THE VALUE OF GRID-SUPPORT PHOTOVOLTAICS IN REDUCING DISTRIBUTION SYSTEM LOSSES

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***Abstract* — Strategically sited grid-support photovoltaic (PV) applications have been proposed to provide value (cost savings) to electric utilities experiencing transmission and distribution (T&D) system overloads. These applications can potentially defer transformer and transmission line upgrades, extend equipment maintenance intervals, reduce electrical line losses, and improve distribution system reliability. This research presents and tests a method to calculate the reduction in distribution system electrical line losses. It also describes how to optimize plant size, plant location along a distribution feeder, and load transfer from an adjacent feeder. Results at Pacific Gas and Electric Company indicate that a 0.50 MW PV plant at Kerman, California, has $37,000 in energy loss savings value over the plant's life with additional value due to capacity loss savings. These results are site specific.**

I. INTRODUCTION

The standard practice of electric utilities experiencing transmission and distribution (T&D) system overloads is to upgrade equipment. In 1988, it was hypothesized that strategically sited photovoltaics (PV) could benefit overloaded parts of T&D systems [1]. An evaluation methodology was developed and applied to a test case (Kerman Substation near Fresno, California). Simulated data suggested that T&D system value could exceed bulk generation system value [1].

The importance of this finding indicated the need for empirical validation. This led to the construction of a 0.50 MW PV demonstration plant at Kerman, California as part of project PVUSA (PV for Utility Scale Applications). PVUSA is a national cooperative research and development effort under the auspices of the United States Department of Energy [2]. PVUSA developed guidelines of how to configure the plant to obtain the greatest value [3] and designed a research test plan [4] to empirically determine the value of PV to the T&D and bulk generation systems. The Kerman PV plant, completed in June, 1993, is reported to be the first grid-support PV demonstration plant in the world.

Grid-support PV can provide many values to T&D systems. It can defer transformer and transmission line upgrades [5, 6], extend equipment maintenance intervals, reduce electrical line losses, and improve distribution system reliability, all with cost savings to utilities. This research focuses on the reduction in electrical line losses in the substation transformer and on the distribution feeder.

Electrical line losses occur as current flows through conductors, transformers and other transmission and distribution system devices. The magnitude of the losses is related to current flow and resistance of the devices. Thus, line losses can be decreased by reducing either the resistance or the current. Reducing the resistance requires replacing or adding equipment while reducing the current requires decreasing the load or serving some of it locally with a technology such as grid-support PV.

Loss savings are classified as either capacity or energy loss savings. Capacity loss savings lessen the need for capital upgrades by reducing peak loads on distribution, transmission, and generation system equipment. Capacity loss savings value is the savings in finance charges that result from postponing a capital investment until a future date. Energy loss savings reduce electricity generation requirements. Energy loss savings value is the cost savings realized by reducing operation and maintenance expenses of existing plants.

Software products exist to accurately calculate losses on distribution feeders [7]. They tend, however, to be data intensive and utility specific. This paper develops a method to calculate capacity and energy loss savings based on a day's worth of load and PV plant output data and a few distribution system characteristics. In addition, it suggests how to optimize plant size and location along a distribution feeder and load transfer from an adjacent feeder.

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II. METHODOLOGY

Loss savings equations are presented in this section and various optimization issues are discussed. The equations use the distribution feeder as an illustration. This approach extends to substation transformers.

A. Loss Savings Equation Form

Instantaneous losses on a distribution feeder equal the product of current (I_F) squared times resistance (R) [8]. Since a distribution feeder has three phases,

$$Losses = 3 I_F^{\,2} R . \tag{1}$$

Instantaneous loss savings (LS) at any point on a feeder equal the difference between losses with the PV plant *off-line* and losses with the PV plant *on-line*. Notice that there are additional losses rather than loss savings when PV current is more than twice as large as feeder current.

$$\mathrm{LS} = 3 I_{\mathrm{F}}^{\,2} R - 3\left(I_F - I_{PV}\right)^2 R = 6 R I_F I_{PV} - 3 R I_{PV}^{\,2} \; . \tag{2}$$

The objective of this paper is to evaluate loss savings on the entire feeder rather than loss savings at only one point on the feeder. Since feeder and PV current can vary along the feeder (see Fig. 1), feeder loss savings are determined by dividing the feeder into n sections (selection of n is based on the distribution of load and PV generation location on the feeder), calculating the loss savings for each section using (2), and summing the results.

