) \quad K = .31$$

Figure IV-14. d.c. Power Line Characteristics From Visitor Center to Control Room

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The constants I_0 , α , and β are picked to give a best fit to the experimental data. For a severe lightning model with a peak current of 200 kA, $I_0 = 206$ kA, $\alpha = 1.7 \times 10^4 \text{ sec}^{-1}$, and $\beta = 3.5 \times 10^6 \text{ sec}^{-1}$. Subsequent strokes can be represented by the same model with a lowering of the current amplitude.

The current present at the base of the stroke propagates vertically with propagation velocities of 2×10^7 to 3×10^8 m/s. A typical value might be 1×10^8 m/s. If the line is considered lossless, then the current at every position along the line can be determined from transmission line theory.

$$i(t, z) = I_0 \left[e^{-\alpha(t-z/v)} - e^{-\beta(t-z/v)} \right] u(t-z/v) \quad (\text{Equation 2})$$

Here z is the vertical propagation direction and v is the propagation velocity. The substitution of equation 2 into the time-domain Maxwell's equations theoretically gives the electric and magnetic fields at all positions in space.

b) Fields from a Vertical Stroke

The quasi-static solution for a vertical lightning stroke is given by

$$\begin{aligned} E_z(t) &\approx \frac{I(t)/v}{2\pi\epsilon_0 D} \\ E_r(t) &\approx \left(\frac{z_0}{D} \right) \frac{I(t)/v}{2\pi\epsilon_0 D} & z_0 < D & \quad (\text{Equation 3}) \\ B\Phi(t) &\approx \frac{\mu_0 I(t)}{2\pi D} \end{aligned}$$

where D is the distance from the discharge to field point and ϵ and μ are constitutive parameters of the propagation medium. In every case, the field waveform follows the current waveform. The vertical electric field

and azimuthal magnetic field are independent of height, while the horizontal electric field is proportional to vertical distance. Typical vertical field intensities are 10^6 to 10^7 V/m. Horizontal electric field strengths are on the order of 10^6 V/m². Typical waveforms for these fields may be found in reference IV-7.

c) Fields from the Horizontal Wire

The horizontal wire can be modeled as an open-circuit transmission line which is driven by a current source at the point of discharge. For this study, the wire was considered to be 30-m long, and the point of discharge was at the center of the wire. Simple, time-domain reflection calculations show that two types of currents are induced on the wire. The first is a current which has a waveform which follows the incident pulse, more or less. This current is localized near the point of discharge. Its magnitude is approximately one-half the driver current magnitude. The second current wave shape is a periodic waveform whose fundamental frequency is 5 MHz. ($\lambda/2$ resonance). It is distributed triangularly over the wire with its peak at the center. Its peak-to-peak amplitude is about 20 percent of the incident waveform peak amplitude. The waveform shape is triangular at the center of the wire and becomes smoother towards the wire's end.

In all cases, radiation damping and other losses were ignored. No attempt has been made to define the exact attachment phenomenon.

The fields due to the first waveform (double exponential) may be calculated using antenna theory in the far field. This is because the double exponential waveform is localized near the point of discharge. In this regime, the horizontal electric field follows the derivative of the current as shown in equation 4.

$$E_y = \frac{-\mu_0 L}{4\pi D} \frac{\partial I}{\partial t} \sin^2 \theta \quad (\text{Equation 4})$$

Because of the presence of the ground, one must include the imaged field to obtain a total horizontal field that varies with position.

$$E_y = \frac{-\mu_0 L}{4\pi} \left[\frac{1}{D_1} \frac{\partial I(t)}{\partial t} - \frac{1}{D_2} \frac{\partial}{\partial t} I\left(t - \frac{4Hh}{cR}\right) \right] \sin^2\theta \quad (\text{Equation 5})$$

where H is the height of the horizontal wire, h is the height of the observation point, D_1 is the distance from the wire to the observation point, and D_2 is the distance from the wire image to the observation point.

3) Coupling to the PV Array

a) Coupling Through the Buried Cable

Electric field coupling to the buried cable has been minimized by orienting the cable perpendicularly to both the vertical discharge and the horizontal wire. However, some cross-polarized fields will impinge on the cable and could possibly drive open-circuit voltages as high as 100-150 V.

