DISTRIBUTION NETWORK OPERATION WITH HIGH PENETRATION OF RENEWABLE ENERGY SOURCES

R.H.A.ZUBO

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DISTRIBUTION NETWORK OPERATION WITH HIGH PENETRATION OF RENEWABLE ENERGY SOURCES

Joint Active/Reactive Power Procurement: A Market-Based Approach for Operation of Distribution Network

Rana Hilmi Abduljabbar ZUBO

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Abstract

Rana Hilmi Abduljabbar Zubo

Distribution Network Operation with High Penetration of Renewable Energy Sources

Joint Active/Reactive Power Procurement: A Market-Based Approach for Operation of Distribution Network

Keywords

Distribution electricity market, uncertainty modelling, social welfare maximization, demand response. Active network management, linearization, Optimization, distribution locational marginal prices.

Distributed generators (DGs) are proposed as a possible solution to supply economic and reliable electricity to customers. It is adapted to overcome the challenges that are characterized by centralized generation such as transmission and distribution losses, high cost of fossil fuels and environmental damage. This work presents the basic principles of integrating renewable DGs in low voltage distribution networks and particularly focuses on the operation of DG installations and their impacts on active and reactive power.

In this thesis, a novel technique that applies the stochastic approach for the operation of distribution networks with considering active network management (ANM) schemes and demand response (DR) within a joint active and reactive distribution market environment is proposed. The projected model is maximized based on social welfare (SW) using market-based joint active and reactive optimal power flow (OPF). The intermittent behaviour of renewable sources (such as solar irradiance and wind speed) and the load demands are modelled through Scenario-Tree technique. The distributed network frame is recast using mixed-integer linear programming (MILP) that is solved by using the GAMS software and then the obtained results are being analysed and discussed. In addition, the impact of wind and solar power penetration on the active and reactive distribution locational prices (D-LMPs) within the distribution market environment is explored in terms of the maximization of SW considering the uncertainty related to solar irradiance, wind speed and load demands. Finally, a realistic case study (16-bus UK generic medium voltage distribution system) is used to demonstrate the effectiveness of the proposed method. Results show that ANM schemes and DR integration lead to an increase in the social welfare and total dispatched active and reactive power and consequently decrease in active and reactive D-LMPs.

Authors’ Publication Record

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Dedication

To my Dad Mr.Hilmi Abduljabbar Zubo of the blessed memory.

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List of Nomenclature and Abbreviations

a) Index and Sets

i,j	Index of buses
ss	Index of substation
l	Index of loads
w	Index of wind turbine
pv	Index of photovoltaic units (PVs)
s	Index for scenarios

b) *Parameter*

$C_i^{l,P}$	Active power bid prices for load at bus *i*
$C_i^{l,Q}$	Reactive power bid prices for load at bus *i*
$C_i^{DR,P}$	Active power bid prices for demand response at bus *i*
$C_i^{DR,Q}$	Reactive power bid prices for demand response at bus *i*
$C_i^{ss,P}$	Substation active power offer prices at bus *i*
$C_i^{ss,Q}$	Substation reactive power offer prices at bus *i*
$C_i^{w,P}$	WTs active power offer prices at bus *i*
$C_i^{w,Q}$	WTs reactive power offer prices at bus *i*
$C_i^{PV,P}$	PVs active power offer prices at bus *i*
$P_{i,s}^{l,\min}, P_{i,s}^{l,\max}$	Minimum and maximum active power for load at bus *i* at scenario *s*
$P_{i,s}^{DR,\min}, P_{i,s}^{DR,\max}$	Minimum and maximum active power for demand response at bus *i* at scenario *s*
$P_i^{ss,\min}, P_i^{ss,\max}$	Minimum and maximum active power for substation at bus *i*
$Q_i^{ss,\min}, Q_i^{ss,\max}$	Minimum and maximum reactive power for substation at bus *i*
$P_{i,s}^{w,\min}, P_{i,s}^{w,\max}$	Minimum and maximum active power for WTs at bus *i* at scenario *s*

$Q_{i,s}^{w,\min}, Q_{i,s}^{w,\max}$	Minimum and maximum reactive power for WTs at bus *i* at scenario *s*
$Q_{i,s}^{PV,\min}, Q_{i,s}^{PV,\max}$	Minimum and maximum reactive power for PVs at bus *i* at scenario *s*
$Q_{i,s}^{l,\min}, Q_{i,s}^{l,\max}$	Minimum and maximum reactive power for loads at bus *i* at scenario *s*
$Q_{i,s}^{DR,\min}, Q_{i,s}^{DR,\max}$	Minimum and maximum reactive power for demand response at bus *i* at scenario *s*
$P_{i,j}^{+}, P_{i,j}^{-}$	active power flow in i,j in the forward/ backward direction
$Q_{i,j,s}^{+}, Q_{i,j,s}^{-}$	reactive power flow in i,j in the forward/ backward direction
$T_{i,j}^{\min} / T_{i,j}^{\max}$	Minimum and Maximum of tap ratio in the OLTC
$I^{\max}$	Maximum current flow of conductors
$R_{i,j}, X_{i,j}, Z_{i,j}$	Resistance and Reactance magnitude and impedance of conductors respectively (Ω/km)
v	Wind speed
c , κ	Scale index and shape index
v_{w1}, v_{w2}	Starting and ending points of the wind speed's interval in state w
v_{ci}, v_r, v_{co}	Cut-in speed, rated speed and cut-off speed of the WTs, respectively
P_{rated}	Rated power
$\gamma_{i,s}^{w}$	Percentage of active and reactive power which are generated by WTs at scenario
μ_l , σ_l	Mean and standard deviation in kWh/m^2/day
R^{tot}	Total number of block in the piecewise linearization
Vc/Ic	Converter voltage/current
V_t	Connection point grid voltage
$\Delta S_{i,j}$	Upper bound of each block of the power flow of branch *i,j*
$m_{i,j}$	Slope of the rth block of the power flow of the branch *i,j*
Q_{mnd}	Mandatory reactive power of PVs and WTs

Q^{min}	Minimum reactive power of PVs and WTs
Q^{max}	Maximum reactive power of PVs and WTs
Q_{av}	Maximum availability reactive power of PVs and WTs
P_{STC}	Power under standard test condition in MW
T_{cell}	Cell temperature in °C
T_{amb}	Ambient temperature in °C
$NOCT$	National operating cell temperature conditions in *°C*
r	Interest rate in (%)
Inst_Cost	Installation cost
Ann_cost	Annual cost
F_{ij}	Maximum capacity in branch i-j
R_{ij}	Resistance of feeders
X_{ij}	Reactance of feeders
M	Large enough positive constant.
X	Reactance of WTs and PVs
m_0	Offer availability price of WTs an PVs
m_1	Offer cost of losses of RDGs
m_2	Offeropportunity cost of RDGs
$QPF_i^{w,pv}$	WTs and PVs reactive power offer prices at bus *i*

c) Variables

$P_{i,s}^{l}$	Active power for load at bus *i* at scenario *s*
$P_{i,s}^{ss}$	Active power for substation at bus *i* at scenario *s*
$P_{i,s}^{w}$	Active power for WTs at bus *i* at scenario *s*
$P_{i,s}^{PV}$	Active power for PVs at bus *i* at scenario *s*
$P_{i,s}^{DR}$	Active power for demand response at bus *i* at scenario *s*
$Q_{i,s}^{l}$	Reactive power for loads at bus *i* at scenario *s*
$Q_{i,s}^{ss}$	Reactive power for substation at bus *i* at scenario s
$Q_{i,s}^{w}$	WTs reactive power at bus *i* at scenario *s*
$Q_{i,s}^{PV}$	PVs reactive power at bus *i* at scenario *s*

$Q_{i,s}^{DR}$	Reactive power for demand response at bus *i* at scenario s
$T_{i,j}$	Tap setting in the OLTC
V_i^{sq}, V_j^{sq}	Square of voltage magnitude
$I_{i,j}^{sq}$	Square of current magnitude
$y_{i,j,s}$	Binary variable of feeder section
$S_{i,j}$	Apparent power flow
$V_i^{\min} / V_i^{\max}$	Min/Max values of the voltage at bus *i*.
$V_{i,s}$	Voltage at bus *i* and scenario *s*.
$V_{j,s}$	Voltage at bus *j* and scenario *s*.
$u_{i,j}$	Binary utilization variable for all feeders (substation, WTs and PV).
π_s	Probabilities of demand load, solar irradiance, and the active offer prices of PV and WTs
π_D , π_w	Probabilities of demand load and wind states.

Chapter 1 Background and Motivations

1.1 Timeliness and Novelty

Provision of electric energy for consumers is mostly based on having a centralized generation which involves the use of conventional generators. Then, the generated electricity is transmitted via a transmission line to substations where the voltage is step down before the electricity is distributed for energy consumption. However, the centralized generation is characterized by the following challenges including transmission and distribution losses, high cost of fossil fuels, and the greenhouse effect (greenhouse effect is a process whereby some of the sunlight energy to the earth is been a trap by the atmosphere). Therefore, the distributed generators (DGs) have been adopted to overcome these challenges [1-8].

Currently, DGs installation in power systems are rapidly increasing due to its ability to maximize the usage of renewable energy such as wind, solar, hydro, geothermal, biomass and ocean energy etc. [1, 9-15]. DGs are considered as an alternative solution to supply power for new costumers especially in the competitive electricity market [5] for the following reasons:

a) Quick response time and minimal risk to investment since it is built in modules.
b) Small-size modules that can track load variation more closely.
c) The government approval for utilizing and land availability can be discarded due to a small physical size that can be installed at load centres.
d) The successive improvement of DG technologies.

In order to achieve maximum potential benefits of renewable DGs, optimal operation of distribution networks help to supply the DGs power to loads with minimum costs. The operation has become much more complicated with the integration of renewable energy resources and has brought great challenges to its economy and regulation [16]. The uncertainties related to future load growth, the output power of renewable DGs, demand response and prices are some of the challenges. These challenges created a new field for developing new methodologies for the system operation in the presence of controllable loads.

Utilization of renewable energy sources (RES) such as wind turbines (WTs) and photovoltaic (PV) cells are taking substantial attention around the world due to the economic and environmental concerns [17-21]. The intermittent behaviour of wind speed and solar irradiance introduces technical challenges such as voltage stability, voltage deviation and power losses to distribution network operators (DNOs) [22, 23]. The DNOs need to consider the development of new methodologies and models to deal with the uncertainty associated with WTs and PVs [3]. Active network management (ANM) schemes at distribution level including coordinated voltage control (CVC) of on-load tap changers (OLTCs) and adaptive power factor control (PFC) offer a feasible solution for DNOs for optimal operation for network assets with a high penetration of RDGs at the same time considering uncertainties related to output power of WTs and PVs, market constraints, and power flows schedule with the interface to the transmission system [4]. ANM seeks to decrease the deviation in voltage and power losses and reactive power compensators [5]. In general, ANM can be defined as smart control techniques based on real-time measurement of voltage and current which provides benefits in facilitating the increasing integration of RDGs [6].

Demand response (DR) is another additional option, which provides economic reliability benefits and mitigates the impact of RDGs uncertainties. DR is defined as the ability of consumers to change their consumption behaviour patterns of electricity in order to improve the reliability of the system [7].

Under the deregulation of electric power systems, the integration of distributed generator (DG) and DR program is becoming the most beneficial way to provide ancillary services in power networks [24-26]. Supporting the reactive power ancillary services is considered as a part of distribution network operators' (DNOs) activities.

In general, the reactive power markets can be cleared separately or simultaneously from active power markets. In reactive power markets, the market structure, payment mechanism and pricing model are the main factors for determining the appropriate components of the reactive power market [27]. Recently, most published papers have discussed the impact of reactive ancillary services in transmission systems; for example, in [28], a quadratic reactive power cost model for transmission system has been proposed to optimize reactive power procurement.

1.2 Aim

The aim of this work is to design and develop a novel model for the operation of distribution networks within a joint active and reactive market environment.

1.3 Objectives

- Model the intermittent behaviour of uncertainties of wind and solar power and load demand by using scenario tree approach.
- Maximizing SW using market-based active and reactive OPF considering ANM schemes and DR. In addition, the impact of wind and solar power penetration on the SW and on active and reactive D-LMPs is also investigated.
- Propose a novel formulation for the optimal operation of distribution networks within a proposed joint active and reactive market model with the integration of ANM schemes including coordinated voltage control (CVC) of OLTC and DR using mixed-integer linear programming (MILP).

1.4 Contributions

- To design and develop a joint active and reactive electricity market model at distribution level.
- To model the uncertainties associated with wind speed, solar irradiation and load demand using Scenario-Tree approach.
- To introduce a novel formulation for optimal operation of distribution networks within a proposed joint active and reactive distribution market with the integration of ANM schemes and DR using mixed-integer linear programming (MILP).

1.5 State of the Art of the Present Research

With the increase in demand for electric power, there is a significant increase in distributed generation (DG) penetration to provide for the demand. Interconnecting DG to an existing distribution system provides various benefits such as peak load saving, enhanced system security and reliability, improved voltage stability, grid strengthening, reduction in the on-peak operating cost reduction in network loss, etc. On the other end, the international concern over climate change is driving many governments to reduce carbon-dioxide emissions and to increase the percentage share of the total electrical supply energy from the renewable energy source. In summary, the present work investigates the effects of the DGs devices on the electric power distribution system in order to put optimal operation of DGs by using renewable resources such as solar and wind within a distribution market environment.

Thus, the main research motivations of the present work is to investigate and optimise the operation of renewable generation located within distribution networks in a liberalised market. This can be illustrated by the following:

- To design a joint active and reactive electricity market model at the distribution level with active ANM schemes.
- To introduce a novel formulation for the optimal operation of distribution networks within a proposed joint active and reactive

distribution with the integration of ANM schemes and DR using mixed-integer linear programming (MILP).

- Modelling the uncertainties associated with load demand, wind speed, and solar irradiation abovementioned uncertainties using Scenario-Tree approach.

It is evident from previous section that none of the recent studies has introduced a stochastic approach for the operation of distribution networks within the proposed joint active and reactive power market model by maximizing the social welfare that represents the state of the art of the gap that this work aims to fill it. The key elements of the present research work including:

- Design and development of a joint active and reactive electricity market model at the distribution level.
- Modelling the correlation between the uncertainties associated with load demand and power generated by WTs and PVs, using Scenario-Tree approach.
- Maximise the SW using market-based active and reactive OPF considering ANM schemes with integratiuon of DR. In addition, the impact of wind and solar power penetration on the SW and on active and reactive D-LMPs is also investigated.
- A novel formulation for optimal operation of distribution networks within a proposed joint active and reactive distribution with the integration of ANM schemes and DR using mixed-integer linear programming (MILP).

1.6 Organization of the Thesis

The thesis is organized into six chapters, the details contents of each chapter is summarized as follows:

Chapter 2: In this chapter, a literature review of the research is presented. This work will cover details of distributed generators as well as the type of technologies, applications and benefits, the challenges to increased penetration of DG, different methods used for uncertainty modelling, and different optimal methods used to solve the optimal DGs location and size problems. Most uncertainty modelling and optimization methods that have been explained in this chapter are just for the purpose of publication.

Chapter 3: This chapter introduces a new model for electricity market at distribution level from the distribution network operators (DNOs) perspective taking into consideration abovementioned uncertainties. Also, a stochastic approach is proposed to investigate the impact of wind power penetration on the social welfare (SW) and active and reactive distribution-locational marginal prices (D-LMPs) from the point of view of DNOs.

Chapter 4: In this chapter, a stochastic approach for the operation of active distribution networks within an active and reactive distribution market environment is proposed. The method maximizes the social welfare using market-based active and reactive optimal power flow (OPF) subject to network constraints with the integration of demand response (DR). Scenario-

Tree technique is employed to model the uncertainties associated with solar irradiance, wind speed and load demands. It further investigates the impact of solar and wind power penetration on the active and reactive distribution locational prices (D-LMPs) within the distribution market environment. A mixed-integer linear programming (MILP) is used to recast the proposed model.

Chapter 5: This chapter proposes a novel technique for the operation of distribution networks with considering active network management (ANM) schemes and demand response (DR) within a joint active and reactive distribution market environment. The objective of the proposed model is to maximize social welfare using market-based joint active and reactive optimal power flow (OPF). Then, a network frame is recast using mixed-integer linear programming (MILP), which is solvable using efficient off-the-shelf branch-and cut solvers. Additionally, this work explores the impact of wind and solar power penetration on the active and reactive distribution locational prices (D-LMPs) within the distribution market environment with integration of ANM schemes and DR. A real case study (16-bus UK generic medium voltage distribution system) is used to demonstrate the effectiveness of the proposed method.

Chapter 6: This chapter summarizes the conclusions of the thesis and the recommendations for further work based on the outcomes of this thesis.

Chapter 2 Literature review

2.1 Introduction

Distributed generators (DGs) are a reliable solution to supply economic and reliable electricity to customers. It is the last stage in the delivery of electric power which can be defined as an electric power source connected directly to the distribution network or on the customer site. It is necessary to allocate DGs optimally (size, placement and the type) to obtain commercial, technical, environmental and regulatory advantages of power systems. This chapter addresses the important details of distributed generators (DGs) based on definitions, benefits, applications and challenges. This also includes a comprehensive literature review of uncertainty modelling methods in order to model uncertain parameters related to renewable DGs; including the various methodologies used for the operation of DGs integration into the distribution network.

