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Paper:

A Novel Approach for Determining Distributed Generations Penetration Level Using Least Square Minimization (LSM) Curve Fitting

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With the publicized benefits offered by renewable energy resources, more and more households embrace the utilization of stand-alone installations ranging from small to medium scale systems. In literature, several studies provide insights on the effects of integration of renewable energy (RE) resources to the distribution systems but have inadequacy of considering the penetration levels. Moreover, RE cost reductions, increasing costs of traditional energy sources, and Renewable Portfolio Standards have created the possibility of significant increase of penetration levels of distributed RE generation being installed on distribution systems. To aid in the evaluation and assist with these expansions, new analysis tools are needed. In particular, new RE high-penetration analysis tools and procedures need to be developed and integrated with existing conventional methods. This paper presents a simulation based study on distribution system with and without integration of RE sources. It takes into account of the impending effects of these RE integrations in the distribution system. This paper emphasizes a novel method of determining the penetration level of Distributed Generation using least square minimization (LSM) method. The studies were tested using IEEE 123 bus distribution test feeder and actual data from an existing distribution system to verify the effectiveness and robustness of the proposed approach.

Keywords: RE resources integration, distributed generation (DG), DG penetration levels, penetration level margin

1. Introduction

In conventional distribution networks, electric power is supplied to the customers from large generating units commonly fired from fossil fuels, hydrothermal or hydropower sources. Normally the electric power begins from these generating sources and is distributed to the consumers through transmission lines. Consumers in the low voltage (LV) distribution networks are increasingly installing solar photovoltaic (PV) systems in their homes motivated by increasing benefits' from feed-in tariff and issues on environmental concerns [1].

In literature, several studies show that different penetration levels and various placements of distributed renewable resources have different impacts on the distribution system [2–4]. The list includes voltage control and stability problems, increased fault duty on circuit breakers and protection coordination problems, islanding conditions, power-quality (PQ) issues, personnel safety, overvoltages, and intermittent [5] or stochastic nature of some renewable distributed sources. With these challenges at hand, this paper presents simulation-based analyses and models of distribution systems specifically focuses on the assessment of the effects of DG penetration levels on the distribution system. Some of the issues that this study covers include: Effects of unbalanced phase distribution of DG's on the distribution system, which is caused by uncoordinated massive installations; Voltage violations like in [6] on some buses and impacts of DG's in system's loss for different penetration level are also presented.

This study considers balanced and unbalanced configurations of the distribution feeders to evaluate parameters like bus voltages, equipment line losses and line flows of the system. Furthermore, a novel method to determine the penetration level margin of RE sources from the current

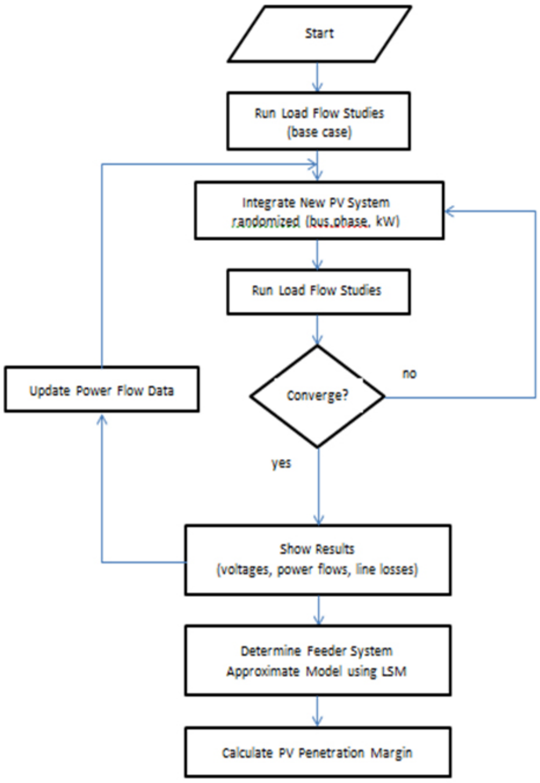


Fig. 1. Flow chart of the proposed methodology.

operating condition at different load levels is presented. The remainder of this paper is organized as follows: Section 2 discuss the methodology and how the study is implemented and show calculations on how system modeling are assumed, Section 3 provides details on the simulation environments including actual data for simulation and the distribution feeders. Section 4 shows the results and analyses of the method and lastly, Section 5 presents concluding remarks.

