MODELING DISTRIBUTION SYSTEM IMPACTS OF SOLAR VARIABILIY AND INTERCONNECTION LOCATION

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ABSTRACT

As the amount of solar energy on the distribution grows, a quick and easy simulation method is needed to model the impact of solar energy and to help distribution planners perform the necessary interconnection studies. This paper demonstrates the functionality and methods of a prototype software that models the variable nature of the distribution system load and solar energy throughout the year with cloud-cover. It also models the spatial impact on the distribution system with GIS integration with Google Maps. OpenDSS is used to model the distribution system with MATLAB providing the frontend user interface. Results are included for several example feeders in Utah and some of the IEEE distribution feeders. Finally, a method is also proposed using the Power Transfer Distribution Factor (PTDF) to analyze the placement of solar on the feeder for improving security, controlling voltage, and decreasing line losses.

1. INTRODUCTION

The power industry is beginning to see a change to larger amounts of generation on the distribution system. This presents a new set of issues, especially for renewable generation with variability. The number of new solar PV interconnections to the distribution system continues to increase, with distribution planners getting constant requests for interconnection studies for both internal utility projects and small-scale residential PV. These studies require knowledge of the solar system power output characteristics and the distribution system itself. The variability in the load, throughout the day and year, and the variability of solar, throughout the year and because of clouds, makes the analysis increasingly complex. Both good data and timeseries simulations are required to fully understand the variations. As the interconnection of solar on the distribution grows, a quick and easy simulation package is needed to model the impact of solar energy and help distribution planners perform the necessary interconnection studies.

This paper presents the methods of an analysis software designed to model solar on the distribution system along with some example resulting figures. Some key features of the prototype software are:

- Modeling solar output and variability for any location in an convenient and accurate way
- Visualizing the setup process with integration to GIS through Google Maps
- Examining timeseries simulations of solar output and feeder demand for the year
- Performing snapshot analyses of identified critical times
- Modeling impact of the variability of solar to voltage
- Analyzing the impact of PV to regulation equipment like load tap changes, switching

capacitor banks, and line voltage regulator operations
- Studying the locational value of where the solar is placed on the feeder

The user interface helps to visualize solar output on the distribution system both spatially and through time. The front-end interface is all done in MATLAB, with the distribution system model analysis being processed in OpenDSS and connected to MATLAB through a COM interface.

Finally, a method is also proposed to analyze the placement of solar on the feeder for improving security, controlling voltage, and decreasing line losses. Using the Power Transfer Distribution Factor (PTDF) calculated for every bus, this function allows a distribution planner to consider possible locations and amounts of solar in order to optimize system security and stability. This work is significant in developing a process for interconnection studies of solar on the distribution system, and it also proposes a method for optimizing where solar energy is connected to the feeder.

2. SOLAR OUTPUT MODELING

Solar resource modeling includes modeling of the irradiance at the site and the conversion of that irradiance to output from the solar array. Each of the three components of irradiance, Direct Normal Irradiance (DNI), diffuse irradiance, and Global Horizontal Irradiance (GHI), must be modeled, measured, or calculated for the location and converted to the plane of array irradiance for the amount of irradiance on the panels. The position of the sun in the sky is found using [1], and the incident irradiance is transformed to plane of the PV array tilt, azimuth, and tracking system. The variability of the solar power output must also be correctly modeled for the location and configuration.

2.1 Maximum Irradiance Potential on Clear Days

Often distribution planners are most interested in the largest impact solar could have grid. This happens on clear days when the highest solar energy is produced. If measured data is provided to the software, clear days can be detected to produce a clear sky model for the year for the location assuming no cloud cover. There are also many published clear sky models that can be applied for different latitudes, longitudes, and elevations. Some of the choices in the software are Ineichen model [2] for GHI and Daneshyar–Paltridge–Proctor model [3, 4], Meinel Model [5], and Laue Model [6] for DNI.