2.2 Distributed generation (DG)

In order to help and understand the DG concept, there are different definitions of DG in the existing literature [1-8], which are defined from the perspective of location and/or capacity. In respect to location, DG can be defined as an electric power generation source connected directly to the distribution network or on the customer side (very close to the demand) [1, 2]. Also, it means small generating units installed in strategic places of the power network close to load centres [3-5]. In perspective of capacity, DG is a large number of small size power (500 kW and 1 MW) generating unit which is distributed within the distribution network [6]. While others defined DG as the strategic placement of small power generating units (rating from 5 kW to 25 MW) at or near customer loads [2]. In perspective of location and capacity, DG is a small unit of power (usually with a rating from less than 1 kW to many tens of MW) that is not a part of a large central power network and is located close to the load [7]. Small generation units of 30 MW or less located at or near consumer centers are also referred to with the same term [8]. In general, DG is defined as an electric power source connected directly to the distribution network or on the customer site of the network [1]. From the perspective of size, Ackerman and et al. [1] have classified DG into four sizes as follows: (1) micro-distributed generation (1 W to 5 kW), (2) small distributed generation (5 kW to 5 MW), (3) medium distributed generation (5 MW to 50 MW) and (4) large distributed generation (50 MW to 300 MW).

Currently, DGs installations in power systems are rapidly increasing due to its ability to maximize the usage of renewable energy such as wind, solar, hydro, geothermal, biomass and ocean energy, etc. [1, 9-15]. According to Borges et al, DGs can be used in an isolated way to supply the consumer's local demand or in an integrated way to supply power to the remaining of the system [3]. Optimum priority during planning should be given to location, size, and types of DG in order to maximize the benefits of DGs [11]. Optimal allocation of DGs reduces system losses and leads to improvement in the voltage profile, enhances system reliability, load ability, voltage stability, voltage security and power quality.

DG is considered as an alternative solution to supply power for new customers especially in the competitive electricity market [5] for the following reasons:

a. Quick response time and minimal risk to investment since it is built in modules.
b. Small-size modules that can track load variation more closely.
c. The government approval for utilities and land availability can be discarded due to a small physical size that can be installed at load centres.
d. The successive improvement of DG technologies.

In the following literature, most of the studies have been carried out to investigate optimal methodologies in order to minimize the power losses and cost of DGs. For example, the authors in [29-32] have focused on reviewing the optimization methods used in DGs operation considering objectives, decision variables, and DG type applied constraints. While, in [33, 34] the authors have reviewed uncertainty modelling approaches for DGs operating to show both the weakness and robustness of these methods.

It is clearly shown from the above description that all the published review work was restricted to consider the DGs operating. According to the author's knowledge, there is no study that covers the uncertainty and optimization methods concurrently, which is most important for any researcher in DGs operating. With the above backdrop, the novelty of this work relates to review the optimization method used in DGs placement problem in addition to uncertainties methods.

2.2.1 Technologies and types of DGs

DGs technology can be classified into three types including:

- renewable technology (green or sustainable),
- non-renewable technology (traditional) and
- Storage technology [35-39].

Renewable technology comprises wind, solar (photovoltaic (PV) and thermal), bio-mass, geo-thermal, tidal and hydro-power (small and micro). Non-renewable technology comprises micro-turbine, gas turbine, reciprocating engines and combustion turbine. Storage technology comprises batteries, super-capacitor, flywheels, compressed air energy storage (CAES) and pumped storage. Each technology has its own benefits and properties [12-15, 29-40]. Furthermore, the deployment of these technologies has started to take place in the electricity market, thereby providing an alternative means of meeting the customer load demand. Figure 2-1 depicts the classification of DGs technologies.

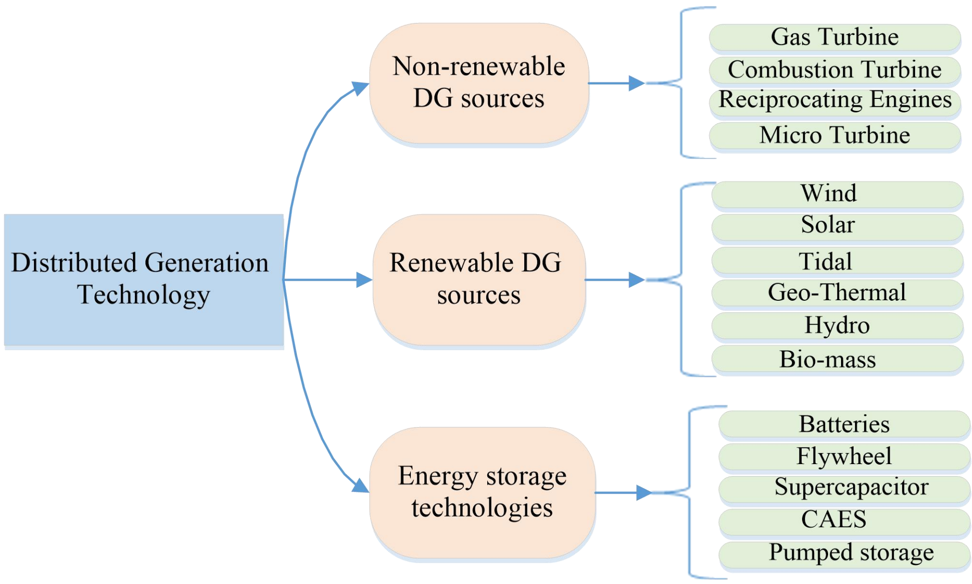


Figure 2- 1 Distributed Generation Technologies

2.2.2 DGs Application

DGs technologies can be used in various applications according to the load requirements, such as [41, 42]:

- As standby sources for supplying the desired power for sensitive loads (e.g. hospitals) during grid outages.
- Standalone sources in isolated areas – rural and remote areas.
- As supply for peak loads at peak periods in order to reduce the power cost.
- To combine heat and power (CHP), also known as Cogeneration, by injecting power into the network.
- To supply part of the load and support the grid by improving voltage profile, power quality and reducing the power losses.
- Grid connection to sell electric power.

2.2.3 DGs Benefits

Several benefits can be attained by connecting DGs to distribution systems. These benefits are categorized into technical, economic and environmental benefits. Table 2-1, gives a description of these benefits according to their category [35, 41-46].

Table 2- 1 DG benefits

Technical point of view	**Economical point of view**	**Environmental point of view**
• Integration of DG at strategic locations leads to reduced system losses. • Integration of DG provides enhanced voltage support thereby improving voltage profile. • Improved power quality. • Enhancement in system reliability and security. • Power supply autonomy of rural or isolated areas. • Increase the overall electric power energy efficiency.	• Deferred investments for an upgrade of facilities. • Lowering operation and maintenance cost. System productivity is enhanced due to the diversification of resources. • It results in an indirect monetary benefit by reducing healthcare costs due to the improve of the environment. • Reduced fuel costs due to increased overall efficiency. • Reduced reserve requirements and associated costs. • Lower operating costs due to peak shaving. • Reduction of investment risks.	• Reduced output emissions of pollutants. • Reduce global warming • Encourages the use of renewable energy

2.2.4 DGs Installation Challenges

Today’s DGs installations are facing multiple challenges that can be classified into four types; commercial, technical, environmental and regulatory. Overcoming of these challenges will lead to maximizing the utilization of DGs [14, 30]. These challenges are better explained in Figure 2-2.

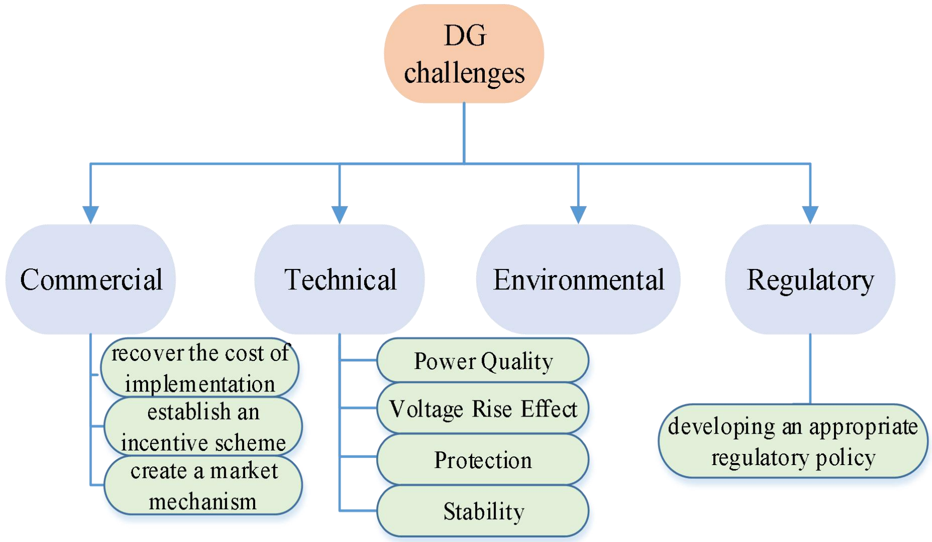


Figure 2- 2 DG challenges

2.2.4.1 Commercial Challenges

The number of DGs can be increased by implementing active management approaches in distribution networks. New commercial arrangements need to be used in order to support the development of active distribution networks and extract the benefits associated with connecting increased amount of DGs. Generally, three approaches are possible [47]:

1. To recover the implementation cost the active management directly through price controls mechanisms (this increases the amount of recoverable capital and operates expenditure associated with active management). Recovery of the cost could be achieved by increasing the charges of network usage.
2. To establish an incentive scheme that would reward the companies for connecting DGs, as has been recently developed in the United Kingdom [48]. These schemes could be funded from increasing the

charges imposed on generators and/or customers such as a green levy.

3. To create a market mechanism and a commercial environment to develop active networks.

2.2.4.2 Technical Challenges

2.2.4.2.1 Power Quality

Power quality commonly takes into account two important aspects: harmonic distortion of the network voltage and transient voltage variations. DGs could decrease or increase the quality of the power factor, current and voltage received by other users of the distribution network which depends on the particular circumstances. Power quality improvement might be obtained by increasing the effect of network fault level. This is done by adding DG to the network [47].

2.2.4.2.2 Voltage Rise Effect

Voltage rise effect can occur when connecting DGs in the network. This is the main factor that limits the amount of extra DG capacity that can be connected to rural distribution networks. Optimal power flow under equality and inequality constraints could be used to control the instability of power supply, and active and reactive power variations that are caused by the voltage rise effect [49, 50].

2.2.4.2.3 Protection

The connection of DGs to the distribution systems depends on some aspects that need to be identified [47]. These aspects are:

- Protection of the generation equipment from internal faults.
- Protection of the faulted distribution network from fault currents supplied by the DGs.
- Anti-islanding or loss-of-mains protection (islanded operation of DG will be possible in the future as penetration of DG increases).

2.2.4.2.4 Stability

The design of the distribution network and transmission network are considering the factor of stability under the impact of different circumstances. As a result, the issue of stability was not recommended to discuss. While, it is worthy to account the stability in case of dealing with DGs, which is hardly subjected to change for bigger network security. There are two areas that need to be considered to assess the renewable DG schemes: transient (first swing stability) as well as long term dynamic stability and voltage collapse [47].

2.2.4.3 Environmental

Increase DG usage is not always beneficial for the environment [51]. This is depending on the market share of the different DGs technologies. For example, DGs technologies which consume fossil fuels like fuel cells, micro turbines have more impact on the environment than renewable energy technology like hydroelectric, wind turbines and solar cells. However, even technologies such as Wind turbine are claimed to be environmentally damaging. As such it is critical to consider each technology carefully.

2.2.4.4 Regulatory

It seems that the developing of appropriate policies is so important to support the integration of DGs into distribution networks due to the absence of clear governmental regulations [52].

2.3 DG Operation Models

Optimal operation of distribution networks is a process to help in supplying the power to loads of feeders in the presence of DGs in order to achieve maximum potential benefits of DGs with minimum costs. Optimal DG planning depends on two factors, these are:

- Technical constraints and
- The optimization of economic targets.

Technical constraints refer to equipment capacity, voltage drop, radial structure of the network, reliability indices. The optimization of economic targets includes minimization of investment and operating costs, minimization of energy imported from transmission, minimization of energy loss, and reliability costs [53].

2.3.1 Objectives of DG integration

The objective functions that are mainly used in DG integration are as follows [11].

- Maximisation of renewable DG penetration.

- Maximisation of system reliability.
- Maximisation of distributed generation capacity.
- Maximisation of social welfare and voltage profiles.
- Reduction in system losses and improvement in voltage profile.
- Minimisation of investment, operational cost and total payments toward compensating for system losses.
- Minimisation of line loss.

2.3.2 Constraints of DG Operation

In distribution generations systems, there are two types of constraints, equality and inequality constraints and they are illustrated as follows:

1. Equality constraints consist of active and reactive power balance at each bus of the system.
2. Inequality constraints consist of voltage profile limits, line thermal limit, phase angle limit, traditional active and reactive power generation limits, substation transformer capacity limit, DG active and reactive power generation limits, number of DG limit, short circuit level limit, Intertie's delivery power limit, power factor limit, tap position limit, total line loss limit, short circuit ratio limit and voltage step limits [11, 54].

2.3.3 Modelling of uncertainties in the operation of renewable DGs

2.3.3.1 Uncertain parameters

Uncertain parameters can be classified into two different groups as follows [55]:

1. Technical parameters: includes demand values, generation values, forced outage of lines and generators or metering devices.
2. Economic parameters: includes uncertainty in the fuel supply, cost of production, market prices, business taxes, labor and raw materials, economic growth, unemployment rates, gross domestic product and inflation rates.

The abovementioned uncertain parameters are summarized in Fig. 2-3.

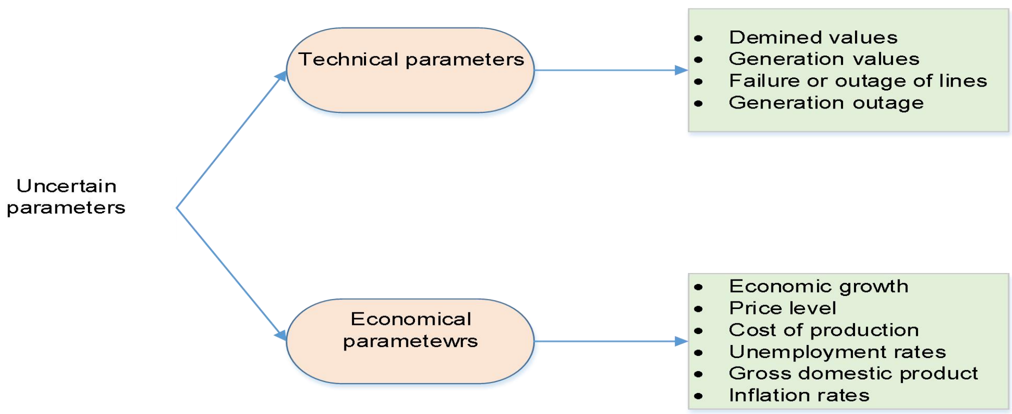


Figure 2- 3 uncertain parameters

2.3.3.2 Methods used in Uncertainty Modelling

There are several uncertainties handling approaches developed for dealing with the abovementioned uncertain parameters as illustrated in Fig. 2-4. This figure derived from [33, 34] and shows a summary of the appropriate PDP (Power Distribution Problem) approaches to model uncertainty parameters. These approaches include robust optimization, interval analysis, probabilistic approach, possibilistic method, hybrid possibilistic - probabilistic approaches and information gap decision theory (IGDT) [33, 34]. The fundamental aim of these approaches is to measure the influence of uncertain input parameters on the output parameters in distribution networks. The details of these methods are described as follows:

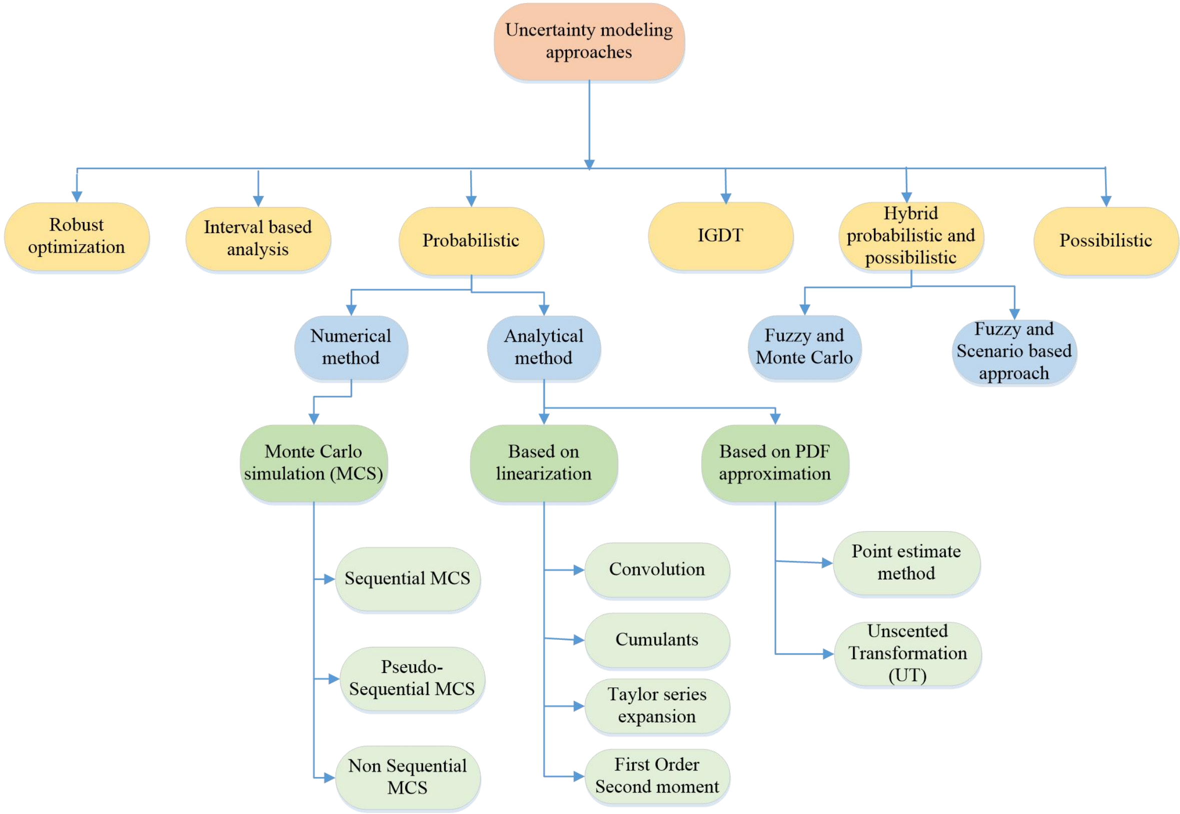


Figure 2- 4 Uncertainty modeling approaches

2.3.3.2.1 Robust optimization (RO):

Robust optimization approach was proposed by Soyster in 1973 [56]. In this method, the uncertainty groups are used to describe the uncertainty related to input parameters. The advantage of applying this technique is to obtain decisions that remain optimal for the worst-case investigation of the uncertain parameter within a specific group. In [57], the authors have proposed an adaptive RO approach for multi-period economic dispatch under the high level of wind resources penetration. Also, this approach has been proposed in [58] to carry out an endogenous stress test for the spot prices as a function of the buy-and-sell portfolio of contracts and green energy generation scenarios. RO is adopted for scheduling of multi-micro grid systems considering uncertainties in variable renewable sources, forecasted load values and market prices [59]. The authors in [60] have established an RO with adjustable uncertainty budget (RO-AUB) model for coordinating reliability and economy of a large-scale hybrid wind/photovoltaic/hydro/thermal power system during uncertainty period in order to reduce the limitation while taking full advantage of clean energy and improving the reliability of the system. RO method has been proposed in [61] to manage uncertainties related to electricity prices and battery demand. Also, this method has been used in [62] to simulate the uncertainties associated with the load demand and the output power of the renewable DGs. In [63], RO is used to model the uncertainties associated with electricity prices.