Feeder current on section i equals a_i, the fraction of feeder current at that point on the feeder, times beginning feeder current, I_F where a_i is between 0 and 1. PV current on section i equals b_i, the fraction of PV plant capacity (the sum of all PV plants) on the remainder of the feeder, times total PV plant current on the feeder where b_i is between 0 and 1. Fig. 1 indicates that load and PV capacity decrease as one moves down the feeder from the substation. That is, both a_i and b_i decrease as i increases.

$$\mathrm{LS} = \left(6 \sum_{i=1}^{n} a_i b_i R_i\right) I_F I_{PV} - \left(3 \sum_{i=1}^{n} b_i^2 R_i\right) I_{PV}^{\,2} . \tag{3}$$

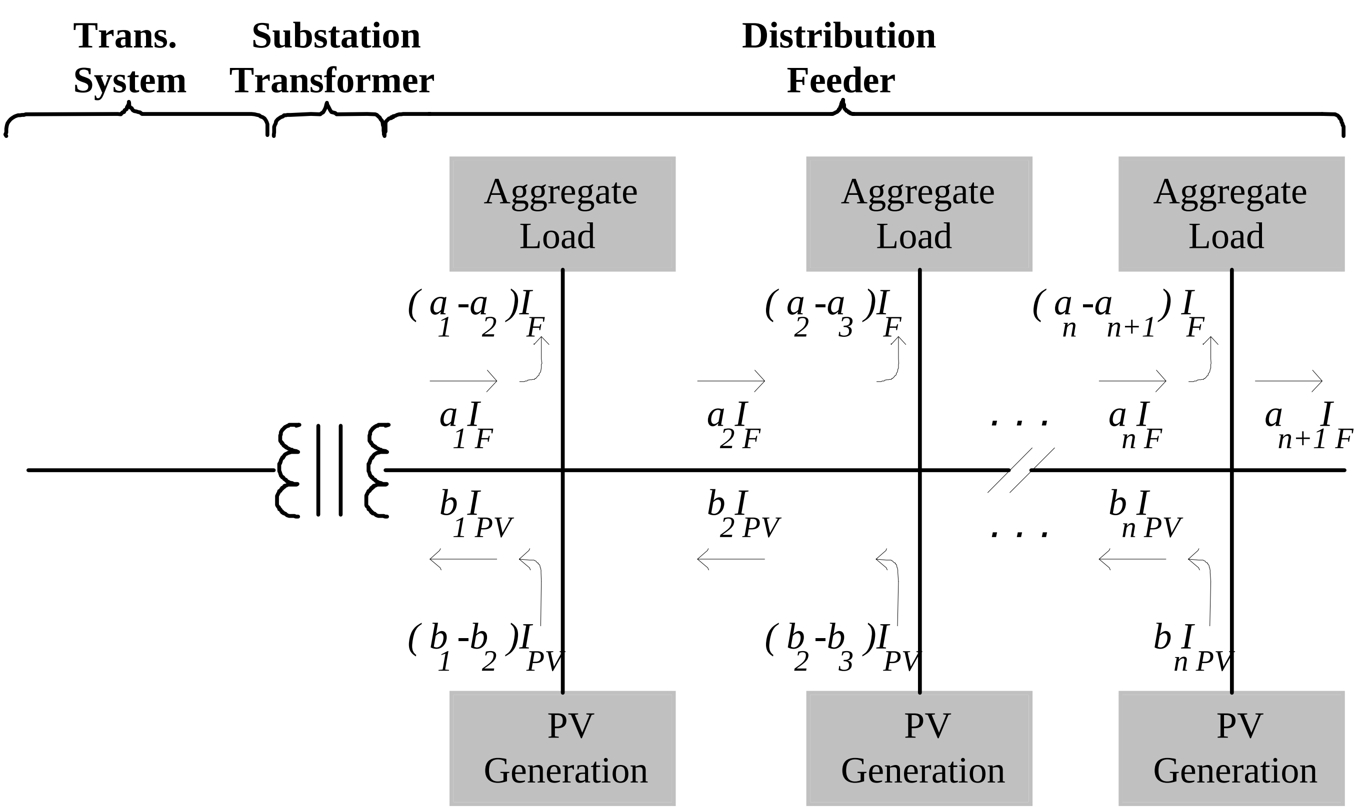

Fig. 1. A schematic of current flow on a distribution system.