2. Methodology

The main focus of the paper is on the impacts of different DG's penetration levels on the distribution feeder system. The proposed methodology uses an exhaustive approach to translate various possible DG's penetration level to get a better insight on its advantages/disadvantages. This is carried out here through the use of steady state load flow studies on the distribution feeder. The flowchart of the proposed methodology is shown in **Fig. 1**.

The methodology starts with the initial simulation of load flow analysis in the distribution feeder using base case load and generation data. Next, integration of randomly selected PV system capacity, bus number and phase to the distribution feeder are considered in the system study. Every complete simulation run of PV integrations on the system updates the feeder data and are saved as current operating scenario. The number of iterations set is distinct to every feeder system to be evaluated. In addition, it is of most important to include simulations where the minimum total line loss of the system is explicitly reflected.

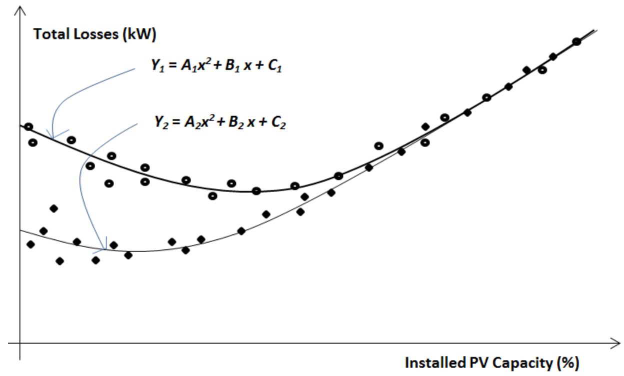


Fig. 2. System performance model derived from data plots using LSM.

Modeling of the distribution feeder performance can be formulated once the system run is completed. This performance model of the distribution feeder can be utilized to study the impacts of different PV penetration levels as illustrated in **Fig. 2**. The data points generated by simulation of PV system integrations are fitted using a least square minimization (LSM) method to create a performance model of the system. Other models considering different load demands can be determined from the data plots from their respective simulations. Furthermore, the nature of the data plots which represent the system performance at a given load can best be expressed by a quadratic function as:

$$y_n = A_n x^2 - B_n x + C_n \quad \text{. . . . .} \quad (1)$$

where $y_n(x)$ is the total kW losses of the system; x is the variable for the amount of PV system integration; and A_n, B_n and C_n are constants determine using curve fitting procedures.

The optimum value of x can be found by setting the first derivative of the quadratic function Eq. (1) to zero.

$$0 = 2A_n x - B_n \quad \text{. . . . .} \quad (2)$$

The value of x calculated from Eq. (2) determines the minimum value of system total power losses (kW) and optimum value of PV penetration level which could be integrated in the distribution system.

Figure 2 shows the system performance models derived from simulations with different load demands. Each model in the figure shows the "total losses in kilowatt (kW) versus installed PV capacity in percentage (%)" in different load demands respectively. Other system performance models of different system load demand using the same approach are illustrated in **Fig. 3**. Individual optimal point of performance of the system is shown in each curve summaries the ease of using this approach on a system with different load demand. Using this approach, the available PV capacity to be installed from its current operating point can be determined. This available PV capacity

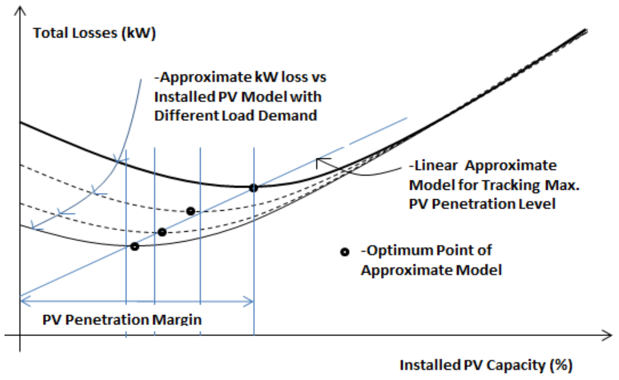


Fig. 3. Optimum point of performance model with different load demand.