In TRANSIENT EFFECTS FROM LIGHTNING (reference IV-7) the X-directed electric field has a peak amplitude of about 10^6 V/m. Even after ground reflections and attenuation from ground losses are subtracted, 10^4 to 10^5 V/m can still be expected to drive the buried cable. The dimensions of the cable are not known, but an external characteristic impedance of 30Ω can be assumed. Then, between 350-3500 A may be present on the outer cable shield. With a transfer impedance of $.001 \Omega/\text{m}$, a distributed cable drive voltage of .3 to 3 V/m can be expected.

Only that portion of the cable which is near normal incidence for the fields will be excited significantly. That is, the portion of the cable which is within 45 degrees of the point of discharge will be driven significantly. For the dimensions of this study, that cable length is about 60 ft. Therefore, an open-circuit transient voltage peak of between 6 and 60 V may be expected on each of the conductors within the buried cable. This is assuming that the

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conductors have been placed in a shielded braid or conduit with fairly good transfer impedance (.001 Ω/m). If this is not the case, then the 300-3000 A that appears on the shield would directly transfer to the conductors and be present at any load.

b) Coupling Through the Cable Harnesses

It is apparent that the PV cells in the array are connected in series and parallel combinations. One would expect that the harnesses which connect the cells together would create loops. Significant magnetic coupling can occur via these loops, since magnetic field strengths of 6000 A/m may be expected. However, no geometrical details of the cable harness and layout were given, and no exact calculation of this coupling phenomena can be performed.

An order of magnitude estimate can be obtained as follows. The voltage induced in a loop of area A is

$$v(t) = -\mu_0 A \frac{\partial H_n}{\partial t} \quad (\text{Equation 6})$$

where H_n is the magnetic field (amps/m) incident normal to the loop. A uniform field has been assumed in equation 6. If $\bar{H}$ is given by equation 3 and we may assume that $I(t)$ follows the waveform of equation 1, then $v(t)$ may have as its peak

$$V_{\text{peak}} = \frac{\mu_0 A}{2\pi D} I_0 \beta = 14000A \text{ (volts)} \quad (\text{Equation 7})$$

Even a 0.1m² loop will create a 1400 V transient.

c) Coupling Through the PV Array Structure

With the potential of up to 200 kA appearing on the horizontal lightning wire, even nanohenries of mutual coupling between this wire and an array itself could give currents of up to 700 A on any cable conductor leaving the array. This is because the mutual inductance coupling follows the derivative of the current waveform. The

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derivative maximum for the waveform given in equation 1 occurs at $T=0$ and has a value of 7×10^{11} A/s. The calculation of the mutual inductance coupling the horizontal wire and an array is beyond the scope of this task and would require a great deal of technical effort. However, a 1 nH mutual inductance is a reasonable number.

4) Summary

The electrical equivalent of the above analyses is a voltage source of 100 V which follows the current waveform and a current source of 500 A which follows the derivative of the lightning waveform. Since all cabling is electrically short, these sources may be used to drive either the array or the electronics on the other end of the cable.

Obviously, much more work is necessary to ascertain the exact magnitudes and wave shapes of the lightning threat fields and coupling currents and voltages. However, this analysis does yield reasonable worst case sources which can be used to assess the susceptibility of the PV array to lightning transients.

b. System Lightning Model

Using the previous information, a system model of the lightning discharges can be determined and incorporated into the d.c. power line. The lightning waveform is defined as

$$i(t) = I_0 (e^{-\alpha t} - e^{-\beta t}) u(t) \quad (\text{Equation 8})$$

where

$$\alpha = 1.7 \times 10^4 \text{ sec}^{-1}$$

$$\beta = 3.5 \times 10^6 \text{ sec}^{-1}$$

The voltage source, V_L , follows the lightning waveform with an amplitude of 100 V. It is given by

$$V_L = 100 (e^{-\alpha t} - e^{-\beta t}) \text{ volts} \quad (\text{Equation 9})$$

where α and β are the same as in equation 8.