2.3.3.2.2 Interval analysis (IA):

In 1966, Moore introduced interval analysis technique [64] assuming that the uncertain parameters are obtained values from a recognized interval. It is somewhat similar to the probabilistic modelling with a uniform PDF (probability density function). This technique finds the bounds of output variables. In [65] the probabilistic distribution-based interval arithmetic approach has been proposed to evaluate the effects of the uncertainties related to loading demand. An approach based on the interval analysis has been proposed to solve the directional overcurrent relays coordination problem considering uncertainty in the network topology [66]. In [67], interval analysis techniques has been used to quantify the impact of uncertain data and to maximize the possibility of reliability improvement and/or loss reduction. The authors in [68] have proposed interval analysis method for power flow solution of a balanced radial distribution system.

2.3.3.2.3 Probabilistic approaches:

One of the earliest work in probabilistic approach was carried out by Dantzing in 1955 [69]. This technique assumed that the PDF of input parameters variables are known. Probabilistic approaches can be classified into two groups: numerical and analytical approaches.

2.3.3.2.3.1 Numerical approaches

Monte Carlo Simulation (MCS) is one of the most common and accurate stochastic approach. This approach has been used in [70] to systematically sample from random processes (i.e. uncertainty in the load demands, the available capacity of conventional generation resources and the time-varying, intermittent renewable resources, with their temporal and spatial correlations, as discrete-time random processes) and emulate the side-by-side power system and transmission-constrained day-ahead market operations. In [71], MCS with the traditional Newton–Raphson method have been used to ensure the coverage of all the possible operating scenarios of the system based on the operating system boundaries and the accuracy of the solution. In [72], the problem of renewable DGs penetration in medium voltage distribution networks has been modelled with MCS which takes into account for the intrinsic variability of electric power consumption. In [73], MCS has been used to deal with the uncertainties related to load values, generated power of wind turbines and electricity market price. Also in [74], the uncertainty associated with load growth has been modelled by MCS, which delivers an estimate of the network response to a set of possible future load scenarios. The uncertainties related to the intermittent generation of PVs and load demands are modelled by MCS in [75]. The authors in [76] have used combined MCS technique and optimal power flow to maximize the social welfare considering different combinations of wind speed and load demands over a year. In [77], MCS has been proposed to handle uncertainties including the stochastic output power of a plug-in electric vehicle (PEV), wind speed, solar irradiance, volatile fuel prices used by a fuelled DG, and future uncertain load growth in the optimal siting and sizing of DGs. There are three types of MCS approach used for probabilistic uncertainty analysis: Sequential Monte Carlo Simulation, Pseudo-Sequential Monte Carlo Simulation and Non-Sequential Monte Carlo Simulation.

1. Sequential Monte Carlo Simulation (SMCS):

Sequential Monte Carlo methods, also known as particle methods, are a class of sequential simulation-based algorithms which provide a convenient and attractive approach to compute the posterior distribution [78]. In [79] SMCS has been applied to assess distribution system reliability. The authors in [80] have used SMCS in order to preserve the characteristics of the time series of the variable energy sources and the variable load. A Sequential Monte Carlo method enhanced by a temporal wind storm sampling strategy was introduced in [81] to evaluate the impacts of wind storms on power distribution. In [82], a pattern search-based optimization method was proposed in conjunction with an SMCS to optimally find the size of the hybrid system components and satisfy the reliability requirements. The authors in [83] have developed the SMCS in order to evaluate the adequacy of power systems with wind farms.

2. Pseudo-Sequential MCS:

Leite da Silva in 1994 proposed, for the first time, Pseudo-Sequential Monte Carlo simulation which is based on the non-sequential sampling of system states and on the chronological simulation of only the sub-sequences associated with failed states [84]. In [85], a method based on the pseudo-sequential MCS technique has been proposed to evaluate the impact of high photovoltaic (PV) power penetration on customers' nodal reliability and system energy and reserve deployment. The authors in [86] have developed a new tool for the reliability assessment of the future smart distribution network (SDN) based on a Pseudo-Sequential MCS. In [87], the pseudo-chronological simulation was introduced to evaluate the loss of load indices, with particular emphasis on loss of load cost assessment, for composite generation and transmission systems considering time-varying loads for different areas or buses.

3. Non-Sequential MCS:

This method is known as the state sampling approach. An efficient method for composite system well-being evaluation based on non-sequential MCS is presented in [88]. Also in [89], non-Sequential MCS is presented to evaluate reliability indices of the composite system. In [90], a novel approach based on non-sequential MCS and pattern recognition techniques was proposed to evaluate well-being indices for a composite generation. The authors in [91], have developed an original non-sequential Monte Carlo simulation tool in order to calculate the optimal dispatch of classical generation in order to minimize polluting gases emissions in the presence of wind power. Also, in [92] a calculation method of wind farms' capacity credit based on Non-Sequential MCS is presented.

2.3.3.2.3.2 Analytical methods:

The basic idea of the analytical approach is to do arithmetic with probability density function (PDF) of stochastic inputs variables. The analytical methods can be classified into two groups: (1) based on linearization and (2) based on PDF approximation.

2.3.3.2.3.2.1 Based on linearization:

The first group of analytical methods are based on linearization and these are:

1. Convolution method:

Convolution method has been used in [93] to deduce the density functions of the unknown quantities but the main problem associated with this method is that the technique demands a large amount of storage and computation time in large systems. The authors in [94] have noted this problem and tried to solve it by applying the discrete frequency domain convolution method to reduce the computational burden.

2. Cumulants method:

Cumulants method was introduced to prevent the convolution operation that appears in the calculation of the PDF of a linear combination of several random variables. In [95] the cumulant method for the probabilistic optimal power flow problem was introduced and the results using the cumulant method had a substantial reduction in computational expense while maintaining a high level of accuracy compared with the results from MCS. Cumulant based stochastic reactive power planning method in distribution systems with the integration of wind generators has been proposed in [96].

3. Taylor series expansion:

Taylor series expansion usually is used to approximate a function. This expansion gives quantitative estimates on the error in this approximation. in [97] Taylor series expansion is proposed for power system state estimation and reliability assessment. In [98] Taylor series expansion of the Markov chain stationary distribution is introduced in order to propagate parametric uncertainty to reliability and performability indices in Markov reliability and reward models.

4. First Order Second moment method (FOSMM):

FOSMM is a probabilistic method to determine the stochastic moments of a function with random input variables which allows the estimation of uncertainty in the output variable without knowing the shapes of PDFs of input variables in detail. This method has been applied in [99] in order to deal with the uncertainties that effects in the computation of transfer capability, transmission reliability margin (TRM). In [100], a new probabilistic load flow method based on the FOSMM has been proposed to solve the probabilistic load flow problems. The aim of this method is to obtain the mean and standard deviation of load flow solution distributions considering various uncertainties in system operation. The authors in [101] have presented a formulation of probabilistic optimal power flow problem using the FOSM method to model the uncertainties and correlations of the system load.

2.3.3.2.3.2.2 Based on PDF approximation:

The second group of analytical methods is based on PDF approximation such as:

1. Point estimate method (PEM):

The point estimation method concentrates on the statistical data provided by the first few central moments of uncertain input. In [102] probabilistic power flow method based on the PEM was introduced to handle various sources of uncertainties including the output of the wind power generators and load demands. In [103], PEM was used to model the uncertainties related to wind power outputs and volatile electricity prices in a competitive electricity market. In [104] PEM has been used for energy management in order to minimize the cost and increase efficiency. In [105] two-point estimate method was proposed to model the uncertainties associated with volatile electricity price, load demand and wind speed. In [106] a new probabilistic framework based on 2m Point Estimate Method (2m PEM) has been proposed to consider the uncertainties in the optimal energy management of the Micro Grids including different renewable power sources.

2. Unscented Transformation (UT):

The UT is a powerful method in assessing stochastic problems with/without correlated uncertain variables. In [107] a new method for power system's probabilistic load flow (PLF) evaluation using the UT method has been presented. In [108] UT was used to study the impact of transformer correlations in state estimation. In [109] UT was provided to calculate the mean and covariance of nonlinear functions of random variables (which represent power system measurements as nonlinear functions of the power system state).

2.3.3.2.4 Possibilistic approach:

In 1965, Zadeh introduced the concept of fuzzy arithmetic [110] where the input parameters are described by using the membership functions. In [111], a fuzzy evaluation tool was proposed for analysing the effect of renewable DGs on active power losses and the ability of distribution network in load supply at the presence of uncertainties. In [112] a new method according to the fuzzy extension principle has been proposed to represent and propagate the possibilistic uncertainties associated with wind power in the power system. In [113] a new possibilistic fuzzy model was presented for multi-objective optimal planning of distribution systems which finds multi-objective solutions corresponding to the simultaneous optimization of the fuzzy economic cost, level of fuzzy reliability, and exposure (optimization of robustness) of the network. In the framework of possibilistic harmonic load flow, the authors in [114] proposed an improved approach which overcomes the possibility of interaction between input parameters.

2.3.3.2.5 Hybrid possibilistic–probabilistic approaches:

In this technique, random and possibilistic parameters are presented to handle the uncertain parameters [115, 116]. A brief explanation of these approaches is described as follows:

1. **Fuzzy and Monte Carlo**:

The authors in [116] have used Fuzzy and Monte Carlo Simulation as a hybrid possibilistic–probabilistic evaluation tool for analysing the effect of uncertain power production of renewable DGs on active power losses of distribution networks.

2. **Fuzzy – scenario-based approach**:

The authors in [117] have presented a hybrid possibilistic–probabilistic tool to assess the impact of DG units on the technical performance of distribution network with taken into account the uncertainty of electric loads, DG operation/investments.

2.3.3.2.6 Information gap decision theory (IGDT):

In 1980, Yakov Ben-Haim proposed IGDT [118]. This technique does not use PDF and membership function (MF) for input parameters. However, it measures the differences between parameters and their estimation. The authors in [119] have applied IGDT in order to handle the uncertainties associated with the uncertainties related to wind speed. In [62], IGDT has been used to model the uncertainty in the load and output of renewable DGs.

In [120], IGDT has been proposed for distribution network operator (DNO) when it is faced with different uncertainties in load demands and renewable DGs. In [121], IGDT has been proposed to address the uncertainty related to renewable DGs.

Table 2- 2 gives a summary of uncertainty approaches used in DGs.

Uncertainty modelling approaches		**References**
Robust optimization		[57-62]
Interval analysis		[65-68]
Probabilistic approach	Sequential MCS	[79-83]
	Pseudo-Sequential MCS	[85-87]
	Non-Sequential MCS	[88-92]
	Convolution method	[93, 94]
	Cumulants	[95, 96]
	Taylor series expansion	[97, 98]
	First Order Second moment	[99-101]
	Point estimate method	[102-104]
	Unscented Transformation (UT)	[107-109]
Possibilistic		[111, 112, 122]
Hybrid probabilistic and possibilistic	Fuzzy and Monte Carlo	[116]
	Fuzzy–scenario-based approach	[117]
Information gap decision theory (IGDT)		[62, 119, 120]

The advantages and disadvantages of each uncertainty modelling approaches are given in Table 2-3.

Table 2- 3 Summary of Evaluation of Uncertainty modelling approaches

Uncertainty modelling approaches			Advantages	Disadvantages	References
Robust optimization			It is useful when only an interval exists	It is difficult to employ in nonlinear problems	[56-62]
Interval analysis			It is useful when just an interval exists	Cannot put the connection among intervals	[64-68]
Probabilistic (Numerical)	Sequential MCS		This method does represent chronological aspects in order that it is the most flexible strategy for assessing distribution system reliability	Sequential MCS requires a more substantial computational effort than the other approaches, and may be infeasible for some applications	[78-83, 123]
	Pseudo-Sequential MCS		It is easy to implement and faster than the conventional SMCS	The number of simulations needed increases as the degrees of freedom of the solution area increases	[84-87]
	Non-Sequential MCS		Non-Sequential MCS has high computational efficiency	cannot simulate the chronological aspects of system operation	[88-92, 124]
Probabilistic (Analytical)	Based on linearization	Convolution method	This method has greater accuracy while providing a breakthrough in computational speed	Requires a large amount of storage and time especially when there are many functions involved due to large systems.	[93, 94]
		Cumulants	The loss of accuracy associated with	The technique demands a large amount of	[95, 96]

			truncation of the order of the cumulants used	storage and computation time in large systems	
		Taylor series expansion	It allows for incredibly accurate (depending on the number of terms) estimates of common functions	Some calculations become tedious or the series doesn't converge quickly.	[97, 98]
		First Order Second moment	Allows the estimation of uncertainty in the output variable without knowing the shapes of PDFs of input variables in detail	Complicated	[99-101]
	Based on PDF approximation	Point estimate method [125]	It is a non-iterative, computationally efficient technique. simple and easy to implement.– There is no convergence problem	It only gives the mean and standard deviation of the uncertain output, no information about the shape of the PDF of the output is provided, gives more reliable answers for non-skewed PDFs, The accuracy would be low when the number of random variables is large	[102-104]
		Unscented Transformation (UT)	efficiency, the accuracy would not decrease when the number of random variables is large,	Its running time depends on the number of uncertain variables and it is only applicable in problems which	[107-109]

			applicable to problems with correlation among multiple uncertain input parameters and it is easy to implement	the input variables are described using their PDF	
Possibilistic			It can convert linguistic information to numerical values	Complicated	[110, 122]
Hybrid probabilistic and possibilistic	Fuzzy and Monte Carlo		Its accuracy is high	It is time-consuming	[116]
	Fuzzy–scenario-based approach		high computational efficiency	Its accuracy is low	[117]
Information gap decision theory (IGDT)			It is useful for decision in severe uncertainties	Too complicated	[62, 118-120]

2.3.3.3 Reliability indices under uncertainty

Power system reliability is one of the most important issues in the power system operation. It can be divided into two parts, adequacy and security. Chowdhury and et al in [126] have presented a reliability model for determining the DG equivalence to a distribution facility for using in distribution system operation studies in the new competitive environment. This model has been extended based on the Distribution Reliability (DISREL) program in order to include: System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Frequency Index (CAIFI), Average Service Availability Index (ASAI), Average Service Unavailability Index (ASUI), EUE (in kWh per year) , and expected outage cost in pound (£). In [127-132] several reliability indices and their corresponding costs are calculated in order to quantitatively measure system reliability and its economic impact. In [133] SAIFI and SAIDI have been calculated as a part of solving the multistage planning problem of a distribution network. In [134], SAIFI, SAIDI, ASAI are calculated in order to quantitatively measure system reliability and its economic impact. Reference [135] has addressed the incorporation of uncertainty and reliability indices (SAIFI, SAIDI, ASAI, Expected energy not supplied (EENS)) in the joint expansion planning of distribution network assets and renewable DGs. The authors in [136] have applied a genetic algorithm based on probabilistic load flow and used different scenarios to model the uncertainty in load demand and wind power generation. Also, reliability was assessed in two stages, namely fault location and fault repair. In [137] the uncertainty associated with the output wind power generation, load types and load variability have been modelled as a multi-state variable by a probability density function. Genetic algorithm was used in order to allow assessing reliability by the calculation of nodal interruption costs based on Monte Carlo simulation. In [138], SAIFI, SAIDI and CAIDI to evaluate the reliability of distribution networks in the presence of wind power are calculated by using the Monte Carlo simulation method. The authors in [139], have evaluated the reliability performance of distribution systems considering uncertainties in both generation and load demands. Reference [140] has presented an analytical approach for the reliability modelling of large wind farms. In [141], the fuzzy numbers approach for reliability calculation of electrical energy indices was proposed. In [142], Monte-Carlo simulation approach to distribution/transmission reliability evaluation assuming loads defined by fuzzy numbers has been introduced. In [143], a fuzzy operation technique for load duration curve modelling in order to evaluate the reliability indices of composite power systems based on probability and fuzzy set methods has been presented. In [144], a possibilistic approach using fuzzy set has been introduced to calculate the possibilistic reliability indices (loss-of-load expectation) according to the degree of uncertainty. In [145], a genetic algorithm guided by fuzzy numbers to evaluate the distribution system EENS index has been introduced. In [146], according to the randomness of the output power of renewable DGs and the time series characteristic of load, a reliability evaluation model based on sequential Monte Carlo simulation for distribution system has been proposed. In [147] a reliability model has been presented to study the impacts of demand response programs on short-term reliability assessment of wind integrated distribution systems.