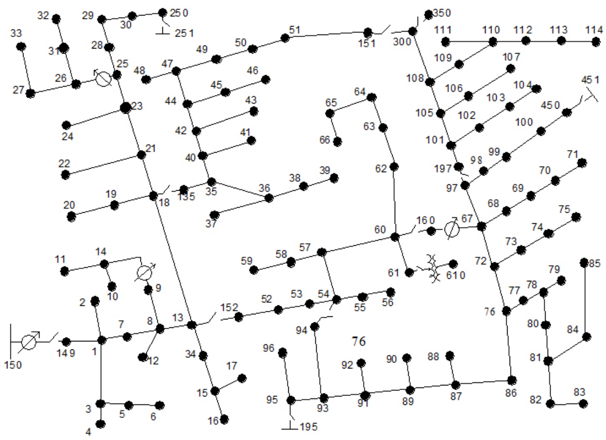


Fig. 4. Standard IEEE 123 Bus Distribution feeder used in the simulation.

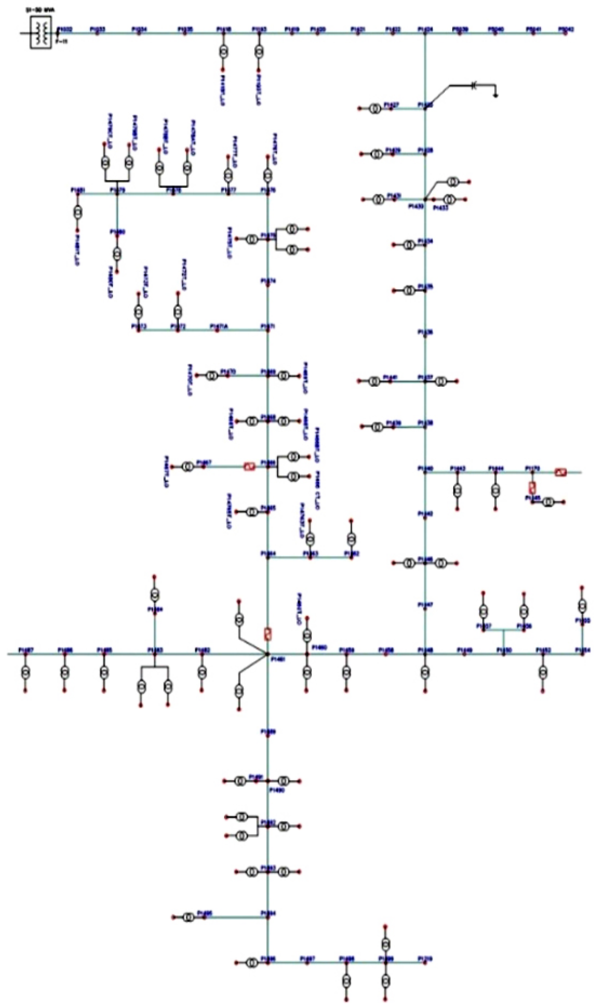


Fig. 5. The real distribution feeder test system.

"PV Penetration Margin" as a percentage of total installed capacity can be computed as;

%PV Penetration Margin = %PV Penetration Level(1) − %PV Penetration Level(0)

where PV Penetration Level(0) is the initial or current percent PV penetration level and %PV Penetration Level(1) is the percent PV penetration level determine from the optimal point of the curve derived from the proposed methodology.