2.2 Average Irradiance for a Location

Because of location-specific weather, the irradiance at a given place on earth does not match the before mentioned clear sky model. Using historical measurements or satellite data, the actual average irradiance can be found for each day of the year. Two good sources of data are Typical Meteorological Year (TMY) [7] or satellite data [8]. Both of these provide a profile more characteristic of the irradiance for a location's given weather patterns. This data can be used to calculate how much solar energy will be produced throughout the year and to perform other high-level yearly simulations.

2.3 Modeling the Variability of Solar

For distribution system assessment of solar PV impacts, the common concern is intermittency and variability of solar energy and how this might impact nearby customers on the distribution system. These issues all relate to the frequency and speed for which the PV output will change. High time-resolution irradiance data is required for this type of analysis. If irradiance data is not available at the exact location, we have implemented techniques in the analysis software to correctly adjust the length and magnitude of a nearby site to the analysis location.

One of the important aspects of modeling high-frequency solar output variability is that the variability of irradiance at a single sensor is not representative of the variability of the solar plant. Many factors determine how fast and frequent solar PV output fluctuates, such as size and layout of the solar facility and if the array is centralized or distributed. The larger the plant, the smaller the per unit variability or percent change over time. In order to accurately model solar on the distribution system, the variable irradiance must have some smoothing applied according to the size and dispersion of the PV array. The wavelet-based variability model was used to correctly model each type of solar scenario [9].

3. DISTRIBUTION SYSTEM MODELING

All electrical modeling is done in the open source software OpenDSS from EPRI [10]. OpenDSS is commonly used to model solar on the grid because of its timeseries capabilities [11-13]. The program was designed to help distribution planners analyze various issues with distributed generation. All power flows were solved with OpenDSS and the results transferred to MATLAB through a COM interface.

A visual interface in MATLAB walks the user through the setup process for a PV array. It is designed to step through each analysis and provide some structure to the interconnection methodology. This front-end MATLAB GUI is shown in Fig. 1.
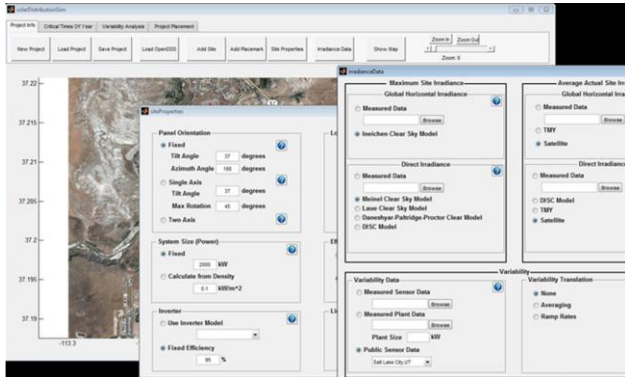

Fig. 1: Graphical user interface for setting up the system and performing analysis

The analysis software is also integrated with a Geographic Information System (GIS) to visualize the location of the distribution system power lines. GIS uses Google Maps to display streets, location names, and satellite images. The API for Google Maps allows MATLAB to interact and download maps with location specific data, including elevation [14]. The interface allows a user to draw the location of a PV plant directly on the map. The user-drawn plant is used to model the maximum plant output and the plant variability using the wavelet-variability model. Fig. 2 displays the Toquerville distribution feeder located in Utah as an example of the GIS functionality.
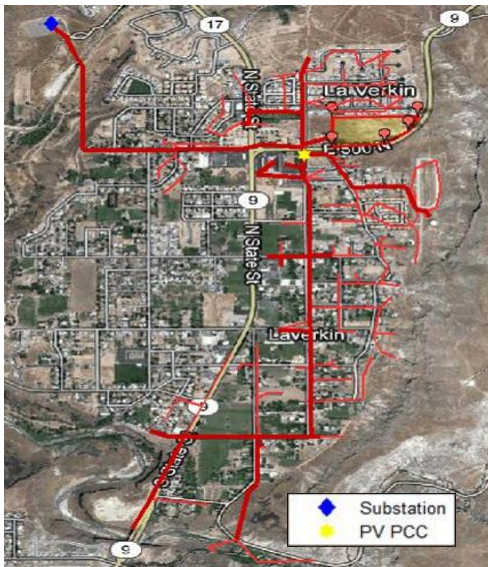

Fig. 2: Toquerville distribution system and an example solar field displayed on a Google Map.

