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An optimal investment planning framework for multiple distributed generation units in industrial distribution systems

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HIGHLIGHTS

- DG allocation for minimizing energy loss and enhancing voltage stability.
- Expressions to find the optimal power factor of DG with commercial standard size.
- A methodology for DG planning to recover investment for DG owners.
- Impact of technical and environmental benefits on DG investment decisions.
- Benefit-cost analysis to specify the optimal location, size and number of DG units.

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ABSTRACT

This paper presents new analytical expressions to efficiently capture the optimal power factor of each Distributed Generation (DG) unit for reducing energy losses and enhancing voltage stability over a given planning horizon. These expressions are based on the derivation of a multi-objective index (*IMO*), which is formulated as a combination of active and reactive power loss indices. The decision for the optimal location, size and number of DG units is then obtained through a benefit–cost analysis. Here, the total benefit includes energy sales and additional benefits, namely energy loss reduction, network upgrade deferral and emission reduction. The total cost is a sum of capital, operation and maintenance costs. The methodology was applied to a 69-bus industrial distribution system. The results showed that the additional benefits are imperative. Inclusion of these in the analysis would yield faster DG investment recovery.

1. Introduction

For the reasons of energy security and economical and environmental benefits, there has been increased interest in the usage of Distributed Generation (DG) worldwide. DG can be defined as small-scale generating units located close to the loads that are being served [1]. It is possible to classify DG technologies into two broad categories: non-renewable and renewable energy resources [2]. The former comprises reciprocating engines, combustion gas turbines, micro-turbines, fuel cells, and micro-Combined Heat and Power (CHP) plants. The latter includes biomass, wind, solar photovoltaic (PV) and ocean-based power plants. From the utilities' perspective, DG units can bring multiple technical benefits to distribution systems such as loss reduction, voltage profile improvement, voltage stability enhancement, network upgrade deferral and reliability while supplying energy sales as a primary purpose [3–13]. In addition, DG units can participate into the competitive market to provide ancillary services such as spinning reserve, voltage regulation, reactive power support and frequency control [14–16]. However, inappropriate allocation and operations of these resources may lead to high losses, voltage rise and system instability as a result of reverse power flow [17,18].

DG planning by considering various technical issues has been discussed considerably over the last decade. Several approaches have been developed to place and size DG units for loss reduction due to its impact on the utilities' revenue. Typical examples are analytical methods [19–21], numerical approaches [22–24] and a wide range of heuristic algorithms such as Genetic Algorithm (GA) [25], Particle Swarm Optimization (PSO) [26] and artificial bee colony algorithm [27]. Moreover, in recent years, due to sharply increased loads and the demand for higher system security, DG

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Nomenclature

AE_y	actual annual emission of the system with DG units (Ton CO_2)
$ALoss_y$	actual annual energy loss of the system with DG units (MW h)
$AVSM$	average voltage stability margin of the system
B	present value benefit over a planning horizon ($)
BCR	benefit and cost ratio
C	present value cost over a planning horizon ($)
C_{DG}	capital cost of DG ($/kW)
CE_y	cost of each ton of generated CO_2 ($/Ton CO_2)
$CLoss_y$	loss value ($/MW h)
d	discount rate
EI_y	emission incentive ($/year)
LF	load factor or average load level of the system over a planning horizon
LF_{base}	load factor or average load level of the system over the base year
ILP, ILQ	active and reactive power loss indices, respectively
IMO	multi-objective index
IRR	internal rate of return
LI_y	loss incentive ($/year)
N	number of buses
ND	network deferral benefit ($/kW)
N_y	planning horizon (years)
NPV	net present value
OM_y	annual operation, maintenance and fuel costs ($/year)
pf_{DGi}	power factor of DG unit at bus i
P_{DGi}, Q_{DGi}, S_{DGi}	active, reactive and apparent power sizes of DG unit, respectively at bus i
P_{Di}, Q_{Di}	active and reactive power of load, respectively at bus i
P_i, Q_i	net active and reactive power injections, respectively at bus i
P_{LDG}, Q_{LDG}	total system active and reactive power losses with DG unit (MW), respectively
P_L, Q_L	total system active and reactive power losses without DG unit (MW), respectively
R_y	annual energy sales ($/year)
TE_y	annual emission target level of the system without DG (Ton CO_2)
$TLoss_y$	annual energy loss target level of the system without DG (MW h)
VSM	voltage stability margin
$\|V_i\|$, δ_i	voltage magnitude and angle, respectively at bus i
Z_{ij}	ijth element of impedance matrix ($Z_{ij} = r_{ij} + jx_{ij}$)
δ	growth rate of demand a year
λ_{max}	maximum loading
$\Delta AVSM$	an increase in the average voltage stability margin