3. Prepared Simulation Environment

The proposed simulations based study on the effects of different penetration levels of DG's on distribution system was initially tested using the modified IEEE 123 bus test feeder [7]. The IEEE 123 bus test feeder as shown in **Fig. 4** has a base load total line losses of 95.5 kW which is 2.72% of total power load of 3517 kW. This distribution feeder includes overhead, underground lines and three-phase and single phase shunt capacitors connected in its network which is ideal for the application of the proposed method. Furthermore, spot loads include single phase and three-phase in nature which makes this system appropriate for unbalanced system study. Significant results on the simulations were further validated for validity of the results using PECO Feeder 11 as a practical feeder system as shown **Fig. 5**. The data taken from the Feeder 11 of Panay Electric Company (PECO) is used as practical test system for this study.

PECO [8] is a private utility company, which has a franchise of operations for distribution system in Iloilo City, Philippines. The company's distribution network structure is ideal for this study because most of its large loads are concentrated within the city and in some part of its urban areas there is a rapid growth of energy demand.

In addition, PECO's total load demand is the biggest among other utility distribution companies in the province of Iloilo, Philippines. Recently, PECO forecasts large load of rapid commercial, residential and industrial growths. Hence, with these structures, the chosen distribution system is appropriate for the study on the effects of different penetration level of DG's integration.

The feeder 11 of the PECO was chosen to be used of practical test system as it supplies electric power to the one of the large load, which part of the old downtown Iloilo City [9]. Most of its distribution loads are

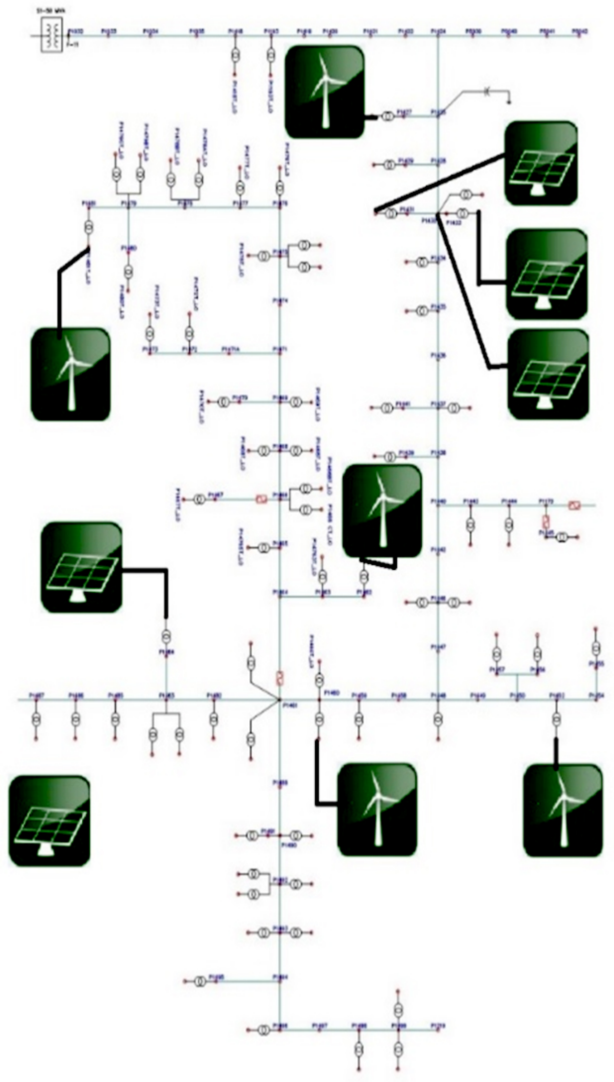


Fig. 6. The real distribution feeder test system with RE integrations.

coming from hotels, commercial establishments, factories and residential establishments. The feeder is consists of ninety (90) transformers, 90 (13.2 kV line) primary and 71 (220 V) secondary poles and 71 loads (single phase and three-phase) supplied from 50 MVA substations. The data used in this study are actual field data collected and consolidated by PECO engineers. Errors on loads, line data, and equipment and DS one-line diagram are personally coordinated from the company to ensure almost exact representation of the distribution feeder. This was done to ensure that the data are accurate and valid before simulations are conducted.

