# Optimal Renewable Resources Mix for Distribution System Energy Loss Minimization

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***Abstract*—It is widely accepted that renewable energy sources are the key to a sustainable energy supply infrastructure since they are both inexhaustible and nonpolluting. A number of renewable energy technologies are now commercially available, the most notable being wind power, photovoltaic, solar thermal systems, biomass, and various forms of hydraulic power. In this paper, a methodology has been proposed for optimally allocating different types of renewable distributed generation (DG) units in the distribution system so as to minimize annual energy loss. The methodology is based on generating a probabilistic generation-load model that combines all possible operating conditions of the renewable DG units with their probabilities, hence accommodating this model in a deterministic planning problem. The planning problem is formulated as mixed integer nonlinear programming (MINLP), with an objective function for minimizing the system's annual energy losses. The constraints include the voltage limits, the feeders' capacity, the maximum penetration limit, and the discrete size of the available DG units. This proposed technique has been applied to a typical rural distribution system with different scenarios, including all possible combinations of the renewable DG units. The results show that a significant reduction in annual energy losses is achieved for all the proposed scenarios.**

***Index Terms*—Distributed generation, distribution system planning, fuel mix, uncertainty.**

## I. Introduction

ELECTRICAL power systems are evolving from today's centralized bulk systems, with generation plants connected to the transmission network, to more decentralized systems, with smaller generating units connected directly to distribution networks close to demand consumption. This type of generating unit is known as distributed generation (DG). Environmental consciousness and sustainable development based on long-term diversification of energy sources are key drivers of these changes, which have contributed to the promotion of renewable energy sources.

Technologies that can supply renewable power to consumers at reasonable prices without degrading the security and reliability of the distribution system have vast potential. If this goal of effectively incorporating renewable power into the electricity supply is to be achieved, the special technical and economic challenges that the intermittent nature of renewable power generation introduces must be met.

Proper allocation of DG units into an existing distribution system plays a crucial role in the improvement of the system's performance; therefore, optimal allocation of DG is one of the most important aspects of DG planning. Considering total power penetration from DG units, [1] and [2] employed the Hereford Ranch algorithm to minimize system losses. With the same objective, [3] presented an iterative technique to determine the near optimal placement of DG units on the power grid. The studies in [5] and [6] utilized an iterative methodology for the allocation of DG units in the distribution system. They used an analysis of power flow equations for both voltage sensitivity and loss sensitivity in order to identify the best sites for placing DG units in the distribution system. In [7], an iterative optimal power flow-based technique was proposed to allocate new generation capacity on predetermined connection points within the existing network. The work considered the network constraints including the fault level constraints imposed by switchgear capabilities. In [8], the optimal penetrations of different DG technologies were determined by analyzing the effect that changing the penetration level had on annual energy losses. A heuristic approach to DG-capacity investment planning with respect to competitive electricity market auctions was proposed in [9]. The optimal allocations of DG units were obtained through a cost-benefit analysis from the perspective of a distribution company. The work in [10] proposed a multi-objective formulation for sizing DG resources and fitting them into existing distribution networks. The methodology permits the planner to decide on the best compromise between the cost of network upgrading, the cost of power losses, the cost of energy not supplied, and the cost of the energy required by the customers served. In [11], an analytical technique was proposed for optimally allocating DG units in a radial distribution system that minimizes power losses. The proposed technique considered different types of load profiles with varying time loads and DG output while also taking into account technical constraints, such as feeder capacity limits and voltage profile. In [12], a GA algorithm was applied for the optimal allocation of DG units in a distribution system. To handle the effect of the uncertainties associated with DG penetration and protection, [13] and [14] used a heuristic optimization algorithm based on decision theory. The work in [15] proposed a multiperiod steady-state analysis for maximizing the connection of intermittent distributed generation through an optimal power flow-based technique. The proposed technique considered the different loading levels of the system under study, as well as

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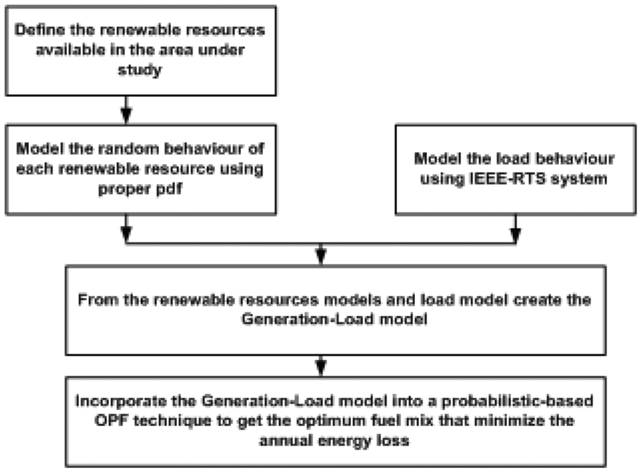