The current is defined as the derivative of the lightning waveform which is

$$I_L = \frac{d i(t)}{dt} = I_0 (-\alpha e^{-\alpha t} + \beta e^{-\beta t}) \quad (\text{Equation 10})$$

Since the peak amplitude is based on 500 A, the following holds true

$$\left. \frac{d i(t)}{dt} \right|_{t=0} = 500 \text{ A} = I_0 (-1.7 \times 10^4 + 3.5 \times 10^6) \quad (\text{Equation 11})$$

and I_0 is found to be

$$I_0 = 0.1436 \text{ mA}$$

Therefore, the current source I_L is

$$I_L = 0.1436 \times 10^{-3} (-\alpha e^{-\alpha t} + \beta e^{-\beta t}) \text{ amps} \quad (\text{Equation 12})$$

with α and β the same as given in equation 8.

The lightning source is modeled as voltage and current sources along with the d.c. power cable characteristics between the array and Visitors Center. It was modeled symmetrically thus providing two voltage sources on each line with each being half of the voltage defined in equation 9. The resistance, inductance, and capacitance are included twice on each line. Therefore, those values are half of those defined in section B-5 for the cable characteristics between the array and Visitors Center. The model and values used are shown in figure IV-15. The 1 M Ω resistors are used to avoid a current source cutset, a modeling requirement of PV-TAP.

Figure IV-15. Lightning/d.c. Cable Line From Array to Visitor Center

Four lightning source cases were evaluated. They are listed in table IV-2. The voltage source polarities were switched by changing the order of the connecting nodes in the PV-TAP input deck. The peak amplitude of the current source was run at 500 A and 5000 A using equation 11 to determine the new I_o .

TABLE IV-2. LIGHTNING ANALYSIS CASES

<u>Case</u>	<u>Lightning Peak Current Amplitude</u>	<u>Voltage Source Polarity (Array Side With Respect to Utility Tie-In Point)</u>
1	500 A	positive
2	500 A	negative
3	5000 A	positive
4	5000 A	negative

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7. Other D.C. Loads

Various d.c. motors and relays are part of the d.c. load of the UPS system. No schematics of these loads were attainable. The phase angle was not available either. Therefore, these d.c. loads were modeled as purely resistive. The voltage across the d.c. loads is 135 V. The motors and relays require 35 A of the 165 A available. Therefore, the resistance of the loads is approximately 3.857Ω .

8. System Models

Two system models were used for this project. The first model, used for the turn-on and turn-off analysis, used all the subsystem models discussed except for the lightning and d.c. line combination model. This system model is shown in figure IV-16. The system model for the lightning analysis used all subsystem models including the d.c. cable model between the array and Visitor Center combined with the lightning discharge sources in the lightning and d.c. line combination model. This system model is shown in figure IV-17.

C. PV-TAP ANALYSES

1. Procedure

All the pertinent subsystem models were connected together as shown previously in figure IV-16 for the turn-on and turn-off analysis. Major nodes and elements are indicated in the figure. For the turn-on analysis, switch S_1 was closed at time equal to zero, and switch S_2 was open. At one second, switch S_2 was closed. Then, at three seconds, switch S_1 was opened, thus providing the two second delay the system controller allows. The simulation time in the run was run 100 sec to ensure the transients decayed completely.

The switching for the turn-off analysis was opposite to that of the turn-on analysis. At time zero, switch S_1 was open, and switch S_2 was closed. At one second, switch S_1 was closed, and at three seconds, switch S_2 was opened. Two circuits were used for this analysis; one for initial conditions and for final conditions. The initial condition circuit was similar to the one used for the turn-on analysis but with the

Figure IV-16. Circuit Model for Turn-On and Turn-Off Analysis

Figure IV-17. Circuit Model for Lightning Transient Analysis

correct switching procedure implemented. Using the circuit, at time a little before one second, there is approximately +67.5 V with respect to ground at the node on the positive line connected to switch S_1 and approximately -67.5 V at the node on the negative line connected to switch S_1 . At one second these two nodes are connected to ground; therefore, theoretically having three different voltage values (+67.5, 0) at those nodes. The PV-TAP circuit response exhibited large oscillations across the d.c. surge capacitors which, in real life, would not occur since the lines with switch S_1 would have some finite amount of resistance in them. Therefore, a second circuit was needed for final conditions. The second circuit had 0.0001 Ω resistors in series with both contactors of switch S_1 . However, this unbalances the d.c. lines at time zero and therefore this circuit is used only for final conditions (time ≥ 1 sec). The circuit responses to both circuits were the same except for the node voltages at time zero and the oscillations across the d.c. surge capacitors. Only the correct plots are presented in the results.