4. ESTABLISHING STUDY SCENARIOS

For research purposes, it is interesting to study a diversity of PV scenarios to analyze the differences in impact on the distribution system. For example, what is the difference if the PV plant is increased by 1 MW? What if the solar is distributed on residential rooftops instead of a large central PV plant? There are hundreds of possible scenarios to consider to different PV plant sizes, connection location on the distribution system, amount the PV is distributed, orientation of the panels, etc. We show a couple scenarios as examples in this paper, and the software allows for looping through huge numbers of different scenarios.

Fig. 3 shows five example PV placement locations: a large 10.5 MW central plant in red, 3.5 MW distributed plant in purple, 2.6 MW distributed plant in yellow, 3.5 MW central plant in blue, and a 2.6 MW central plant in pink. These locations were picked as examples of realistic size areas and locations for rooftop solar for the distributed cases and vacant fields for the central PV plants. The user can select any locations in the area of the feeder for connection and analysis.
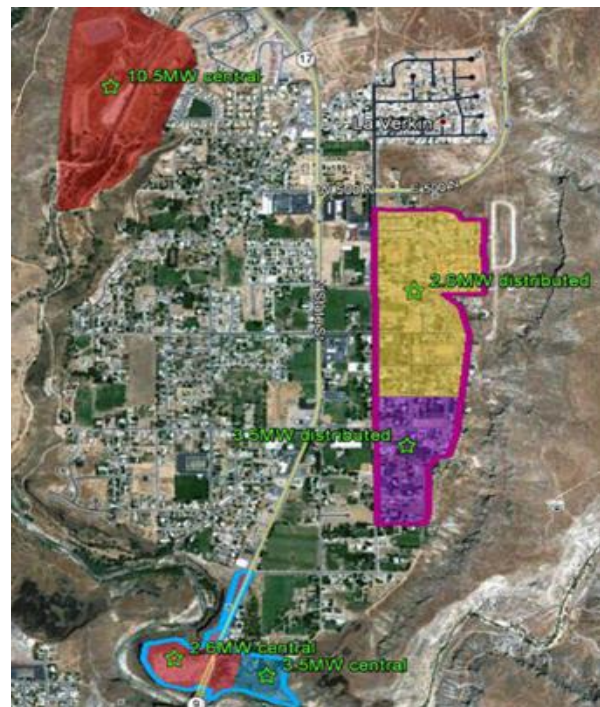

Fig. 3: Example PV placement scenarios on Toquerville

5. IDENTIFYING CRITICAL TIMES OF YEAR

Running a simulation for every minute or every second for an entire year is very time consuming process. Analysis and visualization of the results for every second for a year is also impractical. For these reason, specific times of year are focused on for the analyses. Often integration studies focus on standard time periods like peak load or minimum load days. With accurate solar measurements and modeling, specific time periods are identified as critical and important times to perform a detailed analysis.

As both the load and amount of solar vary throughout the year, one critical time is obviously when there is the highest percentage of solar energy on the grid compared to the feeder load. In the example in Fig. 4, this occurs during the spring when the load is low and solar production is high. Another critical time is at the peak load for the year because this is currently the highest strain time for the distribution system. One other interesting time to look at is the lowest load time of the year. Each of these days is displayed for the user and shown in Fig. 5.

The actual expected generation from solar energy will be less than is shown in Fig. 5 because of cloud cover.