Equation (3) is put in terms of normalized PV plant *output* (*PV* is normalized by dividing output by plant size; this is done to facilitate plant size optimization), *plant size* (*S* in megawatts), and feeder *load* (L_F in megavolt-amperes) using the relationship that phase current equals load divided by $\sqrt{3}$ times line-to-line voltage (*V* in megavolts). In addition, loss savings are divided by 1,000 to convert to kilowatts.

$$\mathrm{LS} = \left[\frac{\left(\sum_{i=1}^{n} a_i b_i R_i\right)}{500V^2}\right]\left(L_F PV\right)S - \left[\frac{\left(\sum_{i=1}^{n} b_i^2 R_i\right)}{1000V^2}\right]\left(PV^2\right)S^2 \cdot \quad (4)$$

(4) is simplified by collecting constant terms into *A* and *B*.

$$\mathrm{LS} = A\left(L_F PV\right)S - B\left(PV^2\right)S^2 . \quad (5)$$

B. Capacity Loss Savings

Loss savings are classified as either capacity or energy loss savings. Capacity loss savings reduce load on T&D and generation system equipment. This lessens the need for capital upgrades. They are calculated by developing feeder and transformer loss savings equations of the form of (5) and evaluating them during peak load conditions.

C. Energy Loss Savings

Energy loss savings (*ELS*) reduce electricity generation requirements. Their value is the cost savings realized by reducing operation and maintenance expenses of existing plants. Value equals the sum of capacity loss savings for each hour (*j*) over a time period of *n* hours times the per unit value of energy. A key simplifying assumption in the following equation is that the distribution of load is the same for each hour in the time period.

$$ELS = \left[A\left(\sum_{j=1}^{n} L_{Fj} PV_j\right)\mathrm{S} - B\left(\sum_{j=1}^{n} PV_j^{\,2}\right)S^2\right]. \quad (6)$$

D. Energy Loss Saving Calculations With Selected Data Set

A difficulty in using (6) is that it requires a large data set. For example, annual energy loss savings calculations require 8,760 hourly load and PV plant output data points. Since the feeder and PV plant have fairly consistent daily load and output patterns, energy loss savings can be estimated by using a 24 hour data set and multiplying the result by 365. The difficulty, however, remains as to how to select the 24 hour data set.

The problem is further simplified based on the assumptions that daily load shape is fairly constant throughout the year while its magnitude varies and that daily PV plant output magnitude is fairly constant throughout the year while the number of hours of plant output per day, i.e., its shape, varies. Thus, as long as one selects a 24 hour data set that is somewhat representative of the year, energy loss savings are approximately equal to

$$ELS = 365\frac{PV_{avg\,y}}{PV_{avg\,24}}\left[A\left(\frac{L_{avg\,y}}{L_{avg\,24}}\sum_{j=1}^{24} L_{Fj} PV_j\right)\mathrm{S} - B\left(\sum_{j=1}^{24} PV_j^{\,2}\right)S^2\right] \quad (7)$$

where L_{avgy} and PV_{avgy} are the average hourly load and PV output for the year and L_{avg24} and PV_{avg24} are the average hour load and PV output for the 24 hour data set. L_{avgy} divided by L_{avg24} adjusts the magnitude of the load and PV_{avgy} divided by PV_{avg24} adjusts for the number of daylight hours. Although it is tempting to have a squared PV term to compensate for the squared PV terms in the second summation, this would impact both the magnitude and the shape (or duration) of the PV output, thus violating one of the assumptions.

E. Determination of Optimal Plant Size

The only variable in (6) is plant size once a location and time period of analysis are selected. Thus, plant size is optimized by taking the derivative of (6) with respect to *S*, setting the result equal to zero, and solving for *S*.

F. Determination of Optimal Plant Distribution Along Feeder

The modularity of PV allows for the possibility of installing several small PV systems distributed along the feeder rather than one large plant. Plant distribution along a feeder is optimized by selecting the correct b_i terms using a Lagrangian analysis [9]. At each section, *i*,

$$b_i = \min\left[1, \frac{a_i \sum_{j=1}^{n} L_{Fj} PV_j}{\left(\sum_{j=1}^{n} PV_j^2\right)S}\right]. \quad (8)$$

Note that there are operational issues of concern to distribution system operators and planners that need to be addressed if PV plants are distributed along the feeder rather than sited in one location.