The simulations include the effect of different penetration levels of PV system on the distribution system by randomly placing PV system on the distribution feeder. Initial consideration of this study is to consider random installations DG's on the practical feeder system as illustrated on **Fig. 6**. Each single phase and three-phase DG's capacity added in the system, the bus location and

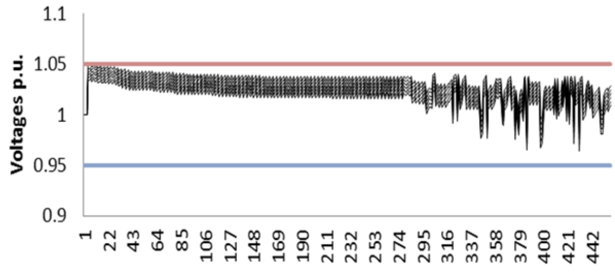


Fig. 7. Effects of different load demand levels in the bus voltage.

phase where they are connected as the simulation progress is randomly selected. With these, the actual scenario of massive PV system installations in the system can be simulated in the study.

4. Results and Discussion

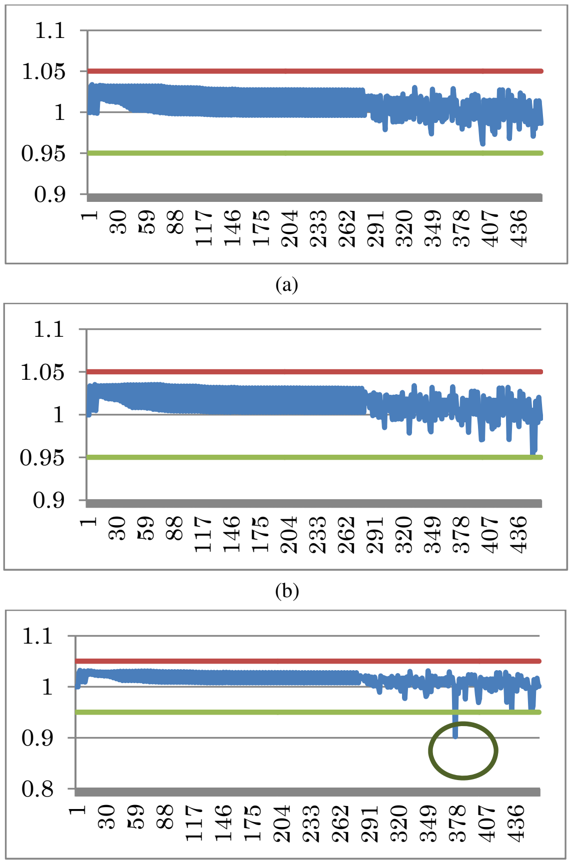
As previously mentioned, the proposed method was further tested in a practical system to test its effectiveness and robustness. More simulations that are detailed for study on the effects of the integration of renewable energy sources were also conducted. Other case scenarios which were basis for this study was been published in [10–12].

4.1. Effects of DG's Penetration Level on the Magnitudes of Bus Voltage

Initially, the PECO Feeder 11 system is tested with increasing load demands. For all load increase scenarios created, the distribution system is assume to have no upgrades on its conductors sizes, no additional lines, feeders and no capacitors banks installed. Several parameters for every load demand increase include bus voltages, line flows and; active and reactive power losses were studied and are plotted for every assumed overloads. In addition, voltage profile of all buses are plotted to identify any occurrence of bus voltages violations. These scenarios are simulated to investigate how far the current distribution system can handle reliably enough growth of load demands [13]. The simulations assume linear load growth on all loads connected to the system. This is a simple yet effective method to determine the loadability [14] of an electric system.