Using the expected average irradiance for that location, the maximum percent from solar is shown in green in Fig. 4. Note that this figure is showing a very high penetration of solar such that most days there is more power being produced by solar than load on the feeder. This is assumed to be allowable because of multiple feeders at the substation such that the net load of the substation will always be positive.
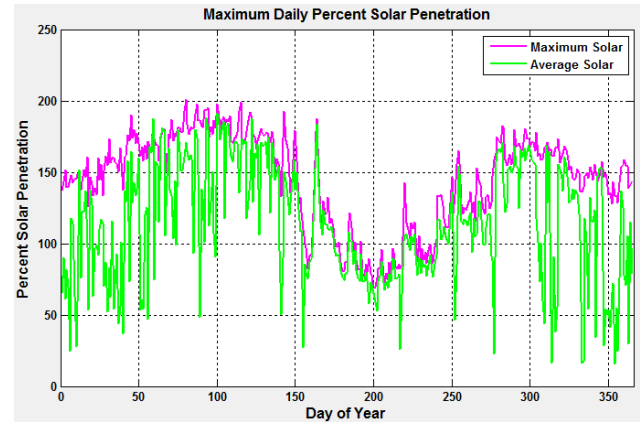

Fig. 4: Maximum percentage of the feeder load being produced from solar energy for both a clear sky model irradiance and expected average irradiance.
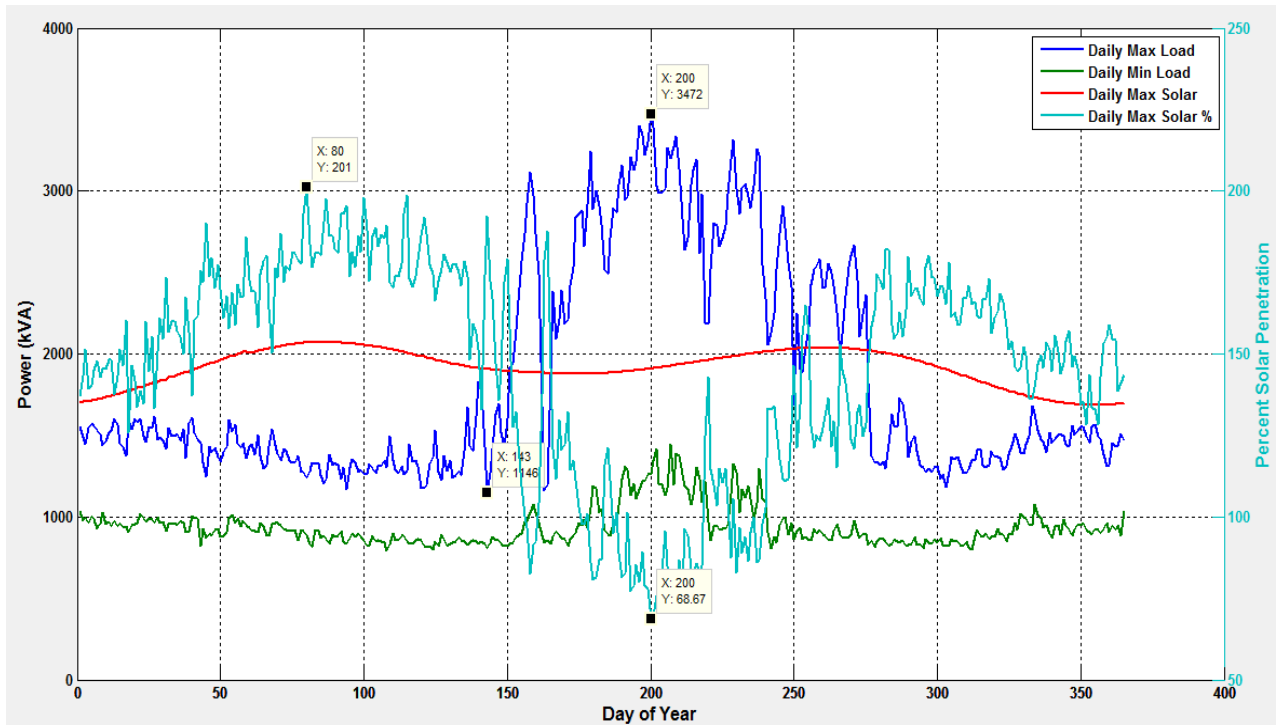

Fig. 5: Daily maximum solar output, maximum load, minimum load, and maximum percent of the feeder load from solar energy throughout the year.