The lightning analysis circuit was shown previously in figure IV-17. Major nodes and elements are indicated in the figure. There were four lightning analysis computer runs made (see table IV-2) with variations in the circuit shown. The circuit shown was for the first run. The second run had the polarities of the four lightning voltage sources switched. The third run had the same voltage source polarity as run number one, but the current source was based on its peak being 5000 A instead of 500 A. (See section B-66b for computations used). The fourth run had the same voltage polarity as run two and the same current source as run three. The lightning discharge transient occurred at a time of 0.5 ms. It was offset from zero time so the steady state level could be observed.

Rough estimates from hand circuit analysis techniques were used to verify the computer results, to ensure the input was correct and the code was operating as expected.

2. PV-IAP Output

PV-TAP was used for these analyses. PV-TAP has the capability of producing plots of voltage, current, impedance, etc., at nodes or across elements (as appropriate) of a circuit as well as listing the

actual calculated values. Both types of outputs were used during this project. Output values indicated in the report are PV-TAP actual computed values. These values are rounded to the nearest axes value on the plots. Plots are used in the report to show waveforms. An explanation of how to read PV-TAP plots follow. The plot in figure IV-18 is used as an example.

The plot abscissa is labeled TIME(+2). This implies time is the variable measured along this axis and the values indicated need to be multiplied by 10^2 . The two variables measured along the ordinate axis are indicated under the title VARIABLE in the lower left corner of the figure. The N stands for node voltage. In parenthesis is the node at which the voltage is taken with respect to ground. The "(+1)" indicates the corresponding values on the ordinate axis needs to be multiplied by 10^1 . The variables listed top to bottom correspond to the ordinate columns left to right. The first variable listed is indicated on the plot by an "x". The second variable is indicated by a "1". If there was a third variable, it would be represented by a "2". The same format is followed through the tenth variable which would be represented by a nine. If two variables have a point at the same place on the plot, only the greater of the numbers will be printed; the "numbers" being x, 1, 2, through 9.

In the results section plots with variables such as I(C1S) are shown. I indicates current across the element in parentheses.

For all plots time is in seconds, voltage is in volts and current is in amps. Refer to figures IV-16 and IV-17 for node locations, variable names, etc.

3. Analysis Results

a. Turn-On Transients

The expected circuit responses (determined by hand analysis) were indeed observed in the PV-TAP output. At time zero, switch S_2 is open, and switch S_1 is closed. The array circuitry is not connected to the UPS and it is also grounded by switch S_1 . The voltage output of the array is zero at this time as shown in figure IV-19. The UPS is operating at ± 67.624 V (this deviation from ± 67.5 V is explained in

section B-2) as shown in figure IV-20. The battery charger is supplying all the power to the loads at this time.

At one second, when switch S_2 is closed, nothing happens to the voltages or currents of the circuit since switch S_1 is still grounding the array output. However, at three seconds, when switch S_1 is opened, the array output is allowed to feed the loads immediately, and the circuit begins to compensate for the extra power.

The d.c. surge capacitors start charging to the array output. An increase in the current through these capacitors occurs at three seconds, as shown in figure IV-21. When the capacitors are charged up, the current returns to approximately zero. This occurs at 10 seconds. Now circuit current and voltage levels change to allow the battery charger to supply only the difference needed between what the array supplies (135 VDC, 154 A) and what the load demands (135 VDC, 165 A). Three seconds later (time equal to 13 sec) the system operates at practically steady state conditions again. (Since the final constructed system operates at slightly different currents and voltages, the results may be slightly different but not to a significant degree.)