Initial simulations conducted include load growth studies for the 20, 40, 60 and 80 percent increase. The impact of different various load growths are shown in **Fig. 7**. The penetration level of DG's in the simulations refers to the total capacity of DG's installed. This entails that lesser number of small capacities DG's are assumed to be connected in the test system for lightly penetrated system, while numerous number of small and large capacity DG's for highly penetrated system.

Figures 8(a), **(b)**, and **(c)** show the bus voltage magnitudes of the test system considering various DG penetra-



(c)

Fig. 8. Bus voltage magnitude profile (a) with lightly DG's penetrated system, (b) with medium DG's penetrated system, (c) with highly DG's penetrated system.

tion levels. The bus voltage magnitudes and imbalances are within the allowable range of variations for lightly penetrated DG's in the distribution system. For system with medium penetrated DG's, the results show some bus voltage rise on some nodes due to the power contributed by DG's. However, negative impact of DG's penetration on some levels caused some bus voltages to drop close to the minimum value. The worst-case scenario is evident from the simulation conducted with highly penetrated DG's. Several nodes have voltage magnitude close to the minimum value and some bus voltage violations can be noticed as the penetration level is further increased. This entails that lesser number of small capacities DG's are assumed to be connected in the test system for lightly penetrated system, while numerous number of small and large capacity DG's for highly penetrated system.

As the penetration level of DG's increases, the higher the possibility of bus voltage violations to occur in the distribution system. Although wind turbine and PV system offer real power local injections and bus voltage magnitude improvement, uncoordinated and unregulated highly penetrated DG's integration in the distribution systems create line flow congestions. Imbalances problems, which are common to distribution system technical issues, will be more complicated with the advent of high penetration

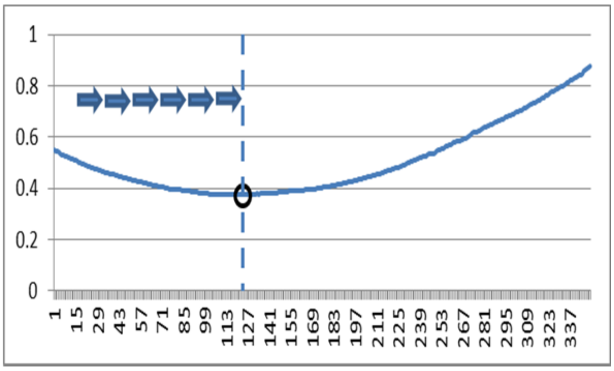


Fig. 9. Typical plot of a simulation on the feeder system.

of distributed generations in the distribution system.

4.2. Implementation of the Proposed Methodology Using Standard Feeder System

The implementation of the proposed methodology on the study of the effects of different penetration level of DG's on the distribution feeder employs the steady state load flow analysis. Series of three-phase load flow studies on the feeder can captures various distribution parameters in all phases as different DG's penetration level are included. The base case data of the distribution test feeder is initially simulated and the results are used to analyze the results at rated loads. Once the base case scenario of the system is established, random placement of PV system and its capacity are added in each simulation. In the IEEE 123 bus test feeder, the base case total kW losses and the amount of PV integrations were monitored in order to determine the effects in the system. Once the performance model of the system is obtained from the simulations, the PV penetration margin from the current operation point of the system can be calculated. This process will determine the current penetration level and the penetration margin of the current system.

Figure 9 shows a typical result of simulation in the IEEE 123 bus test feeder, which plots the values of system losses with respect to the number of PV installations for one complete run of simulation. The point as indicated in the figure shows the maximum amount (in percent of the installed system capacity) of PV system installation, which contributes to a decreasing system total power losses. Further increase in the amount of PV penetration beyond this point as shown in **Fig. 9** results in an increase of the amount of system losses thus negates the over-all purpose of installing RE sources. Initially for the base case condition, the total system power loss of the 123 bus IEEE feeder system is 95.5 kW. This is 23.4% of the total system capacity. Running the proposed methodology for 30 different simulations produces a family of curves shown in **Fig. 10**.