6. ANALYSIS

There are many different possible analyses to run for each of the three identified days from Section 5. The available analyses in the software include

- Voltage contour of the feeder spatially
- Voltage profile of the feeder with the distance to the substation
- Net feeder load throughout the day
- Net feeder power factor throughout the day
- Max/min feeder voltages throughout the day
- Deviation in feeder voltages throughout the day
- Various animations of voltages and power flows

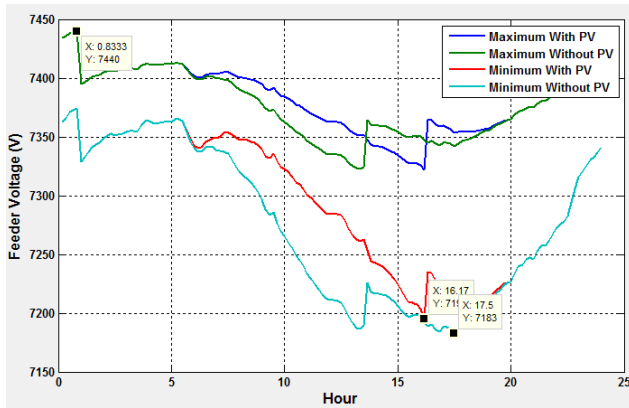An example for the peak load day maximum and minimum voltage is shown in Fig. 6.

Fig. 6: Example of maximum and minimum voltage on the feeder for the peak load day with and without solar.

Fig. 7 shows voltage contour plots that are the results of each PV placement scenario. Note that each figure is plotted with a different voltage range in order to show the geographical diversity of voltages around the feeder at the instant of maximum solar penetration.

Fig. 8 shows a different way the software can display the voltage profile for the feeder. For the basecase without PV, the voltage decreases for buses further from the substation. With the central PV scenario of solar in the center of the feeder, the voltage increases around the location of the PV.

Another item of interest is the effect of the variability on Load Tap Changers (LTC). A cloud initially causes a voltage drop as the PV power output ramps down, and eventually, the feeder regulators react to boost the voltage. When the sun returns, the voltage could go into an overvoltage condition because the regulator taps will be momentarily too high. Also any additional actions on the load tap changer cause extra wear and could decrease

the lifetime. This impact to voltage is modeled and any increase to the number of times the load tap changes acts is recorded.

The software analyzes the impact of solar variability to the regulating equipment in the distribution system like a LTC, switching capacitor banks, and line voltage
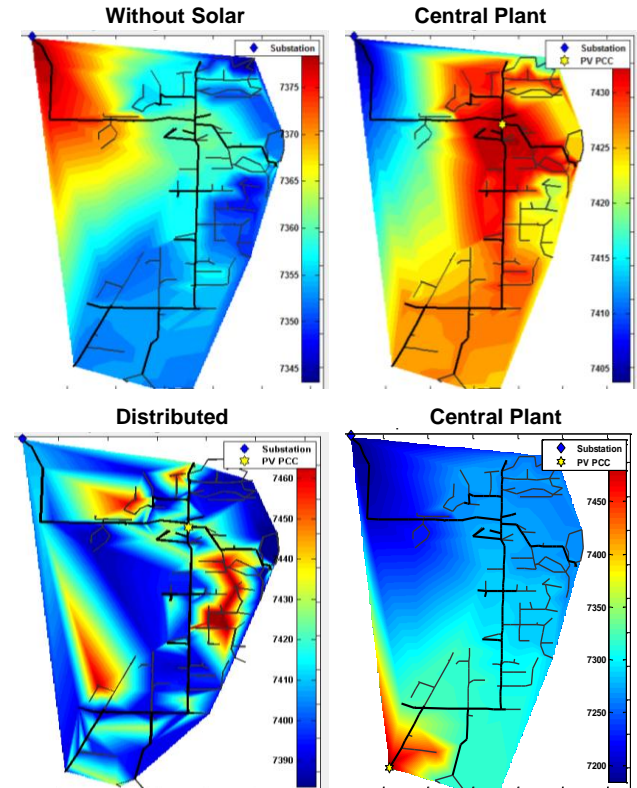