When the array is on-line, there are approximately 154 A flowing from the array into the UPS. This is shown in figure IV-22 as the current through the blocking diodes. No large current spikes occur. There is a small amount of oscillation occurring from 10 sec to 55 sec. The current does not exceed the blocking diodes (d_1 and d_2) maximum current rating. The current is not large enough to affect any of the fuses, switches or contactors at the array. There are no upset possibilities to these devices from current.

The current through the d.c. surge capacitors, as shown in figure IV-21, approaches plus or minus 40 A, depending upon which line the capacitor is connected to. The three capacitors at the array are lumped together; therefore, the voltage and current through the lumped capacitance must be divided by three to determine the levels at each capacitor. This is not enough current to damage such large capacitors.

Figure IV-23 shows the current through the inductors of the battery charger filter indicating how the battery charger adjusts its

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Figure IV-20. Node Voltages of Nodes PLUS3 and MINUS3 with Respect to Ground (Turn-On Transient Analysis)

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Figure IV-21. Currents Through d.c. Surge Capacitors C1S, C2S, C3S and C4S (Turn-On Transient Analysis)

output after the array comes on-line, and the d.c. surge capacitors have charged up to the operating voltage.

Since there are no large transients of current or voltage going into the inverters or other d.c. loads, nothing would be upset, and there is no evidence that anything could be damaged.

b. Turn-Off Transients

For the turn-off transients analysis, the array is initially supplying power to the d.c. loads. Switch S_1 is open and switch S_2 is closed. The system is operating at ± 67.78 V with the array on-line. This is shown in figure IV-24 at time zero to 1 second. Then, at 1 second, the array is grounded by switch S_1 being closed. The array output goes to zero volts immediately as shown in figure IV-25 beyond one second. Since switch S_2 is still closed at 1 sec, the blocking diodes must have a voltage drop across them equal to approximately the operating voltage on each line, since the anodes are grounded, and the cathodes are high. The voltage drops across the diodes are shown in figure IV-26. The operating voltage is changing from ± 67.78 V at one second, to approximately ± 67.62 V at 3 sec due to the battery charger feedback loop regulating the voltage output to compensate for the array no longer supplying power to the UPS. This is shown in figure IV-24. This change can also be seen in the current through the battery charger filter inductors, in figure IV-27, as the current increases at 1 sec to reach a steady state value around 3 sec.

At 3 sec, switch S_2 opens, but the circuit has already had time enough to compensate for the loss of power that was being supplied by the array. At this time, the voltage and current across the blocking diodes are both zero, as shown in figure IV-26 and figure IV-28.

The voltages across the capacitors are shown in figure IV-29. The voltages are well within the capacitor 0 to 750 V rating. The current through the capacitors are shown in figure IV-30. Between 1 sec and 3 sec both switch S_1 and S_2 are closed. The currents through the capacitors spike greatly and begin to decay. This effect is very dependent upon the line resistance between the capacitors, switch S_1 and ground. The line resistance consists of the switch internal impedance

Figure IV-24. Node Voltages of Nodes PLUS3 and MINUS3 with Respect to Ground (Turn-Off Transient Analysis)

Figure IV-25. Node Voltages of Nodes PLUS1 and MINUS1 with Respect to Ground (Turn-Off Transient Analysis)

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Figure IV-26. Voltage Drop Across Blocking Diodes ZD1B and ZD2B
(Turn-Off Transient Analysis)

Figure IV-27. Current Through Battery Charger Inductors L1BC and L2BC (Turn-Off Transient Analysis)

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Figure IV-28. d.c. Line Current Through Blocking Diodes ZD1B and ZD2B (Turn-Off Transient Analysis)

STATE1
 *NEWMAN STATION SWITCHING TRANSIENTS ANALYSIS
 VARIABLE
 I(C1S) (+2)
 I(C2S) (+4)
 I(C3S) (+4)
 I(C4S) (+3)

Figure IV-30. PV-TAP Predicted Currents Through d.c. Surge Capacitors
 CIS, C2S, C3S and C4S (Turn-Off Transient Analysis)

and resistances from any other components such as fuses or contactors, if any exist in the actual system configuration. (Here the $0.0001\ \Omega$ resistor in series with switch S_1 was used as the internal switch impedance.) The greater the resistance is, the lower the maximum current spike value will be, and the greater the decay time will be.