G. Determination of Optimal Feeder Configuration

In addition to optimizing plant size and distribution along a feeder, transferring load from an adjacent feeder may further increase energy loss savings. Suppose, for example, that the feeder with PV (PV feeder) is separated from another feeder (non-PV feeder) by a sectionalizing switch as illustrated at the top of Fig. 2. Transferring load from the non-PV feeder to the PV feeder as illustrated at the bottom of Fig. 2 reduces losses on the non-PV feeder. This transfer, however, increases losses on the PV feeder. The net loss savings is determined by comparing losses on both feeders before and after the load transfer.

Assuming the PV plant is located at the end of the PV feeder and the distribution of load between the two feeders was optimized before the PV plant was added, an optimal load transfer results in a maximum additional energy loss savings of:

$$LS_{load\ \mathrm{transfer}} = \frac{\left(\sum_{i=1}^{m} R_i\right)\left(\sum_{j=1}^{n} PV^2\right)S^2}{1000V^2(1+ratio)}. \tag{9}$$

where *ratio* equals non-PV feeder resistance divided by PV feeder resistance. (See Appendix for detailed calculations.)

This equation suggests that loss savings due to a load transfer decrease with increasing resistance of the non-PV feeder. Although contrary to intuition, this is reasonable when one considers that the previous distribution of load between the feeders was originally optimized prior to the PV installation to take advantage of the differences in resistance. Thus, there is not as much load left to transfer.

The decision of whether or not to make such a transfer requires trading off the added energy loss savings value with the extra load on the substation transformer and other distribution system devices resulting from the transfer.

III. RESULTS

This section applies the methodology from the previous section to a 0.50 MW PV plant located near Pacific Gas and Electric Company's Kerman Substation. Results of the analysis are site specific.

A. Feeder Loss Savings

Transformer load, feeder load, and PV plant output were measured at the Kerman substation; location of PV along the feeder (the b_i terms) and feeder and transformer resistances were also known. Although the distribution of feeder load (the a_i terms) was not measured, it can be approximated. The resulting system configuration for the Kerman location is presented in Fig. 3. Using the data in Fig. 3 and the relationships for A and B from (4), i.e., A equals $\sum_{i=1}^{n} a_i b_i R_i / 500V^2$ and B equals $\sum_{i=1}^{n} b_i^2 R_i / 1000V^2$, the model sates that feeder loss savings at any instant equal:

