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An Integrated GIS, optimization and simulation framework for optimal PV size and location in campus area environments

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HIGHLIGHTS

- The optimal size and locations for PV units for campus environments are achieved.
- The GIS module finds the suitable rooftops and their panel capacity.
- The optimization module maximizes the long-term profit of PV installations.
- The simulation module evaluates the voltage profile of the distribution network.
- The proposed work has been successfully demonstrated for a real university campus.

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ABSTRACT

Finding the optimal size and locations for Photovoltaic (PV) units has been a major challenge for distribution system planners and researchers. In this study, a framework is proposed to integrate Geographical Information Systems (GIS), mathematical optimization, and simulation modules to obtain the annual optimal placement and size of PV units for the next two decades in a campus area environment. First, a GIS module is developed to find the suitable rooftops and their panel capacity considering the amount of solar radiation, slope, elevation, and aspect. The optimization module is then used to maximize the long-term net profit of PV installations considering various costs of investment, inverter replacement, operation, and maintenance as well as savings from consuming less conventional energy. A voltage profile of the electricity distribution network is then investigated in the simulation module. In the case of voltage limit violation by intermittent PV generations or load fluctuations, two mitigation strategies, reallocation of the PV units or installation of a local storage unit, are suggested. The proposed framework has been implemented in a real campus area, and the results show that it can effectively be used for long-term installation planning of PV panels considering both the cost and power quality.

1. Introduction

The demand for electrical energy has been continuously increasing worldwide. Statistics show that the world energy consumption increased 5.6% in 2010. It was the largest increase since 1973, and has a tendency to continue growing in the future [1]. At the same time, utilization of renewable energy resources such as solar, wind, and biomass for electrical energy generation has increased as well due to their sustainability and low carbon emissions. Among the renewable energy resources, solar energy is becoming one of the most promising ones as its generation is silent and involves less liability to breakdown. In recent years, with the development of new technology, the cost of solar panels is decreasing, which makes solar energy more attractive to users. The worldwide electricity generation by Photovoltaic (PV) has increased more than tenfold approximately from, 5.4 GW in 2005 to 67.4 GW in 2011 [1]. Nowadays, most PV systems are installed in the electrical distribution network as grid-connected distributed generators (DGs) since they can improve the quality and security of the distribution system if installed at a proper location and size [2,3].

As the amount of solar power generation depends on the amount of irradiance, many studies are available in the literature to determine PV locations based on geographical concerns. In [4], the expected average annual electricity generation of a standard 1 kW grid-connected PV system is estimated, and the required installation capacity is determined for each European country to

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Nomenclature

Indices/sets

t, f	time period $t, f = 0, 1, 2, \ldots, T$
m	buildings $m = 1, 2, \ldots, M$
k	PV panel types $k = 1, 2, \ldots, K$

Parameters

ASH	annual sunny hours (h)
dr	PV panels derate factor
UR_t	utility rate in period t ($/kW h)
r	discount factor
e_{kt}	output power of panel type k with age t (kW)
F_t	fixed cost of PV panels installed in period t ($)
NSC_{tk}	net variable cost of PV installation in period t for panel type k ($/kW)
C_t	inverter replacement cost in period t ($/kW)
P_t	failure rate of inverter with age t
ρ	average commercial inverter size (kW)
α	operation and maintenance cost ratio
L_t	lower bound of solar generation in period t (kW)
CR_m	roof capacity of building m

Decision variables

n_{tkm}	number of panel type k installed in period t on building m
y_{tm}	1 if PV panels are installed on building m in period t or 0 otherwise
TB	total benefit of PV installation ($)
IC	total installation cost of PV panels ($)
IRC	total invertor replacement cost ($)
OMC	total operation and maintenance cost of PV panels ($)
X_t	total number of inverters installed in period t
I_t	number of inverters installed in year t for newly installed panels
IC_t	installation cost of PV panels in period t ($)
TSC_t	additional cost of installing storage in period t ($)