2.3.3.4 Market and economic operation aspects of renewable DGs under uncertainty

Operation of the power system has become much more complicated with the integration of renewable energy resources and has brought great challenges to its economy and regulation [16]. The uncertainties related to future load growth, the output power of renewable DGs, demand response and prices are some of the challenges. These challenges created a new field for developing new methodologies for the system operation in the presence of controllable loads. The primary objective of proactive customers is to reduce their electricity payments to increase savings, hence they tend to rely on price-based schemes for managing local generation and load resources. In [148], an interior point method has been used to solve the optimal power flow problem with a multi-objective optimization problem for maximizing both social benefit and the distance to maximum loading conditions. In [149], load and price uncertainties within a distribution electricity market environment have been discussed. In [150] uncertainty in future load estimation, as well as renewable DG power production, have been introduced by probabilistic approaches. In [151] the uncertainties related to loading demand and renewable generation have been modelled by using the fuzzy-based method. Demand side management is a set of techniques and strategies that carry out by the grid operators in order to influence and modify the users' energy consumptions [152]. The authors in [153] proposed a combined MCS and optimal power flow to maximize the social welfare with integrating demand response scheme considering different combinations of wind generation and load demand over a year. Stochastic modelling for electric capacity expansion planning under uncertainty in demand has been presented in [154]. In [155] Monte Carlo simulation methods has been used for modelling the uncertainties associated with load demand and renewable sources power production. In[156], the genetic algorithm and the market-based optimal power flow has been proposed to jointly maximize the net present value related to the investment made by WTs' developers and the social welfare within a distribution market environment. In [157] a market-based optimal power flow has been used for optimally allocating wind turbines in order to maximize social welfare considering different combinations of load demand and wind generation. Stochastic programming approach Proposed in [158] for reactive power scheduling of a micro-grid considering the uncertainty of wind power. The authors in [159] have used Monte Carlo simulation method and market-based optimal power flow to maximize the social welfare with the integration of demand side management scheme considering different combinations of wind generation and load demand over a year. In [160], in order to model the random nature of load demand and wind forecast errors, a scenario-based stochastic programming framework has been presented. In [161] Monte Carlo simulation method has been used to determine a probabilistic hourly/seasonal model for wind and solar based DGs, and the system demand. To solve the problem of uncertainties of renewable DG output and load, the multi-scenario technique has been adopted in [162]. In [163] price uncertainty has been modeled through robust optimization technique using duality properties and exact linear equivalences. In [164], Price uncertainty has been modeled by a simple linear programming algorithm which can be easily integrated into the energy management system of a household or a small business. The authors in [165] have proposed a probabilistic method for active distribution networks operation with the integration of demand response. Optimal demand response and energy storage system scheduling for distribution losses payments minimization under electricity price uncertainty has been presented in [63]. In [166], a method for evaluating investments in decentralized renewable distribution network considering price volatility has been presented. In [167], a Monte Carlo simulation-based approach has been proposed for distribution network operation to capture the uncertainties related to the price volatility of renewable DG.

2.4 Optimization methods used for DG operation (DGP)

Due to the increasing penetration of DGs in the distribution network, the location and sizing of DGs in distribution network planning is becoming increasingly important. Various optimization methods employed in DGP to solve different DG problems (optimal location and/or sizing). Briefly, these methods can be divided into three main sets:

1. **Conventional methods** are also called classical or non-heuristic methods. It includes linear programming (LP), non-linear programming (NLP), mixed integer non-linear programming (MINLP), dynamic programming (DP), optimal power flow-based Approach (OPFA), direct approach (DA), ordinal optimization (OO), analytical approach (AA) and continuous power flow(CPF).
2. **Intelligent search-based methods** are also called heuristic methods. It includes simulated annealing (SA), evolutionary algorithms (EAs), tabu search (TS), particle swarm optimization (PSO) ant colony system algorithm (ACSA), artificial bee colony (ABC), artificial immune system (AIS), bacterial foraging optimization algorithm (BFOA), bat algorithm (BA), imperialist competitive algorithm (ICA), cuckoo search algorithm (CSA), intelligent water Drop (IWP) algorithm and fuzzy set theory (FST).
3. **The prospective methods** include firefly algorithm (FA), shuffled frog leaping algorithm (SFLA), and big bang-big (BB-BC) algorithm.

2.4.1 Conventional methods (Non-Heuristic)

2.4.1.1 Linear programming (LP)

Linear programming (LP) is defined as a mathematical technique used for the optimization of linear objective functions and linear constraints [168]. In [169, 170] LP was employed to solve optimal DG placement (ODGP) problem to achieve maximum DG penetration. Also, Abou El-Ela et al. [171] used LP to investigate of varying ratings and locations of DG for losses minimizing in order to maximize DG benefits.

2.4.1.2 Nonlinear programming (NLP)

The nonlinear programming (NLP) refers to the fact that the computation in this method is based on the derivatives. Solving a nonlinear programming problem could be done by first choosing a search direction in an iterative procedure which is specified by the first partial derivatives of the equation (the reduced gradient). This method is referred to as the first-order method and includes the generalized reduced gradient method [172]. The second order methods such as successive quadratic programming [173] and Newton Raphson method [174] require the counting of the second order partial derivatives of the power-flow equations and other constraints. Rau and Yih-Heui [175] have employed a second order algorithm to compute the capacity of DGs in selected nodes to obtain optimum quantities and maximized benefits of DGs. In [176], the Newton Raphson method was introduced to find optimal size and optimal placement of DGs in order to obtain the optimization of both cost and loss. Also, the study focused on the optimization of weighting factors which balance the cost and the loss factors.

2.4.1.3 Mixed-integer nonlinear programming (MINLP)

MINLP was used to solve DGP problem with integer variables with values (0 or 1) to represent if a new DG should be installed [177]. The proposed model in [178] integrated comprehensive optimization model and planner's experience to achieve optimal sizing and location of DGs. This model is formulated as MINLP in General Algebraic Modelling System (GAMS) using binary decision variables with an objective function for minimizing the total system cost. In [179] the optimal planning problem is formulated as MINLP, with an objective function for minimizing the energy losses and for optimally allocating with wind DGs in the distribution network. Atwa et al. [180] have used different types of renewable DGs such as wind and solar in order to minimize the annual power losses considering network constraints. In [181], the authors have employed the MINLP method to find the optimal size and site for the different types of DGs by considering the electricity market price volatility. Also, MINLP was used to determine the optimal placement and number of DGs in hybrid electricity market [182]. The optimal problem for location and sizing of DG is formulated by using MINLP, with an objective of improving the voltage stability margin considering the probabilistic nature of the renewable energy resources and the load [183]. In [184], multi-period OPF used in order to improve the hosting capacity of distribution systems by applying both static and dynamic reconfiguration considering active network management (ANM) schemes. In [185], MINLP is proposed to solve DGP planning problem in order to minimize the total operational cost.

2.4.1.4 Dynamic programming (DP)

Dynamic programming (DP) algorithm is an approach that guaranties the optimal solution of multi-stage decision problems [186, 187]. Celli et al. [186] have used DP for planning an active distribution network with DGs in order to reduce the capital expenditures (CAPEX) and operational expenditures (OPEX). In addition, real-world examples are provided to illustrate the effectiveness of DP for active distribution networks. In [187] DP is used to solve multi-period planning problem with such as minimization of investment and interruption costs and losses. In [188], DP is proposed to determine the optimal feeder routes and branch conductor sizes with simultaneous optimization of cost and reliability. Khalesi et al. [189] have used DP to solve the multi-objective optimization problem in order to determine the optimal site of DGs in the distribution network to minimize power losses and improve both the voltage profile and reliability.

2.4.1.5 Optimal Power Flow-based Approach (OPFA)

OPFA has been developed to increase the capacity of DG and identify available headroom on the system within the imposed thermal and voltage constraints [190]. Dent et al. [49] have used OPF based method considering security constraints to optimally accommodate DGs in the network. In [191], an OPF used to find the optimal capacity and placement of DGs in order to minimize the operational cost. Also in this work, Locational Marginal Price (LMP) is determined as the Lagrangian Multiplier of the power balance equation in OPF. The authors in [192] have proposed OPF to minimize the energy cost taking into account the goodness factor of each DG on the distribution system. The aim of [193, 194] is to find the optimal location and size of new DGs considering the fault level constraints (FLCs) in the OPF problem. The authors in [195, 196] have proposed a multi-period AC OPF to evaluate the optimal size of new DGs which are able to be connected to a distribution network when active network management (ANM) control strategies are in operation. In [197] an OPF is used to analyze the feasibility of DG integration strategies taking into account the uncertainty of DG's output power in the study of different integration concepts, including network losses, voltage profile and line capacity.

2.4.1.6 Direct approach (DA)

Direct approach (DA) is introduced in [198] to reduce the inherent difficulties toward the solution and provides an optimum solution at the same time in order to solve the ODGP problem. In [199] DA is applied for optimal planning by focusing on the minimum cost and higher power reliability in radial distribution systems. In [200] DA was proposed to find the optimal size of fixed and switched capacitors in order to minimize the power losses and maximize the savings in a radial distribution system.

2.4.1.7 Ordinal Optimization (OO)

Ordinal Optimization (OO) approach presented in [201] to find the optimal site and size of DGs with discrete and continuous variables in order to minimize the losses and maximize the capacity of DGs. In [202], the OO approach is applied to find the best solution for planning of distribution network with the integration of electric vehicles (EVs). Zou et al. in [203] have proposed OO to obtain the optimal solution for ODGP considering the uncertainties related to renewable DGs and capability curve of them to improve the voltage profile, voltage stability and reduce the active power losses.

2.4.1.8 Analytical Approaches (AA)

Wang et al. [204] have applied analytical approaches to determine the optimal location of DGs in radial distribution systems in order to minimize power losses. The AA is not iterative algorithms in order that there are no convergence problems involved, therefore, the results could be obtained very quickly. In [205, 206] both the optimal sizing and siting of DGs are determined by an analytical method to minimize the total power losses. In [207] an analytical method proposed to obtain the optimal combination of different DG types in a distribution system such as size, location and operating point in order to minimize the losses. This method applies in two test systems with different configurations by establishing a comparison with the exact optimal solution obtained from the exhaustive optimal power flow (OPF) algorithm. In [15, 208, 209], analytical expressions are proposed to find an optimal size and power factor of DGs to minimize the power losses in a primary distribution network.

2.4.1.9 Continuation Power Flow (CPF)

Continuation power flow (CPF) method was presented in [210] to determine the optimal placement of DGs in a distribution network in order to improve the voltage profile, reduce the power losses, increase the power transfer capacity and maximize the loading and voltage stability. Hemdan and Kurrat have used CPF to analyze the systems to optimally allocate DGs in distribution systems in order to meet increasing demand, obtaining more benefits from DGs, decreasing the losses and improving the voltage profile [211]. Summary of literature review for DGP using conventional techniques is shown in Table 2-4.

Table 2- 4 Summary of literature review for DGP using conventional techniques

Conventional methods	References	Objective function	Contribution	Uncertain parameter	Mathematical modelling of Uncertainty
linear programming (LP)	Keane & O'Malley (2005) [169]	Maximum capacity	The optimal DG placement is solved using LP and take advantage of the interdependence of the buses with respect to the system constraints		Not modelled
	Keane & Malley (2007) [170]	Maximize profit	LP is used to find the optimal model that maximizes the quantity of energy that may be reaped from a given area by taking into account its available energy resources.		Not modelled
	Abou El-Ela et al. (2010) [171]	Improve voltage and reduce line loss	LP is used for (1) demonstrating the influence of DG sitting and sizing to maximize the benefit of DG and (2) confirming the optimization results obtained by genetic algorithm (GA).		Not modelled
Nonlinear programming (NLP)	Rau & Wan (1994) [175]	Minimize real power loss	Second order algorithm was proposed to compute the number of resources in selected nodes.		Not modelled
	Ghosh et al. (2010) [176]	Minimize both cost and power loss	Newton Raphson method was used to find the optimal sitting and sizing in DG by focusing on optimization of the weighting factor, which balances the cost and the loss factors.		Not modelled
Mixed-integer	El-Khattam et al. (2005) [178]	Minimize investment and	Optimal DG model is implemented as an economical alternative option in an	Load demand	Scenario-based approach

nonlinear programming (MINLP)		operating costs	integrated model for solving the DGP problem.	growth	
	Atwa, et al. (2010) [180]	Minimizing the energy losses	MINLP proposed a probabilistic-based planning technique for determining optimal site with different types of DG.	Load demand and renewable DG	Scenario-based approach
	Kumar & GAO (2010) [182]	Minimization of total fuel cost and minimization line losses in the network	Hybrid electricity market of optimal Location and number of DG is presented by MINLP approach.		Not modelled
	Porkar et al. (2011) [181]	Minimize cost and maximize total system benefit	The optimal site, size, and different types of DG considering electricity market price fluctuation introduce by using MINLP method.		Not modelled
	Atwa, & El-Saadany (2011) [179]	Minimize annual energy loss	A probabilistic-based planning technique for optimum capacity and location of wind DG in distribution systems is formulated as an MINLP.	Combined generation –load model	Scenario-based approach
	Al Abri et al. (2013) [183]	Improve the voltage stability margin	Optimal sitting and sizing of DGs is formulated by using MINLP method.	load and renewable DG generation	Scenario-based approach
	Franco et al. (2014)[185]	Minimize operation and investigation cost	MINLP is proposed to solve long term expansion planning and offers low computation time.		Not modelled
	Capitanescu et al. (2015) [184]	Increase the hosting capacity of DG	ODGP problem is formulated as a MILP of multi-period optimal power flow to consider thermal and voltage constraints by centralized ANM		Not modelled

			schemes.		
Dynamic programming (DP)	Celli et al. (2007) [186]	minimizes the capital and operational expenditures (CAPEX&OPEX)	DP is used to introduce optimal multiyear development plan of active distribution networks.		Not Modelled
	Popović, et al. (2010) [187]	Minimize the cost of investment loss and reliability	DP is used to improve the quality of multi-period solutions in DG.		Not Modelled
	Khalesi et al. (2011) [189]	Minimize loss and enhance reliability improvement and voltage profile.	DP is used to solve the multi-objective function of optimal locations in DG network by taking into account the time-varying loads.		Not Modelled
	Ganguly et al. (2013) [188]	Minimization of investment and operational costs and maximization of reliability	DP has been applied to solve distribution system expansion planning problem, considering two variables decision feeder routes and branch conductor sizes.		Not modelled
Optimal Power Flow-based Approach (OPFA)	Vovos, & Bialek (2005) [193]	Maximize profit	OPF is developed to convert FLCs to simple nonlinear inequality constraints.		Not Modelled
	Vovos, et al. (2005) [194]	Maximize profit	OPFA find optimal capacity by taking into account fault level constraints imposed by protection equipment such as switchgear.		Not modelled
	Harrison & Wallace (2005) [190]	Maximize DG capacity.	OPFA has proposed to maximize the capacity of DG and identifies available headroom on the system.		Not modelled
	Gautam, &	Maximization	OPF techniques is used to find the		Not Modelled

	Mithulananthan (2007) [191]	social welfare and profit	optimal capacity and placement of DGs		
	Algarni and Bhattacharya (2009) [192]	Minimize energy costs	OPF method is used to minimize the distribution energy costs in Disco power system tacking into account goodness factor of DGs.		Not modelled
	Dent et al. (2010) [49]	Maximize DG capacity	OPF based method is used to determine the capacity of the system to accommodate DGs. The results show voltage step limit can be more restrictive of DG capacity than a voltage level limit.		Not modelled
	Ochoa et al. (2010) [195]	Maximize DG capacity	Multi-period AC optimal power flow is proposed to find the optimal size of DGs when ANM control strategies are in operation.		Not modelled
	Ochoa& Harrison (2011) [196]	Minimizes energy losses	Multi-period AC -OPF is used to determine the optimal site of renewable DGs.	Load demand and renewable DGs	Scenario-based approach
	Karatepe et al. (2015) [197]	Minimize losses and improve voltage profile	OPFA including the output power uncertainties in DGs is proposed to investigate the comparison between single-and multiple-DG concepts.	the output power of renewable DGs	Scenario-based approach
Direct approach (DA)	Samui et al. (2012) [198]	Minimize the total annual cost	DA is used to solve ODGP problem depending on tracking and calculating the cost for radial paths.		Not modeled
	Samui et al. (2012) [199]	Minimization planning cost.	DA is higher effective in optimal feeder routing considering role of reliability and planning cost of the radial distribution system.		Not modelled
	Raju et al.	Improve the	DA is used to find the optimal location		Not modelled

	(2012) [200]	voltage profile and maximize the net saving	and size for capacitors in a radial power distribution system.		
Ordinal optimization (OO)	Jabr, R. A., & Pal, B. C. (2009) [201]	minimize losses and maximize the capacity of DG	Specific approaches have been chosen for the application of OO for the optimal placement and sizing of DGs.		Not modelled
	Zou, K et al. (2012) [203]	Reduce power losses	ODGP model considering the uncertainties and DG reactive capability has been developed by using OO.		Not modelled
	Lin et al. (2014)[202]	Minimize cost	OO is applied for the planning of distribution network problems with electric vehicle (EV) charging stations.		Not modelled
Analytical approaches (AA)	Wang & Nehrir (2004) [204]	Minimize power losses of the system	Analytical methods are determined for optimal placement in DG in a radial network system.		Not modelled
	Gozel et al. (2005) [206]	Minimize total power losses and feeder losses	The optimal size and placement of DG in a radial feeder are determined by analytical method.		Not modelled
	Acharya & Mithulananthan (2006) [209]	Minimize total losses	AA is used to calculate the optimal size and placement of a single DG.		Not modelled
	Gözel and Hocaoglu 2009 [15]	Minimize power losses	Employ loss sensitivity factor and based on the equivalent current injection to solve ODGP in the radial system.		Not modelled
	Hung et al. (2010) [208]	Minimize losses	AA is used to find the optimal size of DGs that have the capability to deliver both real and reactive power.		Not modelled
	Elsaiah et al. (2014) [205]	Reduce total losses	An analytical method is introduced to solve the optimal location and size problem of DGs.		Not modelled

	Mahmoud et al. (2015) [207]	Loss minimization	Analytical method is employed to obtain the optimal combination of different DG types.		Not modelled
Continuation power flow (CPF)	Hedayati et al. (2008) [210]	Improve voltage profile and reduce power losses	placement of DG is based on the analysis of power flow continuation and determination of most sensitive buses to voltage collapse		Not modelled
	Hemdan, N. G., & Kurrat, M. (2011) [211]	Maximize load ability and voltage limit	CPF is proposed to solve ODGP problem.		Not modelled

2.4.2 Intelligent Searches (Heuristic Methods)

The heuristic methods based on intelligent searches have been implemented in the DG problem to treat with local minimum problems and uncertainties.