The current and voltage across the capacitors should decay to zero after the initial impulse at time equal to 1 sec. On the computer plot, figure IV-30, however, the capacitor currents oscillate beyond time = 3 sec (the time at which switch S_2 opens). This is due to a computational instability in PV-TAP for this particular circuit configuration; therefore, the oscillation should be ignored.

For the turn-off analysis, all voltages and current are within the maximum specifications of all components, fuses, switches, etc., except possibly for the current specification of the d.c. surge capacitors. Although the capacitors are designed to withstand high levels of voltage and current, the actual current specifications were unobtainable. So it is unknown if some degradation could occur to the capacitors when the array is turned off. The maximum current seen is across one of the 4 farad capacitors represented in C2S. It reaches a value of approximately -2900 A. But this value was determined with a switch impedance of $0.0001\ \Omega$ and no other resistance except for the d.c. cable impedance. Since this is conservative the actual current magnitude would be less.

c. Lightning Transients

As discussed in the procedure, there were four different cases run for the lightning analysis. In all cases, the lightning discharge occurs at 0.5 ms. The system is operating with the array on-line supplying maximum power, and the battery charger is supplying the rest of the power required by the d.c. loads.

The first case was based on the current peak amplitude of 500 A. The circuit model is shown in figure IV-17. The system is operating at ± 67.8 V on the plus or minus line, as shown in figure IV-31. The current from the array is at 154 A, as shown in figure IV-32, as the current through the blocking diodes. At 0.5 ms, the lightning discharge

Figure IV-31. Node Voltages of Nodes PLUS3 and MINUS3 with Respect to Ground (Lightning Transient Analysis Case 1)

Figure IV-32. d.c. Line Current Through Blocking Diodes ZD1B and ZD2B
 (Lightning Transient Analysis Case 1)

occurs. The voltages on the array output line decrease, as shown in figure IV-31 and figure IV-33, as the current of the d.c. surge capacitors increase, as shown in figure IV-34. The current peaks in the capacitors about 0.1 ms later. Then the system begins to stabilize.

The d.c. surge capacitors do their job of protecting the circuitry since the only large spikes are in the capacitors. The capacitors at the array take about 333 A each. The capacitors at the d.c. switchboard take 1000 A each, but these levels are within the tolerance of the capacitor.

The second case was with the polarity of the lightning discharge voltage sources switched. In this run, the system voltages with respect to ground rise from ± 67.7 V to ± 68 on the positive line and to ± 67.5 on the negative line as shown in figure IV-35. Since the lightning source is defined as common mode, the voltages across the inverters and other d.c. loads remain at approximately 135 V, while the node voltages rise with respect to ground. The voltages rise approximately 0.3 V in 3 ms and then return to their first values. The current on the d.c. line remains constant in this case, also, as shown in figure IV-36. With the voltage source polarity the way it is, the voltage and current through the capacitors drop, as shown in figure IV-37 and figure IV-38. The surge capacitors provide the protection needed in this case also.

Cases three and four were based on the discharge current peak amplitude being 5000 A, an order of magnitude greater than in cases one and two. Case three had the same discharge voltage source polarity as case one. Case four had the same discharge voltage source polarity as case two. The magnitudes and responses were not much different from those of cases one and two. PV-TAP plots of voltages and currents of the system are shown in figures IV-39 through IV-42 for case three and IV-43 through IV-47 for case four.

There is no evidence of upset or damage to the system from the results shown. Since there was little change between the results of cases 1 and 2 (500 A) and cases 3 and 4 (5000 A), there should be little change in the results if the circuit received higher levels of lightning

Figure IV-35. Node Voltages of Nodes PLUS3 and MINUS3 with Respect to Ground (Lightning Transient Analysis Case 2)

Figure IV-36. d.c. Line Current Through Blocking Diodes ZD1B and ZD2B
(Lightning Transient Analysis Case 2)

Figure IV-37. Voltages Across d.c. Surge Capacitors C1S, C2S, C3S and C4S (Lightning Transient Analysis Case 2)