$$\mathrm{LS_F} = 12.3(\mathrm{L_F}PV)S - 47.6(PV^2)S^2. \tag{10}$$

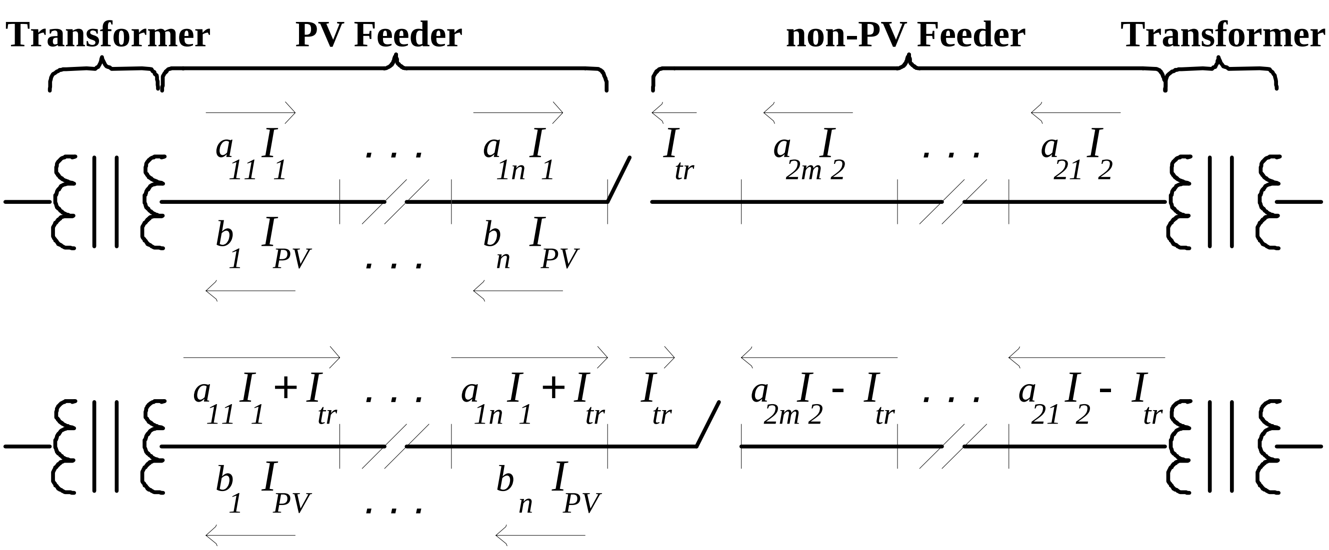

Fig. 2. A schematic of current flow on two distribution feeders *before* and *after* load transfer.

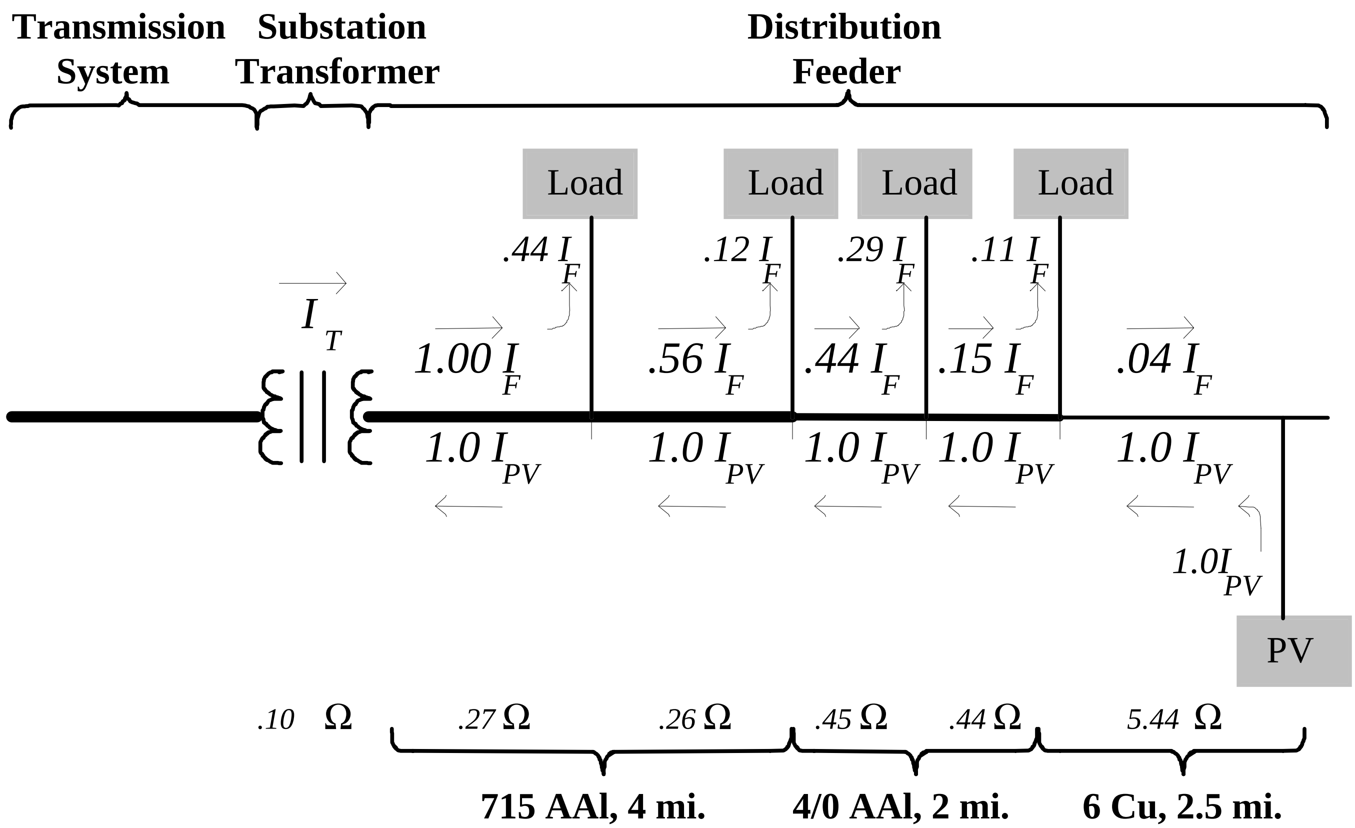

Fig. 3. A schematic of the Kerman 1103 distribution feeder.