2.4.2.1 Simulated Annealing (SA)

In 1983, SA was introduced by Kirkpatrick et al. [212] as a process to simulate the optimization problem as an annealing process in order to find globally optimal solutions. This approach has the ability to escape local minima by incorporating a probability function in accepting or rejecting new solutions. Authors in [213] have used SA as an optimization tool to determine the optimum location and size of DG in order to minimize multi-objective function including the active power losses, emission and contingency. Also in [214] SA is employed to find optimal location and sizing of DGs to minimize the total losses and improve voltage profile in a large radial distribution system. Nahman et al. [215] have applied SA to find an optimal solution for the planning of a radial distribution network in order to minimize the total cost.

2.4.2.2 Evolutionary Algorithms (EAs)

The flexibility of evolutionary algorithms (EAs) leads to widely employ these algorithms for solving power system operation and planning problems. These algorithms are a population-based optimization process and converge to the global optimum solution with a probability of one by a finite number of evolutionary steps performed on a finite group of reasonable solutions [216, 217]. EAs are the type of artificial intelligence methods for optimization based on natural selection, such as mutation, recombination, crossover, reproduction and selection operators on the population of individuals to perform the search. Also, it is a subset of evolutionary computation, which includes Evolutionary Programming (EP), Evolutionary Strategy (ES) and Genetic Algorithm (GA). EP, ES and GA share many similarities [216, 218]. The authors in [10, 219] have used GA to focus on the optimal placement and size of DGs with an objective function to maximize the benefits related to DG and minimize the power losses. GA and an improved Hereford ranch Algorithm HRA (a variant of GA) are implemented in [220] to determine the optimal sizing of DGs. In [221], GA and HRA are used to find the optimal location and size of DGs in a distribution network. In [222], GA is utilized to find optimal re-closer positions when DGs are deployed in a securely optimal manner. Also in [223], GA is used to solve the ODGP problem with different load models in order to minimize the power losses. In [151], DG allocation strategy for radial distribution networks under uncertainties related to load and generation using adaptive GA has been introduced and the uncertainties of load and generation are modeled using a fuzzy-based approach. El-Ela et al. [171] have proposed GA to determine the optimal location and capacity of DG with multi-system constraints to achieve a single or multi-objectives.

In [224], GA based method is employed to find optimal types, locations and sizes of DGs taking into account the benefits and costs of DG. Furthermore, Borges et al. [3] have proposed GA technique to find optimal placement and size of DGs to maximize the benefit/cost ratio of DG. In [225-227] the authors have combined GA and OPF to find the best sites and capacities available for connecting a large number of DGs in the network. Also, the combination of these methods is being as an efficient solution to minimize the overall cost. GA and ant colony optimization (ACO) together with imperialist competitive algorithm (ICA) are proposed to solve the feeder reconfiguration problem in DGs and focus on positive effectiveness of DGs in loss reduction and voltage profile improvement [228]. In [229] a multi-objective programming method based on the non-dominated sorting genetic algorithm (NSGA) is introduced to find maximum sets of distributed wind power generation in order to minimize the power losses and short-circuit levels. In [230] NSGA-II and the market-based optimal power flow has been proposed to minimize the total energy losses and maximize the net present value associated with the wind power investment over a planning horizon. Ahmadi et al [125] have used the NSGA-II algorithm for optimal site and size of DGs in the network in order to minimize the total cost and line losses and improve voltage profile. Carrano et al. [74] have used NSGA-II with four local search strategies to solve the power distribution network design problem taking into account three relevant aspects: monetary cost, reliability and ability to deal with different scenarios of load growth. Also, uncertainties related to the load demands are modelled by a Monte Carlo simulation (MCS) in order to produce an estimate of the network response into the set of the possible future load. Wang & Gao in [231] have used a non-revisiting genetic algorithm (NRGA), GA and binary space partitioning (BSP) to reduce power losses.

2.4.2.3 Tabu Search (TS)

In 1986, Glover and Hansen have developed the first TS algorithm to solve the optimization issues [217]. This approach is an effective solution to achieve optimization within a reasonably short time. Golshan et al. [232] have applied TS method to determine the optimal locations and sizes of DGs in a distribution network along with tap positions of voltage regulators (VRs) and network configuration. The objective function of this method is to minimize the cost of power losses. Also, Nara et al. [233] have implemented TS method to find how much distribution loss can be reduced if DGs are optimally allocated at the demand side of the system. Maciel and Padilha-Feltrin have proposed a multi-objective Tabu Search (MOTS) method to find the Pareto optimal set. This study shows the comparison between MOTS and NSGA-II and confirmed that the MOTS method has a less advantage than the NSGA-II especially in more complex analysis where time requirements become critical [234].

2.4.2.4 Particle Swarm Optimization (PSO)

In 1995, Eberhart & Kennedy have proposed Particle Swarm Optimization (PSO) for the first time [235]. The original objective of their research inspired by social behavior bird flocking or fish schooling. Different variants of the PSO algorithm were applied to different areas of electric systems problems, but the most standard one is the global version of PSO (Gbest) model [236, 237]. Krueasuk & Ongsakul have used PSO method to determine optimal sizes and locations of multi-DGs [238]. The main goal of this study is to minimize the total power losses in the network. Beromi et al. [239] have suggested a PSO method to solve optimal DG size to improve voltage profile, minimize losses and reduce total harmonic distortion (THD) in addition to dealing with both the costs and site. Also [240] PSO approach is presented for optimal operation management of distribution networks with DGs. The authors in [241] have combined PSO and market-based OPF to choose the optimal size and number of wind turbines (WTs) in order to maximize net present value (NPV) within a distribution market environment. In addition, Raj et al. [242] and Wong et al. [12] have employed PSO to identify the optimum generation capacity and location of DG and provide maximum power quality. In [243], Multi-Objective Particle Swarm Optimization (MOPSO) is used to determine the optimal size of the DG considering multi-objective criteria to simultaneously minimize the power losses and improve voltage profile. In [244], PSO has been used for short term planning of DGs to minimize the total operational cost, power losses and voltage stability index. In [245, 246], multi-objective PSO method is proposed to find the optimal size and location of DGs considering load uncertainty in distribution networks. Decimal coded quantum particle swarm optimization (DQPSO) in [247] is used to solve the feeder reconfiguration problem with a different model of DGs in order to minimize the active power losses. The authors in [102], proposed a new method based on adaptive particle swarm optimization (APSO) for investigating the multi-objective stochastic distribution feeder reconfiguration problem. Also in this paper, various sources of uncertainties including the output of the wind power generators and load demands are handled through an effective probabilistic power flow method based on point estimation method (PEM) scheme.

2.4.2.5 Ant Colony System Algorithm (ACSA).

In 1990s, Dorigo et al. [248] introduced Ant Colony Optimization (ACO) as a new technique for solving combinatorial optimization problems. It is inspired by ants' movement to find food. ACO is derived from ant system (AS) algorithm which has the best performance in engineering applications [249-252]. In [253], ACO is used to determine the optimal location and size of DGs to minimize investment and operational costs of the system considering DGs as constant power sources. Authors in [254] have used ant colony system algorithm (ACSA) to seek out the optimal re-closer and DG placement for radial distribution network by using the composite reliability index as the objective function in the optimization procedure. Kaur et al. [255] have used ACSA to solve capacitor allocation problem in radial distribution systems to minimize the total cost of losses. In [256], multi-objective reconfiguration problem which considers the active power losses minimization and the energy not supplied index which is solved by a modified ACO.

2.4.2.6 Artificial Bee Colony (ABC)

ABC algorithm was introduced by Dervis Karaboga in 2005 [257]. This method inspired by the intelligent behaviour of honey bees' swarm to find the nectar [257]. ABC approach is applied in [258] to solve distribution network expansion planning to obtain the optimum value of reinforcements and to find a suitable commitment schedule for the installation of new DGs. In [259], the authors have used ABC algorithm for DG planning problem in order to reduce the power losses and to improve the voltage profile in the radial distribution systems. Also, in [260], optimal DG location and size problem has been solved by ABC algorithm in order to minimize the power losses and enhance the voltage stability level. ABC has been used in [261] to find the optimal location and size of DGs with two control parameters (colony size and maximum iteration number) to be tuned.

2.4.2.7 Artificial *Immune System (AIS)*

Artificial immune algorithm (AIS) is used in [262] to generate a set of nearly-optimal solutions under load-evolution conditions (including the load for each node, and a unique expected mean energy tax). The authors in [263] have used AIS to solve DG placement problem in order to minimize the power losses taking into account the bus voltage and line current limits. In [264], AIS is used to solve the DG planning problem considering uncertainty in the load demands in distribution networks.

2.4.2.8 Bacterial Foraging Optimization Algorithm (BFOA)

In 2002, Passino invented Bacterial Foraging Optimization algorithm (BFOA). This algorithm tried to model the single and set behavior of E. Coli bacteria (kind of bacteria that live in intestines in order to find a simple path for faster convergence [265]. In [266], BFOA is used to solve the optimal radial feeder routing in the distribution systems planning problem. Devi and Geethanjali, [267] have modified the performance of the BFO algorithm (MBFO) in order to find the optimal placement and sizing of DGs in a distribution system to reduce the total power losses and to improve the voltage profile of the distribution system. The result showed that MBFOA is more efficient in finding the minimum cost in less computational time than BFOA. In [268], BFOA was applied to find the optimal size of capacitor banks in order to minimize the power losses by taking into account loss sensitivity factor (LSF) and voltage stability index (VSI). BFOA is presented to find the optimal size and location of multiple DGs in order to minimize the network losses, operational costs and improve the voltage stability of a radial distribution system [269].

2.4.2.9 Bat Algorithm (BA)

Bat Algorithm (BA) was presented by Yang in 2010 as a base on the echolocation behavior of bats [270]. Yammani et al. [271] have used BA to find the optimal location and sizing of DGs to minimize the network losses and improve the voltage profile. In [43], BA is used to determine the optimal location of capacitors in the radial distribution system in order to minimize the power losses and maximize the revenue. In [272], BA was used to obtain the optimal placement, size and the number of DGs in a radial distribution network. In [273], BA and loss sensitivity factor (LSF) are respectively used to find the optimal size of the capacitor banks and find the optimal site of the capacitor.

2.4.2.10 Imperialist Competitive Algorithm (ICA)

ICA is a new approach inspired by imperialists competition and the first using was in 2007 by Atashpaz and Lucas [274]. In [275] ICA is used to find the optimal placement and size of DGs to minimize the network power losses. Moradi et.al [276] have used ICA to find optimal sitting and sizing of DGs and capacitor banks in a distribution network. The objective is to reduce the power losses, increase voltage stability index and improve the system voltage profile. In [277], the optimization problem of DGs at any load level is solved by using ICA in order to reduce the power losses and enhance voltage stability.

2.4.2.10 Cuckoo Search Algorithm (CSA)

CSA is a new approach developed by Yang and Deb in 2009 to solve the optimization problems [278]. This algorithm is inspired by the obligate brood parasitism behavior of certain species of cuckoos by laying their eggs in the nests of other birds of other species. Nguyen et al. [279] have proposed CSA to find the optimum placement and size of DGs to minimize the power losses and voltage stability deviation index. Also, in [280], CSA is used for optimal DG placement to reduce the power losses and improve the voltage profile of the distribution power system. In [281], COA is used to reduce the power losses and improve the voltage profile for two types of DGs: biomass and solar-thermal. The authors in [282] have applied CSA to obtain optimal location and size of DGs in the distribution network to minimize the active power losses and improve the voltage profile by maintaining the fault level and line load within an acceptable limit.

2.4.2.11 Intelligent Water Drop (IWP) Algorithm

Intelligent water drop (IWD) was firstly proposed as a new approach to finding the global optimum solutions by Shah-Hosseini in 2007. This algorithm inspired from the river procedure to find an optimal path to flow from source to destination [283]. In [284], IWP algorithm is used to find the optimal sizing of DGs in radial distribution networks in order to minimize the losses and to improve the voltage profile. In [285] (IWD) is proposed to find the optimal size and site of DGs in microgrids to minimize network power losses, improve voltage regulation and increase the voltage stability.

3.4.2.11 Fuzzy Set Theory (FST)

Fuzzy set theory (FST) was introduced in 1965 by Zadeh [110] as formal tools to deal with data that have non-statistical uncertainties. A fuzzy variable is modeled by a membership function which operates over the range of real numbers zero or one. Momoh et al. [286] have confirmed that FST is widely used in power system planning. In [287] fuzzy-GA is used to solve optimal DG placement problem by transforming the objective function and constraint into multi-objective function with fuzzy set. In [288], FST is used for the modeling of the load and electricity price uncertainties in the system and solved by NSGA-II in order to minimize the operational cost, technical and economic risks. The authors in [289] have applied the two-stage algorithm to solve ODGP problem with voltage and line loading constraints in order to minimize the system losses. In the first stage, fuzzy approach is used to optimal DG locations while in the second stage, PSO is used to find the size of the DGs. Also In [290], Fuzzy Logic is used to find the optimal capacitor locations and BA is applied to determine the size of optimal capacitors in order to reduce the power losses. Table 2-5 presents a summary of the literature review for optimal DGs placement problem using intelligent techniques.

2.4.3 The Prospective Methods

The main perspective revealed methods are presented as follows:

2.4.3.1 Firefly Algorithm (FA):

This algorithm was first introduced in 2009 by Yang [291] for solving nonlinear multidimensional optimization problems. FA is inspired from the natural behavior of the fireflies; a firefly of the maximum brightness has the largest ability to attract other fireflies regardless to their sex. References [292, 293] have used FA to find the optimal site and size of multiple DGs on a balanced radial feeder for power loss minimization. Othman et al. [294] have modified the traditional FA in order to be able to deal with the practically constrained optimization problems. This new algorithm has many advantages such as simple concepts, easy implementation and higher stability mechanism compare with traditional FA [294].

A. Shuffled Frog Leaping Algorithm (SFLA):

This method is formed by mimetic evolution of a group of frogs when searching for an area, where the maximum amount of food available [295]. Optimal site and size of DGs considering system loss minimization and voltage profile improvement as objective functions solved by SFLA [295].

B. Big Bang-Big Crunch (BB-BC) Algorithm:

This algorithm was first introduced in 2006 by Erol and Eksin [296] as a new optimization method. This algorithm relies on one of the theories of the evolution of the universe which is named the Big Bang and Big Crunch (BB-

BC) Theory. In [297], BB-BC algorithm is used to solve distribution network reconfiguration and optimal power allocation of DGs in order to minimize the total active power losses, maximize the voltage stability index, minimize the total cost, and minimize the total emission produce by DGs and the grid.