Fig. 7: Voltage contour plots for PV placement scenarios (clockwise from top left): without solar, central plant in the middle of the feeder, a central plant at the end of the feeder, and distributed solar.
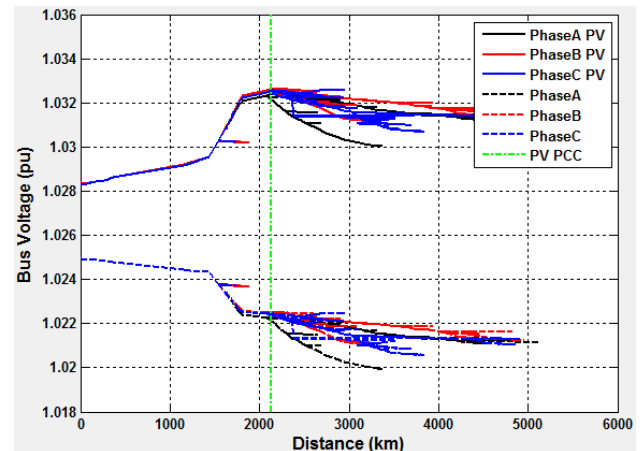

Fig. 8: Bus voltages along the feeder without solar and with a central PV plant in the middle of the feeder.

regulator operations. An example of the tap position for a one week period is shown in Fig. 9 with the analysis showing 20 tap changes for the basecase and 86 operations during the week with a 3.5 MW PV plant in the middle of the feeder.
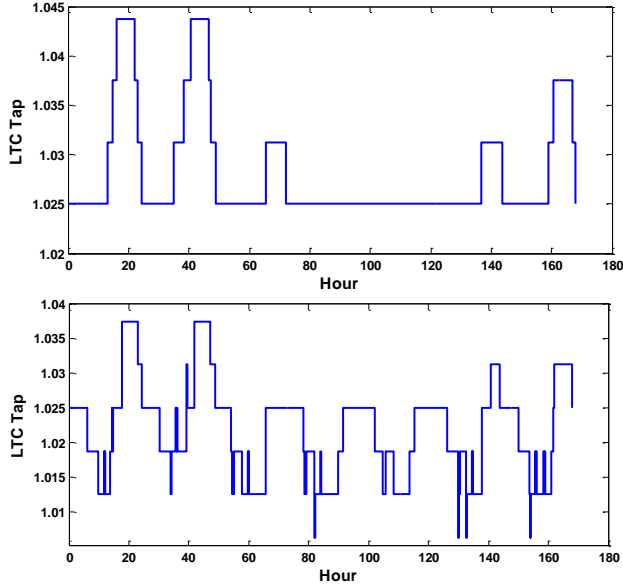

Fig. 9: LTC tap position for a one week period (a) without solar basecase and (b) for a 3.5 MW central PV plant at the end of the feeder.

7. LOCATION VALUE OF SOLAR

All of the previous analyses were evaluating the impact to the distribution feeder given a certain type of solar array connected at a particular location. Where the solar array is located and connected to the distribution system also plays a role in the value to voltage control, line losses, and security [15].