B. Model Validation Using Measured Loss Savings Data

Predicted results (10) can be validated by comparing them to measured feeder loss savings. Four sets of loss savings tests were performed on July 22, 1993 and August 24, 1993. The tests were performed by turning the plant on and off and measuring the load (kW) at the substation with PV plant *on-line* and *off-line*. Loss savings is the difference between load with PV *off-line* and the sum of load with PV *on-line* and PV output.

The PV plant was turned on and off 10 times over the course of an hour on July 22 and 8 times per hour during three hours on August 24. Plant output during the tests ranged from 0.39 MW to 0.45 MW with an average of 0.40 MW. Fig. 4 illustrates one test result. Notice that there was a one second delay between the time the PV plant was taken off-line and the time the load stabilized at its new value. This is due to the fact that the measurement device (transducer) required a half second to stabilize once the plant was turned off and the plant was turned off in two phases with a half second delay between phases.

Since loss savings represent less than one percent of the feeder load in this case, a slight change in load during this one second delay could obscure test results. This difficulty was addressed by eliminating test data for times when the load was not stable enough. Sixty percent of the data remained after this screening.

Fig. 5 (scale equal to one-tenth that of Fig. 4) presents the loss savings test results. The solid line is the predicted loss savings for a plant output of 0.40 MW; the x's are the average of the measured loss savings for each of the four sets of tests; the dots are the actual loss savings measurements. Considering the time delay required to perform loss savings measurements, measured data tend to validate predicted results. Faster measurement equipment is required for further validation.

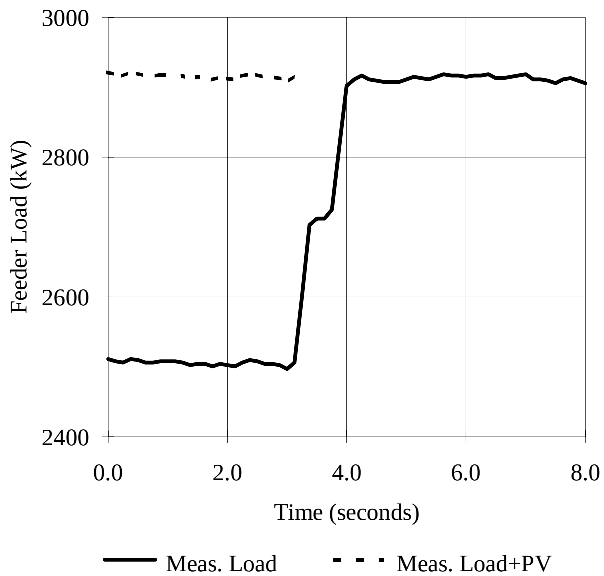

Fig. 4. Feeder load when plant is taken off-line

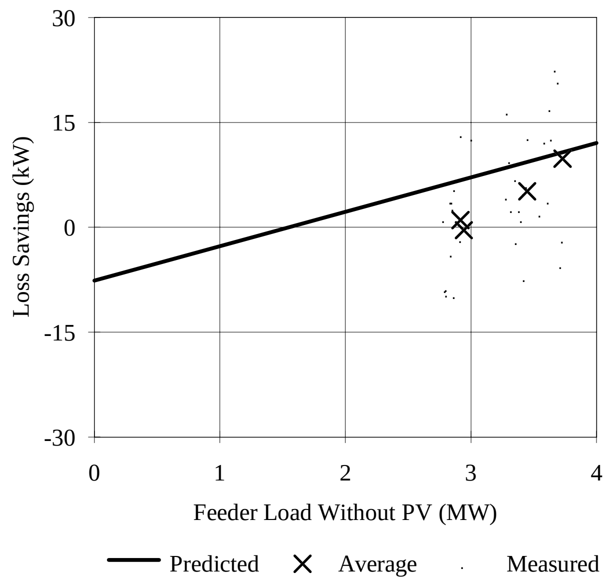

Fig. 5. Measured and predicted loss savings.