Table 2- 5 Summary of literature review for DGP problem using intelligent techniques

Intelligent searches		References	Objective function	Contribution	Uncertainty issue	Mathematical modelling Uncertainty
Simulated Annealing (SA)		Nahman, J. M., & Peric, D. M. (2008) [215]	Minimize investment cost and loss cost	Optimal planning problem of radial distribution is solved by apply SA combination with the steepest descent approach.		Not modelled
		Sutthibun & Bhasaputra (2010) [213]	Minimize power loss and emission	Multi-objective optimal DG placement problem is solved by SA.		Not modelled
		Injeti, S. K., & Kumar, N. P. (2013) [214]	Minimize network power losses and improve voltage stability.	SA is proposed to evaluate the optimal siting and sizing of DGs with unspecified power factor distribution network.		Not modelled
Evolutionary Algorithms (EAs)	HR A	Kim et al. (1998) [220]	Minimize power losses	Conventional GA and HRA are introduced for solving optimal sizing problem in DGs.		Not modelled
		Gandomkar et al. (2005) [221]	Minimizes the power losses	Simple GA and HRA are applied to introduce optimal site and size Of DGs.		Not modelled
	GA	Silvestri et al. (1999)[219]	Maximization of the benefit related to DG	Optimal sitting and sizing problem of DG solved by a GA.		Not modelled
		Teng, et al. (2002)[224]	Maximize the benefit /cost ratio of DG	GA proposed to find the best balance between the costs and benefits of DG placement with optimal types, locations and sizes in distribution feeders.		Not modelled
		Ganguly, S. and	minimizing the	GA used to present a DG allocation	Load, DG	fuzzy-based

		D. Samajpati (2015) [151]	network power loss and maximum node voltage deviation	strategy for radial distribution networks under uncertainties of load and generation.		approach
		Popović et al. (2005)[222]	Improve voltage profile and reduce losses	GA is designed to find optimal re-closer positions when DGs are connected in a securely optimal manner.		Not modelled
		Borges & Falcao (2006)[3]	Minimize the power loss and maximize benefit/cost ratio	Used GA to introduce and solve optimal DGP problem model with reliability.		Not modelled
		Harrison et al. (2007) [226]	Maximize DG capacity,	Combined GA and OPF to solve ODGP problem.		Not modelled
		Harrison et al. (2008) [225]	Maximize profit	A hybrid method employing GA and OPF to apply optimal placement and size a predefined number of DGs.		Not modelled
		Singh & Verma (2009) [223]	Minimize real power loss	ODGP model with different load models solved by GA.		Not modelled
		El-Ela et al. (2010) [171]	Improve the voltage profile, increase the spinning reserve, and reduce the losses.	GA used to propose the optimal location and size of DG with multi-system constraints to achieve a single or multi-objectives.		Not modelled
		Talaat & Al-Ammar (2011) [10]	Minimum losses of the distribution system	Optimal penetration level and optimal locations and sizes of DGs have been investigated using three GA.		Not modelled
		Falaghi et al. (2011) [227]	Minimize cost	GA and OPF approaches are employed as the solution tool to solve ODGP problem.		Not modelled
		Mirhoseini, et al.	Minimize real	GA and ACO together with ICA are		Not modelled

		(2014) [228]	power losses and improve voltage profile	proposed to solve the feeder reconfiguration problem in DGs.		
	(NS GA)	Ochoa et al. (2008) [229]	Minimize power losses and short-circuit levels.	NSGA is applied in order to find configurations that maximize the integration of distributed wind power generation.	Demand and generation	Scenario-based approach
		Ahmadi et al. (2008) [125]	Minimize total cost, minimize line losses and improve voltage profile	NSGA-II algorithm used to find optimal location and size of DGs.		Not modelled
		Siano, P. and G. Mokryani (2015) [230]	maximize the net present value associated with the WT investment over a planning horizon	NSGA and the market-based OPF have proposed to find the optimal numbers and sizes of WTs.	Load demand and renewable generation	Scenario-based approach
		Carrano et al. (2014) [74]	Minimize cost	ODGP problem solved by (NSGA-II) with taking account monetary cost, reliability and load growth uncertainties.	Load demand	Scenario-based approach
	(NR GA)	Wang & Gao (2013) [231]	Reduce losses	NRGA, GA and BSP are used to solve distribution network optimization problem for loss reduction.		No modelling
Tabu Search (TS)		Nara et al. (2001) [233]	Reduce distribution power loss	ODGP are solved by TS method for the case of uniformly distributed loads with unity power factor.		Not modelled
		Golshan & Arefifar (2006)[232]	Minimize the cost of power and losses and	DGP problem is solved by using TS method, the amount of DGs and reactive power sources RPSs are		Not modelled

		reactive power capacity.	counted in selected buses.		
	Maciel& Padilha-Feltrin, (2009) [234]	Optimal solutions set	Apply a Multi-objective TS to find the Pareto optimal solutions set, it is a better performance comparing to the NSGA-II method.		Not modelled
Particle Swarm Optimization (PSO)	Krueasuk & Ongsakul, (2006)[238]	Minimize the total real power losses	ODGP of multi-DGs determines by PSO.		Not modelled
	Niknam (2006) [240]	Summation of electrical energy generated by DGs and substation bus	The optimal operation problem solved by PSO and presents better performance in comparison with GA.		Not modelled
	Beromi et al. (2008) [239]	Improve voltage profile, reduce loss and reduce THD	ODGP considering load flow and harmonic calculations for decision-making is applied by PSO.		Not modelled
	Raj et al. (2008) [242]	Reduces line losses, improve voltage profile and improves power quality	Find the optimal value of the DG capacity by using PSO method.		Not modelled
	Wong et al. (2010) [12]	Reduces total power losses	PSO and Newton-Raphson load flow method are proposed to determine the optimal location and size of the DG.		Not modelled
	Jain et al. (2011) [243]	Minimizing power loss and improve voltage profile	Multi-Objective PSO method proposed to determine the optimal size of the DG.		Not modelled
	Siano, P., & Mokryani, G.	Minimizing energy costs and	PSO and market-based OPF are used to choose the optimal size and		Not modelled

	(2013) [241]	power losses	number of WTs in the system by considering security constraints and inter-temporal effects.		
	Aghaei et al. (2014) [244]	Reduce overall cost, power losses and voltage stability index	PSO used to solve short time planning problem of DG.		Not modelled
	Zeinalzadeh et al. (2015) [246]	Minimize the cost	Multi-objective PSO method is used to find the optimal location and capacity of DGs and shunt capacitor banks with considering load uncertainty in the system.	Load demand	Fuzzy-based approach
	Jamian et al. (2015) [245]	Minimize the cost	ODGP problem is solved by using rank evolutionary PSO method.		Not modelled
	Guan et al. (2015) [247]	Minimizing real power loss	DQPSO used to solve the feeder reconfiguration problem with a different model of DGs.	Renewable DG	Monte-Carlo simulation
	Malekpour, et al. (2013) [102]	Reduces total power losses and Minimize the cost of power	A new method based on adaptive particle swarm optimization (APSO) is offered for investigating the multi-objective stochastic distribution feeder reconfiguration (SDFR) problem.	Renewable DG	Point estimation method (PEM) –based approach
Ant Colony Optimization (ACO).	Teng & Liu (2003) [251]	Minimize the cost	ACO is used to solve the optimum switch relocation problem.		Not modelled
	Gómez et al. (2004) [250]	Minimize the investment and operation costs	ACO is proposed to solve the planning problem of distribution systems.		Not modelled
	Vlachogiannis et al. (2005) [252]	Minimize real power losses	ACO approach is applied to the solution of the constrained load flow (CLF) problem as a combinatorial		Not modelled

			optimization problem.		
	Falaghi & Haghifam (2007) [253]	Minimizing the DG operation and investment cost	ACO used as the optimization tool to solve optimal location and size problems in DG.		Not modelled
	Wang, L., & Singh, C. (2008) [254]	Minimizing a composite reliability index and minimizing the customer interruption costs	ACO is proposed to seek out the optimal re-closer and DG placement.		Not modelled
	Kaur, D., & Sharma, J. (2013) [255]	Minimize the total cost	Multi-period optimization problem solved by ACO.		Not modelled
	Mirhoseini et al. (2015) [256]	Minimizes both real power losses and energy not supplied index	Multi-objective reconfiguration problem considers the real power losses and the energy not supplied index was discussion together by a modified ACO.		Not modelled
Artificial Bee Colony (ABC)	Padma Lalitha et al. (2010) [259]	Maximum loss reduction	ABC algorithm and Fuzzy are used to find the optimal DG locations and sizes in the system.		Not modelled
	Abu-Mouti et al. (2011) [261]	Minimize the total real power loss	ABC used to find the optimal site, size and power factor of DGs.		Not modelled
	El-Zonkoly (2013) [258]	Minimizing cost	ABC is applied to solve the dynamic expansion planning problem of DGs through discuss unit commitment (UC) mathematical model and a multistage expansion planning strategy.		Not modelled
	N. Mohandas et al. (2015) [260]	Improve voltage profile	Optimal DG location and size problems have been solved by the ABC algorithm.		Not modelled

Artificial Immune System (AIS)	Carrano et al. (2007) [262]	Minimizing cost	Immune algorithm (IA) used to generate a set of nearly-optimal under a set of load-evolution conditions.	Load demand	Monte-Carlo simulation
	Aghaebrahimi et al. (2009) [263]	Minimize power losses	AIS is used to solve DG placement problem in the power network.		Not modelled
	Souza et al. (2011) [264]	Minimize total costs	AIS used to solve the DGP problem by taking into account the effect of uncertainty in electric distribution networks.	Load demand	Monte Carlo simulation
Bacterial Foraging	Singh et al. (2012) [266]	Minimizing cost	Bacterial foraging introduces to provide rapid solutions with the best probability in order to obtain a global optimal solution of the distribution planning problem.		Not modelled
	Devi, S., & Geethanjali, M. (2014) [267]	Reduce the total loss and improve the voltage profile	MBFO is proposed to improve the convergence characteristics of BFO algorithm to solve optimal problems of radial distribution systems.		Not modelled
	Kowsalya, M. (2014) [269]	Minimize network power losses	BFOA is proposed to solve the various optimization problems at different load levels.		Not modelled
	Devabalaji et al. (2015) [268]	Minimize power losses	BFOA was used to find the optimal size of the capacitor bank with taking account both LSF and VSI.		Not modelled
Bat Algorithm	Yammani et al. (2013) [271]	Minimize system loss and improve voltage profile	BA used to find the optimal location and sizing of the DGs.	Load demand	Scenario-based approach
	Injeti et al. (2015) [43]	Loss minimization	Optimal Location problem of capacitors in radial DGs is solved by BA and Cuckoo Search (CS).		Not modelled
	Candelo-	Minimizing power	BA was used to obtain the optimal	Renewable	Scenario-

	Becerra et al. (2015) [272]	losses	solution of DGs problem in the radial distribution network.	DG	based approach
	Devabalaji et al. (2015) [273].	Reduce the total power loss	BAT Algorithm used to find the optimal size of the capacitor banks and LSF used to pre-find the optimal site of the capacitor placement.		Not modelled
Imperialist Competitive Algorithm (ICA)	Mahari et al. (2012) [275]	Minimizing the total system of active power losses	ICA used to find the optimal location and size of DGs.		Not modelled
	Moradi et al. (2014) [276].	Reduce power loss, increase voltage stability index and improving system voltage profile	ICA employed to solve the ODGP problem of DG and capacitor banks in the distribution network.		Not modelled
	Poornazaryan et al. (2016) [277].	Reduce power losses and enhance voltage stability.	Optimal location and size of DG unit are obtained by proposed ICA with considering load variations.	Load demand	Scenario-based approach
Cuckoo Search Algorithm (CSA)	Fard et al. (2012) [281].	Reduce the losses and improve the voltage profile	CSA introduce to solve the ODGP problem for different types of DG in the network.	Load demand	Monte Carlo method
	Moravej et al. (2013) [280].	Minimize real power losses and improve voltage profile	Optimal location and size problem is solved by employing CSA.		Not modelled
	Buaklee et al. (2013) [282].	Loss reduction and improve voltage profile	CSA is proposed to find the optimal site and size of DGs by considering the fault level constraints.		Not modelled
	Nguyen et al.	Minimize total	CSA employs to solve optimal		Not modelled

	(2016) [279]	power loss and enhance voltage stability.	location and size problems in DGs network.		
Intelligent Water Drop (IWP) Algorithm	Prabha et al. (2015) [284].	Minimize the losses	IWD used to find optimal sizing and the loss sensitivity factor (LSF) for the installation of DGs in the radial distribution network.		Not modelled
	Moradi et al. (2016) [285]	Minimize network power losses, improve voltage regulation and increase the voltage stability.	IWD method with GA is proposed to find the size and site of DG in microgrids.		Not modelled
Fuzzy Set Theory (FST)	Kim et al. (2002) [287]	Reduce power loss costs	Fuzzy-GA method used to solve the ODGP problem by transforming the objective function and constraints it to multi-objective function with fuzzy sets		Not modelled
	Haghifam et al. (2008) [288]	Minimization of the total cost, technical and economic risk	Load and electricity price uncertainties in the system are modelled using fuzzy numbers and solve by non-dominant sorting genetic algorithm (NSGA-II).	Load demand	Fuzzy numbers
	Lalitha et al. (2010) [289]	Reduce power losses and improve the voltage profile	Fuzzy and PSO algorithm including voltage and line loading constraints proposed to find the optimal DG locations and sizes.		Not modelled
	Reddy, V. U., & Manoj, A. (2012) [290]	Reduce power losses	BA used to determine the size of optimal capacitors in DGs.		Not modelled

The above table shows that the trend of using intelligent methods has been gradually increased to find the optimum solution in DGs placement problem. In addition, the scientists have recently applied two or three methods as a combination to obtain new strategies in order to solve the optimization of DGP problem efficiently, such as [12, 220, 221, 225-228, 231, 259, 285, 287-289]. Tables 2-6 and 2-7 show the summary of the advantage and disadvantage of conventional and intelligent methods characteristics.

Table 2- 6 Advantages and disadvantages of conventional methods

Conventional methods	**References**	**Advantages**	**Disadvantages**
Linear programming (LP)	[169-171]	Easy to implement, and it accommodates a large variety of power system operating constraints	Used just when the objective function is linear.
Nonlinear programming (NLP)	[175, 176]	Simple and Efficient.	Long time to run.
Mixed-integer nonlinear programming (MINLP)	[178-185, 298]	It is fast, robust, efficient and deals with very large scale DGP problems.	It may insert errors due to the linearization of the nonlinear characteristics of DGP.
Dynamic programming (DP)	[186-189, 298]	Efficient and easy.	Not suitable for large-scale DGP problems
Optimal Power Flow-based Approach (OPFA)	[49, 190-197]	Easy, simple and efficient in computational time	The results may not be optimal when the problem is highly complex and Hard to understand and implement
Direct approach	[198-200]	Robust, very efficient and suitable for large-scale distribution systems	Not deals with the radial network structure.
Ordinal optimization (OO)	[201-203]	It is deal with non-deterministic polynomial (NP) complete problems	Need a long time.

		such as DG planning with discrete and continuous variables.	
Analytical approaches (AA)	[15, 204-209]	Simple, easy implementation and efficiency in computational time.	Only obtains an approximate solution.
Continuation power flow (CPP)	[210, 211]	Faster, very efficient, robust, qualified to treat different level penetration of DG.	May not find the optimal solution.

Table 2- 7 Summary of Evaluation Intelligent Methods

Intelligent methods	References	Advantages	Disadvantages
Simulated Annealing (SA)	[213-215]	Ease of implementation, get best solutions and robust.	It requires excessive computation time.
Evolutionary Algorithms (EAs)	[219-221]	Simple, speedy processing time, efficient and accurate results, very useful for complex problems	Used a larger population size, repeated fitness function evaluation for large and complex problems may be time-consuming.
Tabu Search (TS)	[232, 233]	It is efficient to achieve near-optimal solution within a reasonably short duration.	Need considerable parameters to be defined
Particle Swarm Optimization (PSO)	[12, 238-244, 299, 300]	It is easy to implement Insensitive to scaling of design variables, Simple implementation, easily parallelized for concurrent processing, derivative-free, Very few algorithm parameters, and very efficient global search algorithm.	Need to the solid mathematical background.
Ant Colony System Algorithm (ACSA).	[250-256]	Easy to understand and code Rapid discovery of good solutions	Theoretical analysis is difficult
Artificial bee colony (ABC)	[257-261, 301, 302]	Very simple, robust, efficient algorithm, fast-converging, capable of handling complex optimization problems and it does not require external parameters.	The performance of this method may be influenced depending on the constraint handling method used
Artificial immune system (AIS)	[262-264]	Effective, can find and maintain a set of suboptimal solutions	Complex system

		simultaneously with the existing better solution.	
Bacterial foraging	[266-269]	Efficiency to find the result in less computational time	It requires the tuning of a great number of parameters.
Biologically inspired algorithm (Bat Algorithm)	[43, 271-273, 290]	Efficient and Accurate.	The convergence rate is very much influenced by adjustment parameters.
Imperialist Competitive Algorithm (ICA)	[275-277].	effective, fast, and capable of handling complex nonlinear mix-integer optimization problems in DGs.	harder to code fewer literature example
Cuckoo Search Algorithm (CSA)	[278, 280-282]	It is more generic and robust, efficient, easy to code, less parameters setting.	Slow convergence.
Intelligent Water Drop (IWP) Algorithm	[283, 284]	fast, efficient, easy to implement and needs fewer iteration to find good results	fewer literature example
Fuzzy Set Theory (FST)	[287-289]	Easy to comprehend, and suitable to model uncertainties to find better solution	fewer literature example

2.5 Conclusion

The detail of distributed generators (DGs), the general information of the methods which are used for uncertainty modelling have been presented based on the solution algorithms and the DGs operation problems.

This literature review showed that most of research focuses on increasing the penetration of DGs to gain different objective functions such as minimizing the generation cost, improving voltage profile, minimizing the loss, etc. Some of them take into account the study of uncertainty related to the renewable energy resource and load. The present review suggested that the intelligent methods are mostly used to obtain an optimum solution of DGs placement problem. They also stated the use of combining more than one method would be the possible optimum solution. However, in all of these research works theywere either in active power or in reactive power. None of them considered both active and reactive power together at the same time.

In order to further investigate the issue of active and reactive power optimisation, the following chapters investigate such operational performance of the DGs in which the uncertainty modelling and useful insights could be gained.

Chapter 3 Stochastic Approach for Active and Reactive Power for Market Management

3.1 Introduction

The intermittent and unpredictable nature of wind energy introduces a significant operational variability and uncertainty that must be managed with the renewable energy sources (RES) integration into distribution networks [303]. Distribution network operators (DNOs) have to develop a reasonable operating strategy taking into consideration the quantity of active and reactive power that can be injected/absorbed to/from the grid and interrupting loads while keeping network security. This chapter provides a stochastic method in order to assess the quantity of active and reactive power that can be injected/absorbed into/from the grid by WTs. It also investigates the impact of wind power penetration on social welfare (SW) and on the active and reactive distribution-locational marginal prices (D-LMPs) by considering wind speed and load demands uncertainty in the electricity distribution market environment. It should be noted that the wind speed and load demand uncertainty are modelled by Scenario-based approach and the proposed model is examined and tested with 16-bus UK generic distribution system.

To the best of the present author knowledge, the current work [304] has not been considered and tackled in previous literature or published papers. The methodology is new to assess the active and reactive distribution-locational marginal prices (D-LMP) in distribution networks from the distribution network operators (DNOs) perspective within a distribution market environment that considers the uncertainties related to wind speed and load demands.

3.2 Related Work to Active and Reactive Market

Several studies have involved the use of DGs as providers of reactive power support. The authors in [305] introduced a proper Coordination technique among the DGs and on an on-load tap changing transformers, substation switched capacitors and feeder-switched capacitors without requiring communication. In [306], the possibility of providing reactive power and primary frequency support to the grid from modern wind farm's output as a part of the ancillary service provisions, including a detailed analysis of WFs capability curves and different cost components related with reactive power generation are examined.