7.1 Power Transfer Distribution Factors

Calculating the Power Transfer Distribution Factors (PTDFs) for transfers from the substation to a different bus in the distribution system give the derivatives for the different bus voltages, bus angles, and change to power transfer in the lines.

$$PTDF_{km,\mathbf{T}} = \underbrace{\begin{bmatrix} \dfrac{\partial P_{km}}{\partial \theta_k} & \dfrac{\partial P_{km}}{\partial \theta_m} & \dfrac{\partial P_{km}}{\partial V_k} & \dfrac{\partial P_{km}}{\partial V_m} \end{bmatrix}}_{\text{Line Derivatives}} \underbrace{\begin{bmatrix} \dfrac{\partial \theta_k}{\partial \mathbf{P}} \\ \dfrac{\partial \theta_m}{\partial \mathbf{P}} \\ \dfrac{\partial V_k}{\partial \mathbf{P}} \\ \dfrac{\partial V_m}{\partial \mathbf{P}} \end{bmatrix}}_{\substack{\text{Rows of the} \\ \text{Jacobian Inverse} \\ \text{Matrix}}} \mathbf{T} \qquad (1)$$

The rows of the Jacobian Inverse Matrix can be used to obtain the change in each bus voltage and angle in the system for a given transfer of power from the substation to the PV bus. The Line Derivatives are a function of the bus voltages, angles, and the Ybus.

7.2 Evaluation

Using the calculations for the PTDF, the impact to line currents and bus voltages is determined. This is calculated for a 10 kW transfer to each bus in the distribution system from the substation, which is equivalent to trying the solar array at every location. The calculation was limited to only the 3 phase buses in the system because of the final size of the solar array that is being modeled. An example result is shown in Fig. 10 where line losses are decreased more by placing the solar array on buses farther from the substation (located at the upper left of the figure).

The distribution planner can use these graphs to determine where to place the solar array on the feeder in order to optimize any of the parameters. For example, if the solar array is placed closer to the substation, the analyses show that the PV output will have less impact to the other bus voltages and less voltage flicker, but the load tap changer may have to act more often. This method also provides the ability to model few PV scenarios by calculating the differences from connecting at different locations around the feeder without having to fully model each scenario.
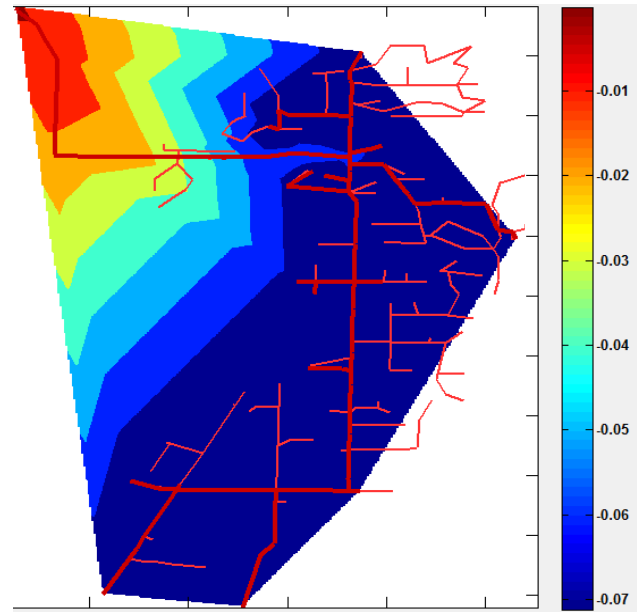

Fig. 10: Decrease in line losses due to a transfer of 10 kW power generation from the utility at the substation (upper left) to various potential PV buses locations.

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8. CONCLUSIONS

This prototype simulation software integrates the simulation power of OpenDSS with the visual user interface of MATLAB. Contouring and Google Maps are used to visualize the spatial effect of solar, and timeseries simulations show the time-varying nature of solar energy and load. Finally a simple method is proposed for determining value of the location of a solar array on a feeder to regulate voltage or decrease losses. This work is significant in developing a process for interconnection studies of solar on the distribution system, and it also proposes a method for optimizing where solar energy is connected to the feeder.

9. ACKNOWLEDGMENTS

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