All independent curves derived from different simulations under the same load demand behave similar characteristics, which could be approximated to as a single curve using least-square minimization (LSM) approach.

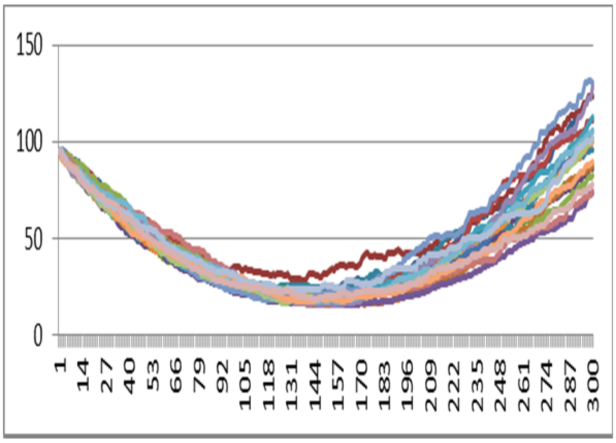


Fig. 10. Plots of total kW losses vs. number of PV installations of different simulations.

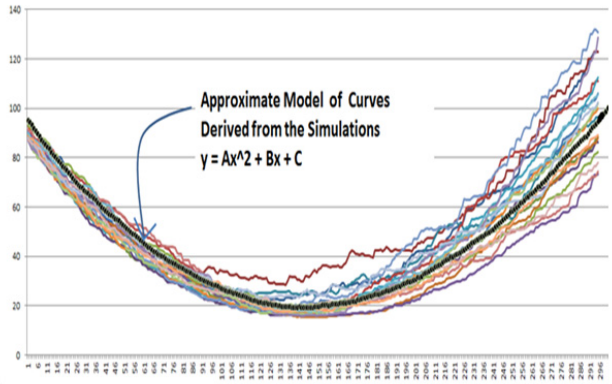


Fig. 11. Distribution performance model derived from simulations using LSM.

The simplified curve shown in **Fig. 11** as indicated is an approximate performance model of the system to study the impacts of different penetration level of PV system integrations. Furthermore, the point of maximum penetration level can easily be determined by finding the value of PV system penetration level at the point where the total kW losses is minimum.

4.3. Implementation of the Proposed Methodology Using Real Distribution Feeder

The procedures to determine the maximum PV penetration level on the IEEE 123 bus feeder system were repeated to study the real feeder system. To include load variations in the proposed method, load demand of all buses is reduced. In this study, one-half of the base loads is also investigated and included in the simulations. The family of curves derived from various simulations considering base case load of the real distribution feeder is shown in **Fig. 12**. The family of curves derived from various simulations considering half-load of the system is shown in **Fig. 13**. These curves consist of independent curves plotted from data points of 20 simulations.

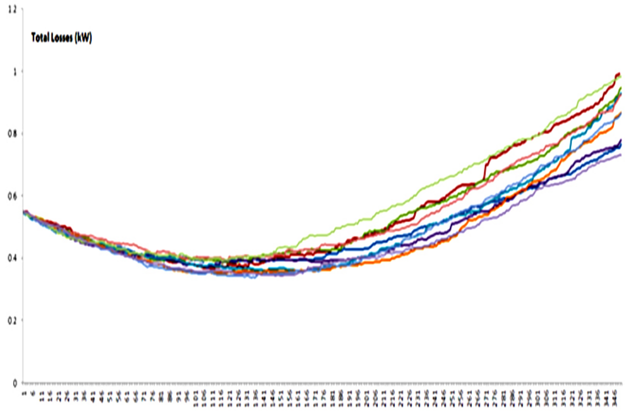


Fig. 12. Plots of total kW losses vs. number of PV installations of different simulations with base case load.