Few studies have been carried out on simultaneous considering of active and reactive power optimal power flow. A general optimal power flow (OPF) problem was introduced for the first time by Carpentier in early 1960's [307]. In [308], OPF was divided into two suboptimal problems, optimal reactive power problem and optimal active power problem, where these two suboptimal problems were solved separately. In [309] OPF has been used to determine the optimal penetration of DGs in a way that minimizes the system energy losses. In [310] a Security Constraint Optimal Power Flow (SCOPF) is used to model the reactive power procurement which incorporates the voltage stability criterion to minimize the cost of reactive power procurement and energy losses. The authors In [311] proposed reactive power market to minimize total generation costs of reactive power and transmission losses at different voltage stability margins. In [312] a theory of real-time pricing of active and reactive powers by using the objective function that maximizes social benefits (which customarily consists of the benefit function of consumers and cost function of real power generation) was presented. In [313] a three-step approach has been presented which considers the calculation of marginal benefits and the maximization of social welfare. In [314], a modified nodal pricing method has been used to calculate reactive power price which can be derived from OPF in normal and emergency conditions. In [315], the authors have used a modified OPF to minimize the active and reactive power production costs. Dai et al [316] have included the opportunity cost of dispatching reactive power from generators into OPF problem in order to obtain reactive power marginal price. In [317] a new design of reactive power capacity market based on an annual auction had been proposed to procure of the reactive power service. The authors in [318] have solved the reactive power pricing by considering the production costs of both active and reactive power of generators and capital cost of capacitors in the OPF problem to find reactive D-LMPs. Also, AC-OPF has been used to calculate the D-LMPs for active and reactive power[319]. Hao and Papalexopoulos [320] have discussed the characteristics of structure reactive power that must be taken into consideration in order to improve a framework for reactive power pricing and management. The results show that the reactive power marginal price is typically less than 1% of the active power marginal price and depends strongly on the network constraints. In [321] a probabilistic algorithm for optimal reactive power provision in the electricity market has been proposed takes into account load forecasting uncertainties. A pay-as-pay mechanism has been considered by the authors in [322] to design a new reactive power market. This mechanism implicitly considers the local nature of reactive power. in [323] a new design of reactive power market basis on procurement of reactive power resources on a seasonal basis and a real-time reactive power dispatch has been proposed.

Regarding the uncertainty, the probability density function (PDF) and membership function are used to describe uncertainty parameters. PDF uses the historical data of uncertainties when they are available such as wind speed or load demand. Otherwise, if no statistical data about uncertainty parameter are available, membership function will be used [33]. A powerful tool to assess the impact of DGs takes into account the uncertainties related with operation/investments of DGs on distribution network has been introduced by Soroudi in [117].

3.3 Main Contributions of the Current work

To the best of author’s knowledge, no stochastic method to assess the active and reactive D-LMP in distribution networks from the DNOs perspective within a distribution market environment considering uncertainties has been reported in the literature. The main contributions of this work are listed below:

1. To provide a stochastic approach for evaluating the SW and the impact of WTs’ penetration on the reactive and active D-LMPs in distribution networks within a distribution market environment considering uncertainties.

2. To model the uncertainties associated with load demand and wind speed in the distribution system by using a scenario-based approach.
3. To maximize the social welfare by using market-based active and reactive OPF.

3.4 Joint Active/Reactive Power Market formulation

A joint active and reactive market model at the distribution level is proposed in this section. The structure of the proposed market is based on bilateral contracts and pool within DNOs control zone, which is shown in Figure 3-1. In this market model, the DNO acts as the operator of the distribution market where it manages the operational facilities and buying active and/or reactive power through the pool or from bilateral contracts. Dispatchable loads (DLs) and renewable generators (such as WTs and PVs) send offers and bids prices of active and reactive power in form of blocks to the distribution market every hour. Then, the DNO combines offers and bids prices in order to maximize the consumers' benefit function while minimizing the cost of energy and which is called maximizing social welfare [324]

The following actions are carried out by the proposed market:

1. A day-ahead schedule of renewable generators (WTs, PVs) and DLs according to the market prices. In every trading day, renewable generators (WTs and PVs) and DLs provide offer and bid prices and active and reactive power quantity information for every 24-hour trading period one day ahead. For every trading duration, the dispatch schedules are determined [324].

2. An adjustment market, which closes a few hours earlier before delivery and allows adjustment in correction due to unexpected supply-demand imbalances occurred during the day due to load or generation variations.
3. A real-time intraday optimization operation for economic requirements and operation is done by changing scheduling every 15-minutes (balancing market).

In this distribution market, active and reactive power, which are produced by renewable power sources (wind and solar), contributes to the pool including the three consecutive and autonomous short-term trading floors as explained above. In the day-ahead market, to eliminate or reduce the variation between the amount of energy cleared and the expected generation, the processes carried out in the adjustment and real-time distribution markets are required. In the adjustment market, wind and solar producers are allowed to update their estimated generation in their offers, which is lead to reduce the related uncertainties. Imbalances at real-time between generation and demand are settled at balancing the market in order to ensure that the electricity demand equals to electricity supply in real time [325].

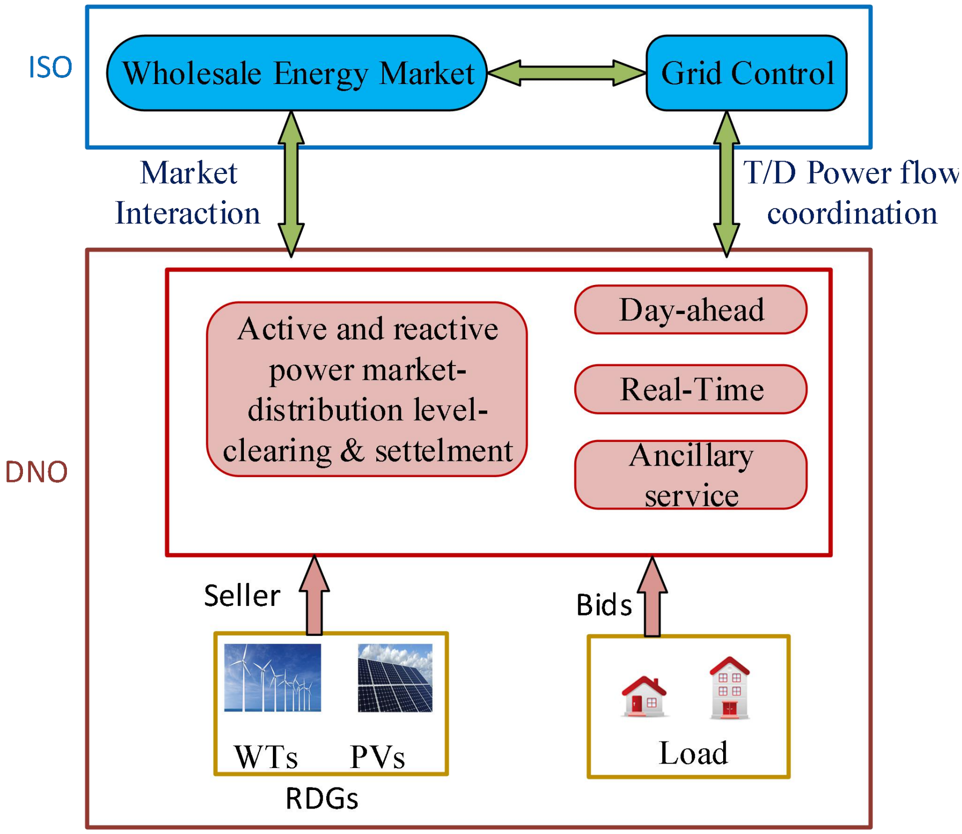


Figure 3- 1 The structure of the proposed distribution marker

In Figure 3-1, the wholesale market provides the power at a given or estimated price and DG send price and quantity power offers to the DNOs. DNO is defined as the market operator of its market acquisition market which determines the optimization process and the price estimation for the acquisition of active and reactive power [22]. In other words, DNOs purchase active and reactive power according to the offers of DGs, bids of loads and delivered it to the final customers while keeping system security. The major aim of DNO is to maximize social welfare that includes the maximum consumers' benefit function and minimum cost of energy [326]. The active and reactive power offers from generators (substation and renewable power sources) and active and reactive bids of loads are sent to the DNO acquisition market in the form of blocks [324]. The difference between them known social welfare which can be as follows:

$$\text{Maximize SW} = \left(\sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{l,P} P_{i,s}^{l} + \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{l,Q} Q_{i,s}^{l}\right) - \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,P} P_{i,s}^{ss} - \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,Q} Q_{i,s}^{ss} - \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{w,P} P_{i,s}^{w} - \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{w,Q} Q_{i,s}^{w} \quad (3.1)$$

where, $P_{i,s}^{l}$, $P_{i,s}^{ss}$ and $P_{i,s}^{w}$ are the active power for load, substation (slack bus) and WTs at each bus *i* at scenario *s* respectively. $Q_{i,s}^{l}$, $Q_{i,s}^{ss}$ and $Q_{i,s}^{w}$ are the reactive power for load, substation and WTs at each bus *i* at scenario *s,* respectively. $C_i^{ss,P}$ / $C_i^{w,P}$, are the offer prices for active power of substation / WTs at each bus *i s*. $C_i^{ss,Q}$ / $C_i^{w,Q}$ are the offer prices for reactive power of substation / WTs at each bus. $C_i^{l,P}$ and $C_i^{l,Q}$ are the bid prices for active and reactive power load at each bus *i*, respectively. π_s is the corresponding probability at scenario *s*.

3.5 Constraints market-based active and reactive OPF

In market-based active and reactive OPF, constraints can be categorized into two groups [28]

3.5.1 Equality constraints:

1. Active power balance at each bus

$$\sum_{i=1}^{NB} P_{i,s}^{ss} + \sum_{i=1}^{NB} P_{i,s}^{w} - \sum_{i=1}^{NB} P_{i,s}^{l} = \sum_{j=1}^{NB} V_{i,s} V_{j,s} \left[G_{i,j} \sin(\delta_{i,s} - \delta_{j,s}) - B_{i,j} \cos(\delta_{i,s} - \delta_{j,s}) \right] \tag{3.2}$$

2. Reactive power balance at each bus

$$\sum_{i=1}^{NB} Q_{i,s}^{ss} + \sum_{i=1}^{NB} Q_{i,s}^{w} - \sum_{i=1}^{NB} Q_{i,s}^{l} = \sum_{j=1}^{NB} V_{i,s} V_{j,s} \left[G_{i,j} \sin(\delta_{i,s} - \delta_{j,s}) - B_{i,j} \cos(\delta_{i,s} - \delta_{j,s}) \right] \tag{3.3}$$

where $\mathrm{G}_{\mathrm{i,j}}$ and $B_{i,j}$ are the real and imaginary parts of the elements in the admittance matrix corresponding to the *ith* row and *jth* column, respectively.

3.5.2 Inequality constraints

1. Active power capacity constraints at the substation

$$P_{i,s}^{ss,\min} \le P_{i,s}^{ss} \le P_{i,s}^{ss,\max} \tag{3.4}$$

2. Reactive power capacity constraints at the substation

$$Q_{i,s}^{ss,\min} \le Q_{i,s}^{ss} \le Q_{i,s}^{ss,\max} \tag{3.5}$$

3. Active power constraints for WTs generation

$$P_{i,s}^{w,\min} \le P_{i,s}^{w} \le P_{i,s}^{w,\max} \tag{3.6}$$

4. Reactive power constraints for WTs generation

$$Q_{i,s}^{w,\min} \le Q_{i,s}^{w} \le Q_{i,s}^{w,\max} \tag{3.7}$$

where, $P_{i,s}^{ss,min}$ / $P_{i,s}^{ss,max}$, $Q_{i,s}^{ss,min}$ / $Q_{i,s}^{ss,max}$, $P_{i,s}^{w,min}$ / $P_{i,s}^{w,max}$ and $Q_{i,s}^{w,min}$ / $Q_{i,s}^{w,max}$ represent the min/max values they can assume.

5. Voltage constraint at each bus

$$V_{i,s}^{\min} \le V_{i,s} \le V_{i,s}^{\max} \tag{3.8}$$

where, $V_{i,s}^{\min}$/ $V_{i,s}^{\max}$ are the min/max values they can assume.

3.6 Uncertainty Modelling Process

The uncertainties of wind speed and load demand are modelled by Scenario-based approach which can be defined as a probable realization of an uncertain parameter. In this work, 24 scenarios are generated using probability density function (PDF) of each wind speed and load demand.

3.6.1 Wind Speed Modelling

The behaviour of wind power generation usually is modelled by Weibull probability density function (PDF) [327-329]. Weibull PDF is based on a comparison of actual wind speed at different sites and wind speed estimated using the Weibull PDF. The PDF for this distribution is given by [330, 331]:

$$f_w(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} \exp\left[-(\frac{v}{c})^k\right] \tag{3.9}$$

where v , c and κ are respectively the wind speed, the scale index and the shape index.

In order to combine the output power which, introduce by WTs, the continuous PDF has been divided into states with tacking into account the specific limits of wind speed. The probability of every state is calculated using the following equation:

$$\pi_w = \int_{v_{w1}}^{v_{w2}} f_r(v)\,dv \tag{3.10}$$

$$v_s = \frac{v_{w1} + v_{w2}}{2} \tag{3.11}$$

where v_{w1} and v_{w2} are the starting and ending points of the wind speed's interval in state w, respectively.

Hence, the active power which is generated by WTs can be determined by using its power curve as follows [331, 332]:

$$P_w(v) = \begin{cases} 0, & 0 \le v \le v_{ci} \\ P_{rated} \times \frac{v - v_{ci}}{v_r - v_{ci}}, & v_{ci} \le v \le v_r \\ P_{rated}, & v_r \le v \le v_{co} \\ 0, & v_{co} \le v \end{cases} \tag{3.12}$$

where v_{ci}, v_r and v_{co} are the cut-in speed, rated speed and cut-off speed of the WTs, respectively. where P_w is the generated power of WTs, P_{rated} is the rated power. Figure 3-2 shows the speed power curve of WTs.

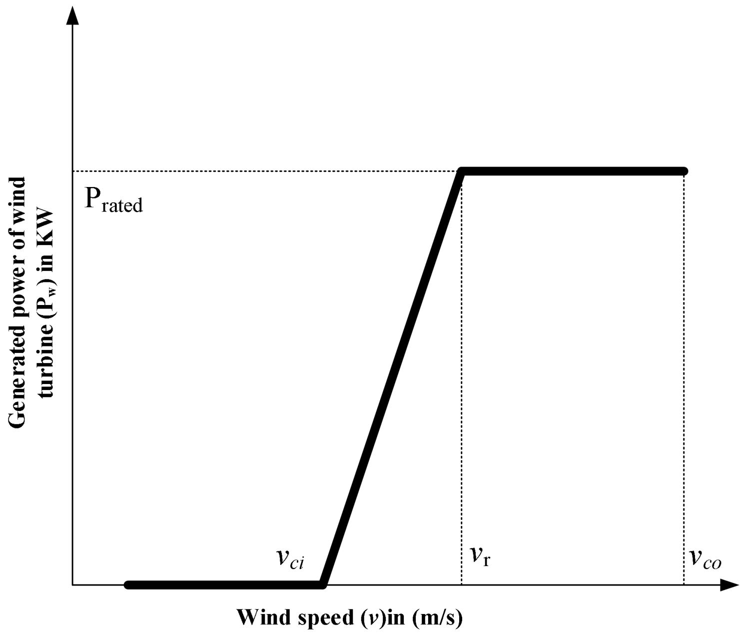


Figure 3- 2 the idealised power curve of a wind turbine

Therefore, the active and reactive wind power at bus *i*, and scenario *s* are calculated as follows:

$$0 \le P_{i,s}^{w} \le \gamma_{i,s}^{w} \times P_{i,rated}^{w} \quad (3.13)$$

$$0 \le Q_{i,s}^{w} \le \gamma_{i,s}^{w} \times Q_{i,rated}^{w} \quad (3.14)$$

where $\gamma_{i,s}^{w}$ is the percentage of active and reactive power which are generated by WTs at scenario

3.6.2 Load Modelling

The load demands at each bus are also modelled using a Normal PDF [333]. The PDF of the normal distribution for uncertain load l is [334-336]:

$$PDF(l) = \frac{1}{\sigma_l\sqrt{2\pi}} \times \exp\left[-\left(\frac{(l-\mu_l)^2}{2\sigma_l^2}\right)\right] \tag{3.15}$$

where, μ_l and σ_l are the mean and standard deviation, respectively.

The load will be divided into four levels (states) using a clustering technique, which verifies that choosing four states with different probabilities provides a reasonable trade-off between accuracy and fast numerical evaluation. Table 3.1 shows the four states accompanied by their probabilities.

Table 3- 1 Combined wind and load states and corresponding probabilities

State #	Load (%)	Wind (%)	π_s	State #	Load (%)	Wind (%)	π_s
s_1	100.00	100.00	0.0008	s_{13}	55.00	100.00	0.0120
s_2	100.00	85.30	0.0030	s_{14}	55.00	85.30	0.0450
s_3	100.00	58.50	0.0080	s_{15}	55.00	58.50	0.1200
s_4	100.00	40.60	0.0025	s_{16}	55.00	40.60	0.0375
s_5	100.00	35.10	0.0010	s_{17}	55.00	35.10	0.0150
s_6	100.00	00.00	0.0006	s_{18}	55.00	00.00	0.0090
s_7	75.00	100.00	0.0088	s_{19}	35.00	100.00	0.0024
s_8	75.00	85.30	0.0330	s_{20}	35.00	85.30	0.0090
s_9	75.00	58.50	0.0880	s_{21}	35.00	58.50	0.0240
s_{10}	75.00	40.60	0.0275	s_{22}	35.00	40.60	0.0075
s_{11}	75.00	35.10	0.0110	s_{23}	35.00	35.10	0.0030
s_{12}	75.00	00.00	0.0066	s_{24}	35.00	00.00	0.0018

3.6.3 Combined Generation-Load Model

The wind speed and the load states are assumed to be independent in order to construct the whole set of scenarios by combining scenarios as follows [337]:

$$\pi_s = \pi_D \times \pi_w \tag{3.16}$$

where π_D and π_w are the probabilities of demand load and wind states. Table 3-1 gives combined wind and load states and corresponding probabilities.