C. Transformer Loss Savings

In addition to feeder loss savings, there are transformer loss savings. Transformer specifications [10] state that there are 48 kW in copper losses at a load of 8.4 MW. This translates to 0.1 Ω resistance for one phase of the transformer. Using (4), transformer loss savings at any instant equal

$$\mathrm{LS}_{\mathrm{T}} = 1.4\left(\mathrm{L}_{\mathrm{T}} PV\right)S - 0.7\left(PV^{2}\right)S^{2}. \tag{11}$$

D. Transmission System Loss Savings

Although not measured or estimated by this paper, a picture of loss savings is not complete without including transmission system loss savings. Earlier analytical work [1] estimated the loss savings on the transmission system to be 15.8 kW (about 3 percent of plant capacity).

E. Total Capacity Loss Savings

Capacity loss savings at the transformer equal the sum of feeder and transformer loss savings. The 1993 feeder and transformer peaks occurred coincidentally on June 25 at 16:00 PST. Feeder and transformer loads with PV *off-line* were 4.93 MVA and 9.94 MVA; PV plant output was 0.41 MW. Thus, according to (10), feeder loss savings were 17 kW; according to (11), transformer loss savings were 6 kW for a total loss savings at the transformer of 23 kW (5 percent of the PV plant rating).

Capacity loss savings lessen the need for capital upgrades by reducing load on distribution, transmission, and generation system equipment. As such, their value depends on other values. To illustrate, consider the capacity loss savings value as it applies to the substation transformer. An earlier work [5] suggested that the value of the 0.50 MW Kerman PV plant to the Kerman substation transformer was about $360,000. Since there are 5 percent capacity loss savings at peak conditions, the capacity loss savings value to the substation transformer is approximately $18,000. Capacity loss savings value includes value to the other T&D and generation system components as well.

F. Total Energy Loss Savings Value

Annual energy loss savings equal the sum of feeder, transformer, and transmission system loss savings. Feeder and transformer loss savings are calculated using the feeder and transformer capacity loss savings equations, and load and PV output data; annual transmission system loss savings were estimated to be 33,500 kWh. Assuming that the net present value of 1 kWh of electricity generated annually for 30 years is $.60, energy loss savings value equals

$$ELS\ Value = \$96{,}000S - \$43{,}000S^{2}. \tag{12}$$

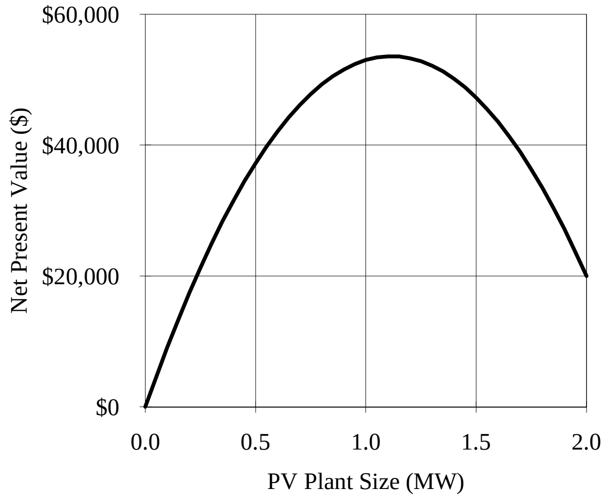

Fig 6. Energy loss savings value.

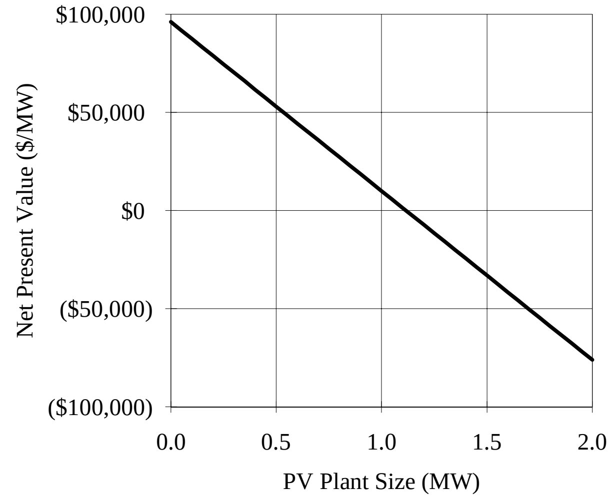

Fig. 7. Marginal energy loss savings value.

Figs. 6 and 7 present energy loss savings value and marginal energy loss savings value versus plant size. Fig. 6 suggests that the energy loss savings net present value for the 0.50 MW Kerman PV plant is $37,000: $20,000 for the transmission system (estimated in an earlier work) and $17,000 for the feeder and transformer.