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Figure IV-38. Current Through d.c. Surge Capacitors C1S, C2S, C3S and C4S (Lightning Transient Analysis Case 2)

IV-60

Figure IV-39. Node Voltages of Nodes PLUS3 and MINUS3 with Respect to Ground (Lightning Transient Analysis Case 3)

STATE1
PNEUMAN STATION SWITCHING TRANSIENTS ANALYSIS
VARIABLE
I(C1S) (+3)
I(C2S) (+3)
I(C3S) (+3)
I(C4S) (+3)

Figure IV-40. Current Through d.c. Surge Capacitors C1S, C2S, C3S and C4S (Lightning Transient Analysis Case 3)

Figure IV-42. d.c. Line Current Through Blocking Diodes ZD1B and ZD2B
 (Lightning Transient Analysis Case 3)

Figure IV-43. Node Voltage of Nodes PLUS3 and MINUS3 with Respect to Ground (Lightning Transient Analysis Case 4)

IV-65

Figure IV-44. Node Voltages of Nodes PLUS1 and MINUS1 with Respect to Ground (Lightning Transient Analysis Case 4)

IV-66

Figure IV-45. Current Through d.c. Surge Capacitors C1S, C2S, C3S and C4S (Lightning Transient Analysis Case 4)

IV-67

STATE1
 *NEWMAN STATION SWITCHING TRANSIENTS ANALYSIS
 VARIABLE
 V(C1S)(+1)
 V(C2S)(+1)
 V(C3S)(+1)
 V(C4S)(+1)

Figure IV-46. Voltage Across d.c. Surge Capacitors C1S, C2S, C3S and C4S (Lightning Transient Analysis Case 4)

IV-68

Figure IV-47. d.c. Line Current Through Blocking Diodes ZD1B and ZD2B
 (Lightning Transient Analysis Case 4)

discharge. The analysis was not performed at high peak currents due to this reasoning and also because higher levels are not expected in the El Paso area.

D. CONCLUSIONS AND RECOMMENDATIONS

The circuit voltage and current levels determined during the analyses were not high enough to damage any of the elements or subsystems. Since no voltages or currents higher than the upset criteria were reached in the analyses, the system would not be upset. The large d.c. surge capacitors provide ample protection of the Newman Power Station UPS, for the situations and systems evaluated. However, for the turn-off analysis large current spikes were determined across the d.c. surge capacitors. The current peak is a function of the resistance. PV-TAP was run with a small impedance for this case, and therefore the current spikes are probably a lot higher than would be the actual case. The capacitors could be stressed if the actual currents were close to the analysis currents.

Although the results of these analyses show no system upset or damage (except possible stress to the d.c. surge capacitors) a few areas of concern do exist. Many discrepancies between references existed on the actual system configuration. However, great efforts were taken to obtain the latest system information for these analyses. The response of the inverter could not be analyzed thoroughly since the schematics were proprietary and Cyberex would not release any information other than the input capacitance. The possibility of upset occurring in the inverter could only be analyzed with more information on the inverters used. A significant amount of lightning discharge could couple into the back of the PV modules. This could only be analyzed by knowing the exact as-built configuration of the array. The instrumentation and equipment connected to the system may be vulnerable to transients. Covering these issues was beyond the scope of this project. A more in-depth, detailed analysis would be necessary to evaluate these issues.

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In the final constructed system, additional surge protection devices were utilized in addition to the surge capacitors. This additional protection should relieve some of the stress on the surge capacitors in a lightning environment and provide a more effective transient protection design.

The change in the final operating system, which reduces the delay between switch activations from 2 sec to 0.4 sec, will have little effect on the results since 1) during turn-on, no charging occurs until the second switch is closed and 2) during turn-off, discharging is unaffected by the opening of the second switch.

CHAPTER V
OPTIMUM TILT ANGLE AND FIXED VOLTAGE ANALYSIS

A. OBJECTIVE

The objectives of this analysis are twofold:

- (1) Determine the annual net energy yield for one module at several constant load voltages. This will generate an annual energy yield versus voltage plot. Compare this to the annual energy yield from maximum power-tracking.
- (2) Determine the optimum tilt angle of one module.