allocation for voltage stability at the distribution system level has attracted the interest of some recent research efforts. For instance, DG units are located and sized using different methods: iterative techniques based on Continuous Power Flow (CPF) [8] and a hybrid of model analysis and CPF [28], power stability index-based method [29], numerical approach [30,31], simulated annealing algorithm [32] and PSO [33–35]. However, the cost–benefit analyses of DG planning have been ignored in the works presented above. Furthermore, a few recent studies have indicated that network investment deferral and emission reduction are other attractive options for DG planning. For instance, an optimal power flow-based method was successfully developed to place and size DG units for postponing network upgrade [4]. An immune-GA method was presented for placing and sizing DG units to reduce the total emission while minimizing the total cost as a sum of electricity purchased from the grid, installation, operation and network reinforcement costs [36]. An improved honey bee mating optimization approach was also proposed for locating and sizing DG units to reduce the total emission while minimizing the capital, fuel, operation and maintenance costs, voltage deviation and energy loss [5]. In addition, an planning framework was also developed for PV integration by reducing the installation, operation and maintenance costs and the energy imported from the grid [37]. It is obvious from the above review that numerous methodologies have developed for DG allocation in distribution systems with different applications. However, most of them have assumed that DG units operate at a pre-defined power factor. Depending on the nature of loads served, DG operation at optimum power factor may have positive impacts on system losses, voltage stability, and system capacity release.

Recently, a few studies have presented DG allocation while considering the optimal power factor, to which the active and reactive power injections of each DG are optimized simultaneously. For instance, a rule of thumb for DG operation was developed for minimizing power losses [20]. For this rule, it is recommended that the power factor of DG should be equal to the system load factor. A PSO-based method was presented to identify the location, size and power factor of DG for minimizing power losses [26]. In [21], three different analytical approaches were presented to determine the location, size and power factor of renewable DG (i.e., biomass, wind and solar PV) for minimizing energy losses. A dual index-based analytical approach was proposed to find the location, size and power factor of DG for minimizing power loss and improving loadability [38]. Finally, a self-correction algorithm was proposed to specify the size and power factor of PV and battery energy storage units for minimizing energy losses and enhancing voltage stability [39]. The above review shows that a few works have discussed the optimal power factor of DG units. However, the size of DG units obtained from the existing studies may not match the standard sizes available in the market. Furthermore, a comprehensive benefit–cost study on multiple DG allocation with optimal power factor while considering the issues of energy loss and voltage stability has not been reported in the literature.

This paper aims at expending the previous preliminary study in [40] where analytical expressions were developed based on a single objective to identify the optimal power factor of each DG unit for minimizing energy losses. In this paper, analytical expressions are presented based on a multi-objective index (*IMO*) to determine the optimal power factor for reducing energy losses and enhancing voltage stability in industrial distribution systems over a given planning horizon. Here, new analytical expressions are developed to efficiently determine the optimal power factor of each DG unit with a commercial standard size to ease the computational burden. In this study, it is assumed that DG units are owned and operated by distribution utilities. To make the work comprehensive, in addition to the analytical expressions presented to specify the optimal power factor, a benefit–cost analysis is carried out in the paper to determine the optimal location, size and number of DG units. The total benefit as a sum of energy sales, energy loss reduction, network upgrade deferral and emission reduction is compared to the total cost including capital, operation and maintenance costs.

The rest of the paper is structured as follows: Section 2 describes the modeling of loads and DG units. Section 3 presents active and reactive power loss indices and a combination of both