If the feeder and transformer analysis is repeated using a data set consisting only of the peak day and (7), energy loss savings value for the transformer and feeder equals $16,000. This is only 6 percent less than the value based on an entire year's worth of data. This tends to confirm the validity of a reduced data set approach.

G. Optimization Results

Plant size can be optimized for loss savings value using Figs. 6 and 7. Additional value can be obtained, however, by optimizing plant distribution along the feeder and load transfer from an adjacent feeder. Using (8) and repeating the analysis presented above, results indicate that optimally distributing the plant along the feeder can provide a 20 percent relative increase in value. Using (9), it is estimated that there is a maximum possible 30 percent relative increase in value due to transferring load from an adjacent feeder.

IV. CONCLUSIONS AND FUTURE RESEARCH

A simple method to calculate energy loss savings based on a day's worth of load and PV plant output data and a few distribution system characteristics was presented in this paper. This provides a good first cut estimate of the loss savings value.

Results indicated that the 0.50 MW Kerman PV plant has system wide (feeder, transformer, and transmission system) energy loss savings equal to 6 percent of the plant's energy output for a value of $37,000 over the plant's life (net present value). Peak load loss savings at the transformer equal 5 percent of its capacity for a value that may exceed energy loss savings value. Optimizing plant distribution along the feeder and load transfer from an adjacent feeder could provide a relative increase in value by up to 50 percent. These results are site specific.

One area of future research is to evaluate how the percentage distribution of load varies throughout the year, what are the primary factors that influence this variation, and what is the effect of this variation. Another area is to more accurately measure loss savings using faster speed measurement equipment. A third area is to evaluate other systems using this model.

V. APPENDIX

A detailed presentation of calculations used to determine the additional loss savings due to a load transfer from a non-PV feeder to a PV feeder is presented below. Suppose that a feeder with PV is separated from another feeder by a sectionalizing switch as was illustrated in Fig. 2. Transferring load from the non-PV feeder (feeder 2) to the PV feeder (feeder 1) will reduce losses on the non-PV feeder. This transfer, however, will increase losses on the PV feeder. The net effect is determined by comparing losses before and after the transfer is made. Note that the calculations in this section are the loss savings due to the load transfer; they are in addition to the loss savings due to the PV plant.

After performing all the calculations and simplifying the result, instantaneous loss savings, LS_{tr}, due to a load transfer of L_{tr} equal:

$$LS_{tr} = \frac{6\left(L_2 \sum_{i=1}^{m} a_{2i} R_{2i} - L_1 \sum_{i=1}^{n} a_{1i} R_{1i} + PV \times S \sum_{i=1}^{n} b_i R_{1i}\right) L_{tr}}{3000V^2} - \frac{3\left(\sum_{i=1}^{n} R_{1i} + \sum_{i=1}^{m} R_{2i}\right) L_{tr}^2}{3000V^2}. \quad (13)$$

The first subscripts on a and R as well as the only subscript on L represent feeder number (1 for PV feeder and 2 for non-PV feeder). The optimal load transfer from the non-PV feeder to the PV feeder, L_{tr}, is determined by taking the derivative of (13) with respect to L_{tr}, setting the result equal to zero, and solving for L_{tr}.

$$L_{tr} = \frac{L_2 \sum_{i=1}^{m} a_{2i} R_{2i} - L_1 \sum_{i=1}^{n} a_{1i} R_{1i} + PV \times S \sum_{i=1}^{n} b_i R_{1i}}{\sum_{i=1}^{n} R_{1i} + \sum_{i=1}^{m} R_{2i}}. \quad (14)$$

The optimal load transfer must be zero when PV plant size is zero if the two feeders were optimized prior to the addition of the PV plant. This is only true when the first and second terms in the numerator of (14) cancel. Based on this assumption, (14) is substituted into (13) and the result reduces to:

$$LS_{tr} = \frac{\left(PV \times S \sum_{i=1}^{n} b_i R_{1i}\right)^2}{1000V^2 \left(\sum_{i=1}^{n} R_{1i} + \sum_{i=1}^{m} R_{2i}\right)}. \quad (15)$$

Thus, the maximum possible loss savings due to load transfer would be the summation of (15) for every hour in the time period. In essence, this is saying the amount of load to be transferred is optimal at every point in time. The actual value will be lower than this in reality.

VI. BIOGRAPHIES

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