B. APPROACH

The SOLCEL Computer program was used to satisfy these analysis objectives. It generated the data points for the plots depicted in the results section. This analysis was done with one module since all modules were assumed to have the same nominal performance characteristics. Then, the module model in SOLCEL was validated with actual measured data of a solar power module in Sandia Laboratories' Solar Test Facility.

C. RESULTS

The analysis results indicate that the tilt angle has a small effect on annual performance (figure V-1). A total annual energy loss of 2.6 percent is realized when a constant load voltage of 15.4 volts is used instead of peak power tracking (illustrated in figure V-2). These analyses do not take into account two items which probably have second order effects on the system performance. The first item is intra-array shading losses in the mornings and evenings. The second item is the efficiency of a peak-power tracker which is assumed to have the same efficiency characteristics of a voltage regulator.

These results were validated by comparing the SOLCEL model with measured data for a Solar Power module in Sandia Laboratories' test

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Figure V-1. Comparison Between Peak-Power-Tracking and Constant Module Voltage

Figure V-2. Annual Energy Generated as a Function of Collector Tilt Angle

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facility. Sandia measured data was selected for two time periods of the day. Then, data with the same insolation values were selected from the SOLCEL computer listing. An additional run was made with SOLCEL because the Sandia module was tilted at 52° from the horizontal. As illustrated in table V-1, the SOLCEL model is within 3 percent of the measured data. The adjustments were made since the ambient temperature and wind speed are not the same. The following procedure was used to adjust the modeled data for temperature and wind speed differences.

$$\Delta T_{\text{Ambient}} = T_{\text{Sandia}} - T_{\text{SOLCEL}}$$

The assumption is made that ΔT in the ambient air is approximately the same as the ΔT in cell temperatures. The total adjustment is calculated by adding the estimated wind temperature difference and the ambient air temperature difference.

$$T_a = \Delta T_{\text{Ambient}} + T_{\text{wind}}$$

The temperature difference caused by wind was estimated using SOLCEL data points. Four points were selected with the same ambient temperature and insolation. The ratio of calculated cell temperature to wind speed was calculated to be approximately 1°C/m/sec. This ratio was used to determine the wind chill temperature T_{wind} for each of the data sets in table V-1.

Then the module power was adjusted as follows. The change in power is proportional to the change in voltage; therefore,

$$P_{\text{adjusted}} = \left[1 - \frac{T_a \left(\frac{\Delta V}{\Delta T} \right)}{V_{\text{cell}}} \right] P_{\text{SOLCEL}}$$

These results indicate that a voltage regulator or constant load can be used with minimal change in annual energy produced. Also, the tilt angle of the collector has little effect.

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TABLE V-1. VALIDATION OF SOLCEL MODULE MODEL WITH SANDIA LABORATORIES' MEASURED DATA OF A SOLAR POWER MODULE

	INSOLATION DATE	TIME	INSOLATION	AMBIENT TEMP.	WIND SPEED	MODULE POWER @ 15.4 VOLTS	PERCENT DEVIATION
Sandia Data	12/17/79 Albuquerque	11:32	297.5(W)	3.63°C	1.41(M/S)	32.2(W)	
Modeled Data	1/31/74 El Paso, TX	12:30	297.6(W)	14.5°C	3.3(M/S)	30.6(W) 32.0(W) @ -9°C Cell Temperature adjustment *	.6% difference
Sandia Data	12/10/79 Albuquerque	9:36	228.5(W)	4.37°C	1.24(M/S)	25.1(W)	
Modeled Data	2/9/67 El Paso, TX	9:30	228.7(W)	6.14°C	5.1(M/S)	24.7(W) 24.5(W) @ 2°C Cell Temperature adjustment *	2.4% difference
Sandia Data	12/7/79 Albuquerque	11:44	297.9(W)	7.78°C	.56(M/S)	30.6(W)	
Modeled Data	1/31/74 El Paso, TX	12:30	297.6(W)	14.5°C	3.3(M/S)	30.6(W) 31.2(W) @ -4°C Cell Temperature adjustment *	2% difference

*Combined ambient and wind temperature differences

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