Fig. 1. Block diagram of the proposed work.

the intermittent nature of wind outputs. For determining the optimal fuel mix of different DG technologies, [16] and [17] formulated a mixed integer linear program to optimally utilize the available energy resources for a section of a distribution network. The objective function incorporates loss adjustment factors (LAFs) along with individual generation load factors (LFs), thus facilitating the determination of the optimal DG plant mix for a network section.

This review of the literature shows that considerable work has been done with respect to the allocation of DG units in the distribution system; however, most of the work presented assumes that the output of the DG is dispatchable and controllable. Most of the available methods are unable to model the intermittent nature of the output power. To the authors' knowledge, only a few studies have considered the uncertainties in the power output from renewable DG units [11], [13]–[15] or the optimal fuel mix problem [16], [17]. Hence, the problem regarding the optimal allocation and fuel mix of renewable DG units still requires attention.

In this work, as in Fig. 1, a probabilistic-based planning technique is proposed for determining the optimal fuel mix of different types of renewable DG units (i.e., wind-based DG, solar DG, and biomass DG) in order to minimize the annual energy losses in the distribution system without violating the system constraints. The proposed algorithm takes into consideration both the discrete size and maximum allowable penetration limits of the DG. The problem is formulated as mixed integer nonlinear programming (MINLP), taking into consideration the uncertainty associated with the renewable DG resources as well as the hourly variations in the load profile.

The paper is organized as follows: the next six sections explain the objective function, the renewable resource modeling, the load modeling, and the combined generation-load modeling. Section VIII presents the mathematical formulation of the proposed planning technique, and Section IX introduces a sample case study of a distribution system. The results and conclusions are presented in Sections X and XI, respectively.

## II. Objective Function

Due to the environmental concerns and fuel cost uncertainties associated with the use of conventional energy sources, attention has been directed toward implementing renewable DG units in distribution systems. Therefore, in Canada, based on Ontario's Standard Offer Program (SOP) [18], local distribution companies (LDCs) are required to accept a given percentage of *customer-owned* wind-based DG units in their system. Consequently, LDCs can use the proposed method to select the allocations that will maximize benefits.

In general, benefit maximization in any normal planning problem means minimizing cost while maintaining the performance of the system within acceptable limits. Costs include the following.

- *Capital cost*: In this case, the capital cost of the renewable DG units is the sole responsibility of the customer.
- *Running cost (operation and maintenance cost)*: As with the capital cost, operation and maintenance are the sole responsibilities of the customer.
- *Cost of unserved energy due to interruption (maximizing the system reliability)*: Based on the current practice of deploying DG units in distribution systems, this cost represents the impact of renewable DG on the reliability of such distribution systems. In this regard, the following should be noted.
  1) A distribution network is fed from a transmission network, and when the connection to the transmission system is lost, i.e., the distribution network is islanded, all DG units are required to shut down for loss-of-main protection. This practice is normal, and DG therefore does not play a role in increasing the reliability of the supply [19].
  2) If islanding is allowed, the system cannot rely solely on renewable DG units to supply the island's load. Renewable DG units are characterized by high levels of random power fluctuation that result in power mismatch issues, causing stability problems with respect to voltage and frequency [20].
  3) Conversely, renewable DG has the potential to increase the reliability of the system from the perspective of relieving substation transformers and main feeders during peak load periods. This relief may result in extending the usable lifetime of the transformer and reducing the probability of premature failure due to overloading. However, this potential increase in reliability does not depend on the placement of the DG units on the feeders and is therefore outside the scope of this study. Thus, for the purposes of this study, it is assumed that the location of renewable DG units on a given feeder has no direct influence on the reliability of the distribution system.
- *Feeder power losses*: Network losses are a key consideration in the planning problem for the following reasons.
  1) While DG may unload lines and reduce losses, if they are improperly allocated, the reverse power flows from larger DG units can give rise to excessive losses and can overheat feeders.
  2) Minimizing system power losses has a positive impact on relieving the feeders, reducing the voltage drop, and improving the voltage profile and has other environmental and economical benefits.

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