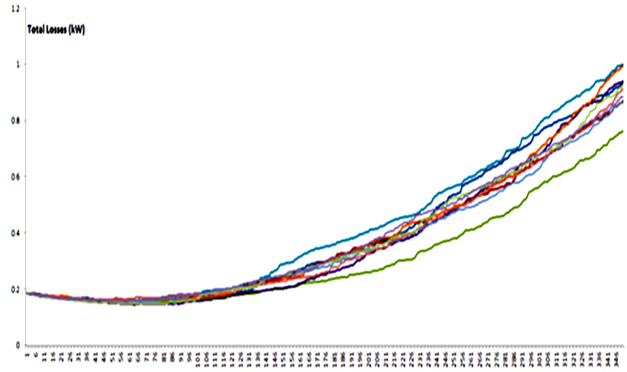


Fig. 13. Plots of total kW losses vs. number of PV installations of different simulations with half load.

Based on the results of the simulations with different load levels of the system, it is evident that both have similar characteristics from the previous results. What actually distinctly differentiate them individually from the others are the initial system kW losses at different load levels.

From the generated family of curves derived from both simulations the system performance models of half load and base case load can be determined. Using LSM methods, this family of curves at a given loading can be reduced into one approximate function using Eq. (1) in Section 2. These simplified equations and graphs respectively are reflected in **Fig. 14**. The optimal points for both cases are also reflected. The PV penetration margin from Eq. (3) can be computed from the initial operating points. For the base case load of the system, the PV penetration margin computed based from Eq. (3) is 1500 kW. This is 28.98% of total power load. For the half-load case of the system, The PV penetration margin is 55 kW which 197.84% of the total power load connected. These should be noted that the computed values of PV capacity to be installed were derived from considering random bus and phase locations. The most significant results drawn out from this study is that the PV penetration margin of a system is not constant but instead dependent on the other fac-

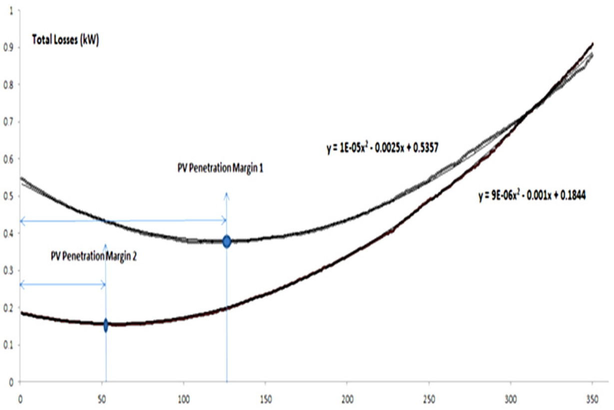


Fig. 14. System performance models of half-load and base case load.

tors affecting the power flows. The PV penetration margin of a system is not constant with different load levels; the lower the system load demand, the smaller the PV penetration margin. The over-all results from the standard test feeder and real system show similar findings with the test feeder system which simply shows reliability and robustness of the proposed method.

5. Conclusion

The electric distribution system has been designed traditionally with central generation. As energy demand increases, renewable energy resources are becoming prevalent changing the paradigm of distribution system. This study assesses the effects of integrating Distributed Generations (DG's) like photovoltaic system (PV) and wind turbines (WT), which are examples of promising alternatives to fulfill the ever-growing energy demands. The results on the simulations using real system show that higher possibility of bus voltage violations occurs when penetration levels increases. In addition, more important research would be to provide methodology as to how coordinate the integration of alternate energy sources into the DG without increasing amount of total losses.

The proposed methodology to determine the penetration margin of RE integrations shows effectiveness and consistency of the results using standard test feeder and real distribution system. The distribution system performance model derived from the exhaustive simulations from the system is a simple yet very promising to help assist DG's integration evaluations. The practical applications of this study can be integrated with other existing assessment tools for detailed and accurate planning and analysis methods for distribution system studies to mitigate the harmful effects of DG's prior to its connection to grid.

However, there are still issues that should be considered in order to maximize the technical benefits obtained from this study. In the future an intensive level of research must be conducted to consider the dynamic of characteristics of distributed resources in Distribution System to be implemented for real time applications.

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