supply 1% of national electricity consumption from PV. European solar radiation database generated by photovoltaic Geographical Information System (GIS) system is utilized. For example, rooftop's solar potential in the northern Germany city Osnabruck is represented using ArcGIS Desktop Model Builder application in [5], where angle and alignment of the roofs, shadows caused by chimney or other rooftops, and sun's path across the sky are considered in optimal PV locations. Similarly, in [6], a solar map is generated using Solar Radiation Tool in ArcGIS for a four square miles area surrounding the University of Arizona in Tucson, USA. In their work, filters are developed and used to identify appropriate rooftop areas that have high solar radiation, are south facing, and are not too steep. Gastli and Charabi [7] presented a solar radiation map using GIS for the country of Oman and yearly potential electricity generations for different solar technologies are calculated. Similar studies have been conducted in Los Angeles [8], Lisbon [9], and Kingston, Ontario [10]. Ludwig et al. [8] calculated the solar potential for suitable rooftops of Los Angeles in Chile based on LIDAR data. Roof orientation, slope, radiation energy, shadow and the appropriate size of the roof are considered for the final calculations. Later, based on Digital Surface Model derived from LIDAR data for Lisbon, an analysis is presented in [9] to determine the buildings with highest solar potential. Solar energy on each rooftop is calculated based on the result of surface level that considers slope and elevation. In [10], a methodology is presented to help end users to analyze the solar potential of selected rooftops in Kingston, Ontario using LIDAR data of an urban area for solar PV placements on a municipal unit. Strzalka et al. [11] used GIS to estimate the PV potential of buildings roofs on city scale. Orientation, inclination, and roof areas of buildings are considered for calculations. The building energy consumption is also considered for the total energy consumption calculations. Recently, Lukac et al. [12] proposed a solar potential estimation for building's roof tops within urban areas using LIDAR data. Cloud cover and atmospheric scattering, inclination and orientation, shadowing effect due to the nearby objects, and surrounding terrain are considered to accurately estimate the irradiance needed for PVs. These works in the literature reveal that GIS has a wide application for solar energy and is an effective tool to determine appropriate locations for PV installations.

In addition to geographical concerns, designing a power system that utilizes renewable energy sources requires optimum selection of the size and location of DG that economically satisfies budgetary constraints. Different tools based on analytical methodologies, optimization programs or heuristic techniques have been developed to identify optimal locations to install DG [13]. The model in [14] proposes a heuristic approach to optimize DG capacity investment planning of a distribution company considering investment and operational costs of new DG installations, payments toward the power purchased from the main grid and cost incurred in case of unmet power. The approach yields the optimal DG sizes and locations under both competitive electricity market auction and fixed bilateral contract scenarios. In [15], a heuristic method based on genetic algorithm is developed to maximize the benefit-cost ratio of the distribution utility accrued by new DG installations. The considered benefits are reduction in both losses of energy and unsupplied energy, and considered investment and operational costs of DG units.

The model in [16] considers DG as one of the alternative scenarios that a distribution company can implement to meet the load demand growth at the utility scale. The model minimizes the investment and operational costs of the system considering different scenarios (adding DGs, expanding existing substations or adding a new feeder to buy power from other utility companies) and determines sizes and locations of new facilities. A binary swarm optimization based method is presented in [17] for optimal location and size of grid connected PV system. Initial investment, maintenance and operation costs, benefits from sales of electrical energy generated by PV system, and maximum installed peak power are considered in the objective function that considers costs and benefits. A multi-objective model including costs of installation and operation, power losses and unsupplied load is presented in [18]. A genetic algorithm based procedure is used to determine allocation of DG units, considering time variation of the load and uncertainty in DG power production. Another multi-objective model for integration of DG into the distribution network is developed in [19] consisting of costs of DG investment and running, emissions and environmental pollutions and active power losses. While satisfying technical constraints such as maintaining bus voltages with acceptable limits, the model determines the best plan for a utility company.

The introduction of DGs to the existing power systems can significantly impact the system losses and voltage profile since the traditional distribution systems were designed to operate without any generation at the end user side [2,20,21]. Voltage of all buses (connection points for loads, generators, and lines) should be