3.7 Case study and Simulation Results

The following analyses are based on 33kV, 16-bus UK generic distribution system (UKGDS) and its data are available in [338]. Here, it is assumed that three WTs are installed at bus 3, 10 and 13. The voltage limits are assumed to be between Vmin=0.94 p.u and Vmax= 1.06 p.u. The power factor of WTs assumed to be 0.95 lagging. The total peak demand for active and reactive power are 38.2MW and 7.7 MVAr, respectively. Figure 3-3 shows the single-line diagram of 16-bus UKGDS. It is assumed that 660 kW WTs are installed at candidate buses. Normal and Weibull PDF are used to model four states for demand loads and six states for WTs, respectively. The corresponding probabilities of combined load demand and wind states are presented in Table 3-1.

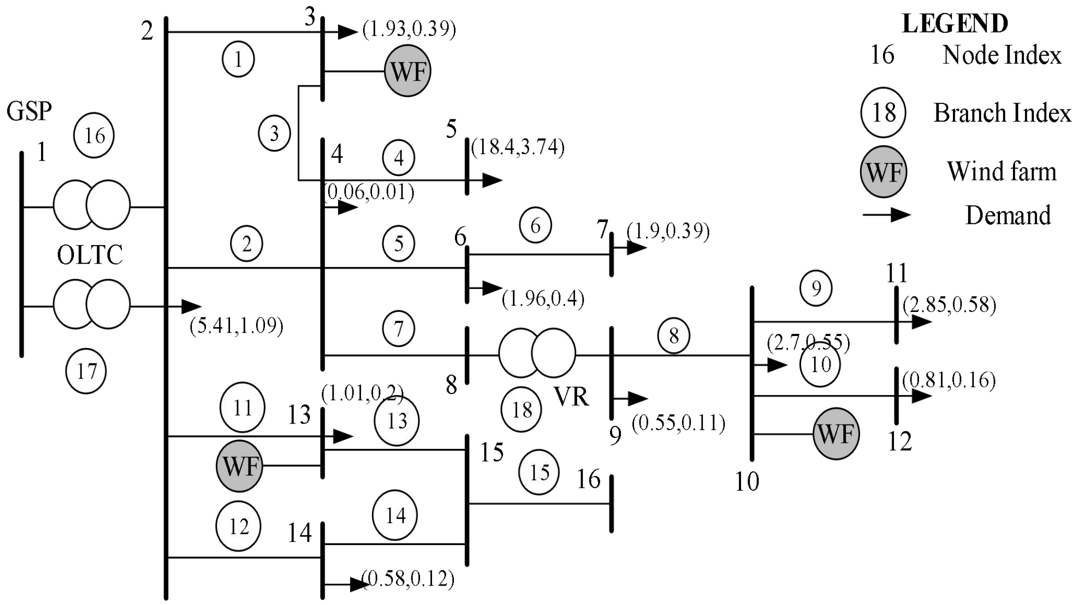


Figure 3- 3 Single- line diagram of 16-bus UKGDS

The active and reactive bid prices of loads are respectively presented in Tables 3-2 and 3-3. It is assumed that there are three blocks for each maximum demand load. The active and reactive offer prices of substation are assumed to be 160 £/MWh and 120 £/ MVArh, while for WTs are 70£/MWh and 50 £/MVArh respectively. [159, 326, 339, 340].

Table 3- 2 Active bid prices for the loads

Bus No.	Active power bid price Blocks (MW@£/MWh)		
	b1	b2	b3
2	2.50@280	1.90@260	1.01@250
3	1.10@260	0.70@250	0.13@230
4	0.03@260	0.02@250	0.01@240
5	9.20@250	6.10@240	3.10@230
6	1.10@240	0.60@230	0.26@230
7	0.90@250	0.60@220	0.40@220
9	0.22@220	0.19@220	0.15@220
10	1.40@220	0.90@210	0.40@200
11	1.60@210	0.80@200	0.45@200
12	0.40@220	0.26@200	0.15@190
13	0.70@200	0.20@190	0.11@170
14	0.30@190	0.20@180	0.08@170

Table 3- 3 Reactive bid prices for the loads

Bus No.	Reactive power bid price Blocks MVAr@£/MVArh		
	b1	b2	b3
2	0.600@240	0.300@220	0.190@210
3	0.210@220	0.120@210	0.060@190
4	0.005@220	0.003@210	0.002@200
5	2.100@210	1.200@110	0.440@190
6	0.200@200	0.150@190	0.050@190
7	0.210@210	0.100@180	0.080@180
9	0.060@180	0.030@180	0.020@180
10	0.220@180	0.190@170	0.150@160
11	0.300@170	0.200@160	0.080@160
12	0.090@180	0.060@160	0.030@150
13	0.100@160	0.070@150	0.030@130
14	0.060@150	0.040@140	0.020@130

The proposed method has been implemented in GAMS environment and the non-linear program solved using IPOPT solver [341] on a PC with Core i7 CPU and 16 GB of RAM. Market-based active and reactive optimal power flow is used to maximize the social welfare subject to network constraints. Figures. 3-4 and 3-5 show the total dispatched active and reactive power generated by WTs in all scenarios at buses 3, 10 and 13.

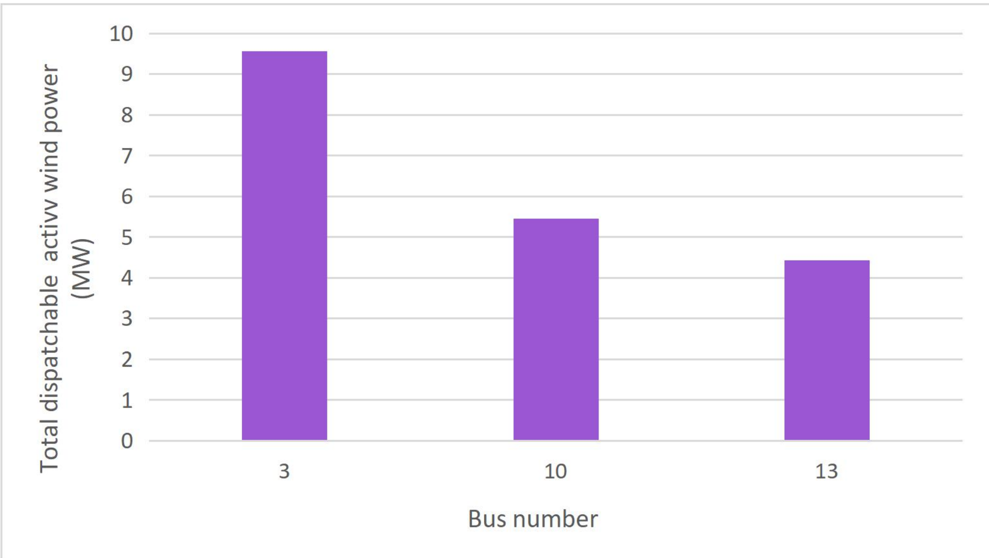


Figure 3- 4 Total dispatched active power at candidate buses in all scenarios

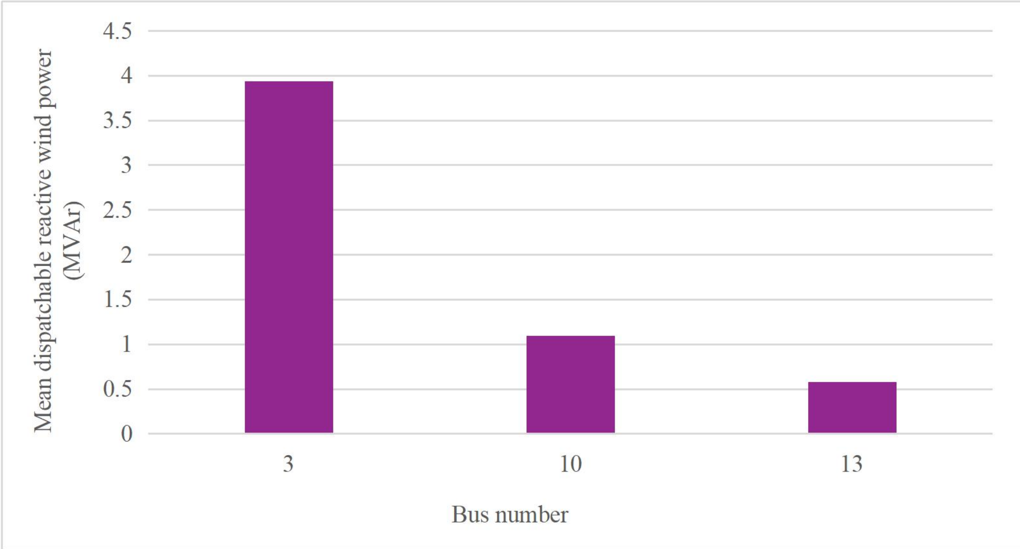


Figure 3- 5 Total dispatched reactive power at candidate buses for all scenarios

Bus 3 and bus 13 have respectively the highest and lowest dispatched active and reactive power compared to bus 10. The dispatched active and reactive power by WTs at each bus is limited by WTs' active and reactive offer prices, bid prices of active and reactive loads, and voltage constraints at each bus and thermal limits of the lines.

Fig. 3-6 shows the social welfare (SW) in each scenario. In scenario 15, SW has the highest amount which is equal to about 52 £/h which is due to the highest probability of this scenario compared to other ones (i.e. 0.12) as presented in Table 3-1.

Figs. 3-7 and 3-8 show the active and reactive D-LMPs at candidate buses. Bus 3 has the lowest active and reactive D-LMPs whereas bus 13 has the highest active and reactive D-LMPs. This is mainly due to the highest and lowest dispatched active and reactive power at these buses respectively.

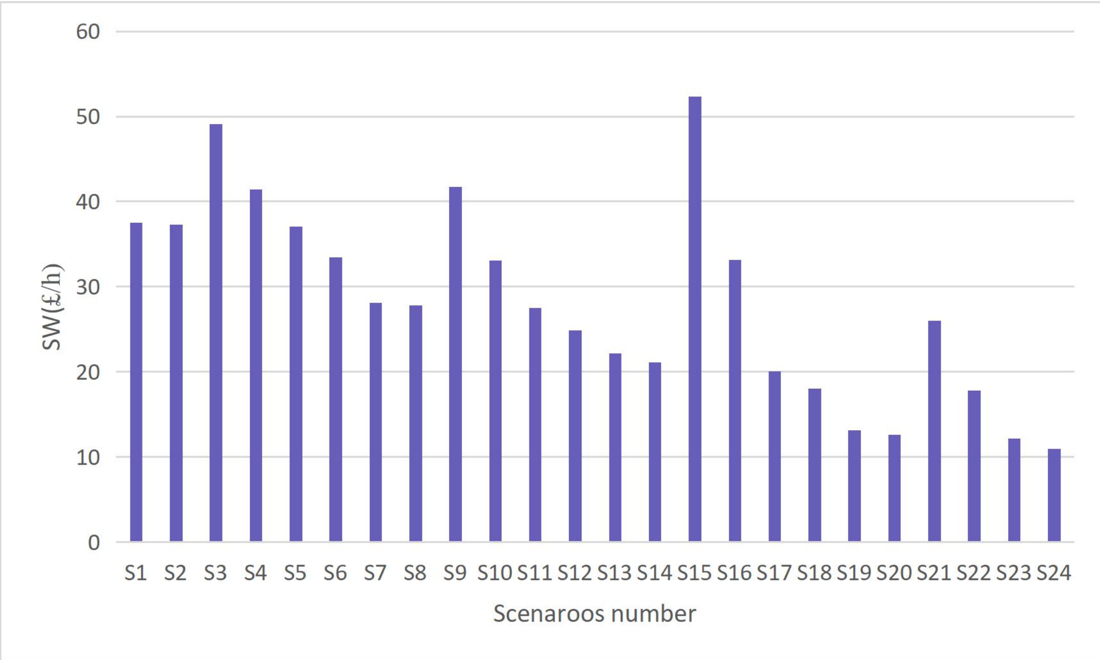


Figure 3- 6 Social welfare for each scenario

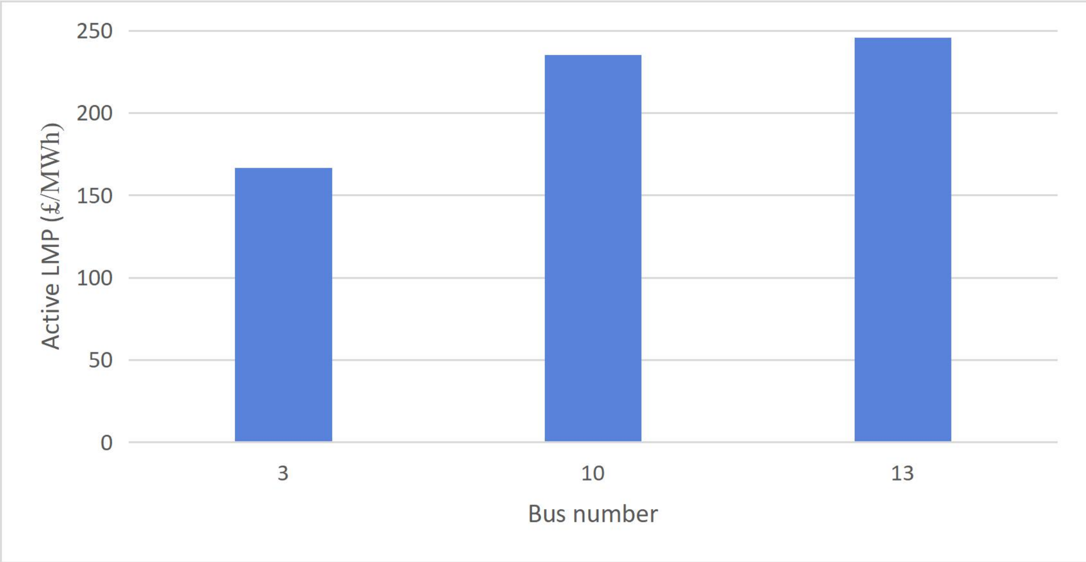


Figure 3- 7 Active D-LMP at candidate buses for all scenarios

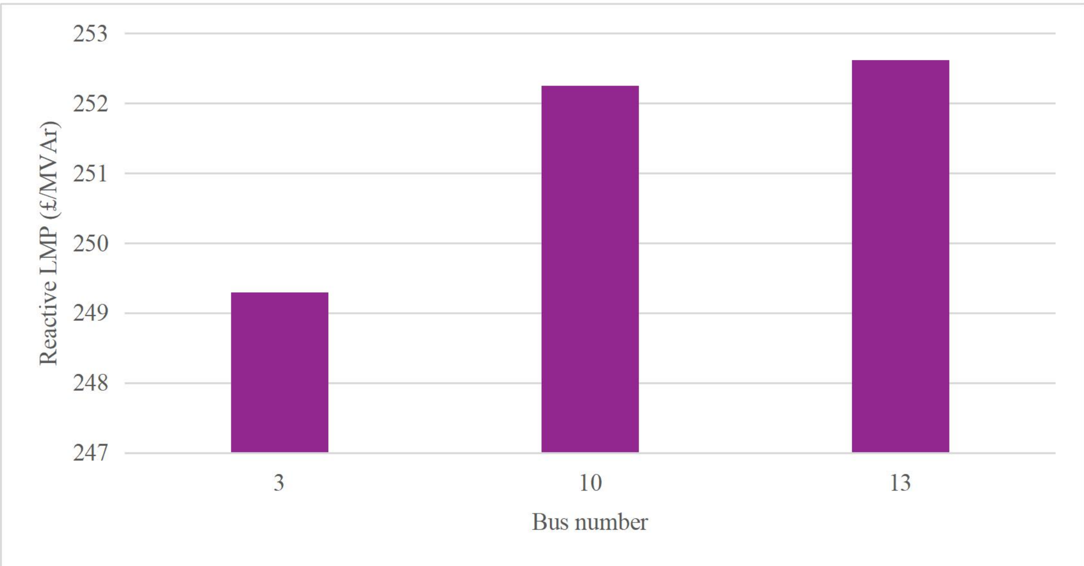


Figure 3- 8 Reactive D-LMP at candidate buses for all scenarios

3.8 Conclusions

idea novel electricity market at distribution level for was proposed. . A stochastic approach has been proposed to evaluate the amount of active and reactive power that can be injected/absorbed to/from the grid from WTs. A scenario-based approach has been used to model the uncertainty related to wind speed and load demand. The impact of wind power penetration on the SW and on active and reactive D-LMPs from the point of view of DNOs was investigated. In addition, the proposed method has investigated the impact of the amount of active and reactive power that WTs can inject/absorb to the grid on active and reactive D-LMPs SW.

Chapter 4 Optimal Operation of Distribution Networks

4.1 Introduction

Utilization of renewable energy sources (RES) such as wind turbines (WTs) and photovoltaic (PV) cells are taking substantial attention around the world due to the economic and environmental concerns [17-21]. The intermittent behavior of wind speed and solar irradiance introduces technical challenges such as voltage stability, voltage deviation and power losses to distribution network operators (DNOs) [22, 23]. DNOs have to introduce a reasonable operating strategy to model the uncertainties of electric loads and intermittent power generations of WTs, PVs. Also, demand response (DR) has been introduced in [342] as an option to mitigate the impact of uncertainties and intermittencies of wind speed and solar irradiance and improving the system's efficiency. DR is defined as the ability of consumers to alter their electricity demand in order to keep the reliability of system [165, 343].

Under the deregulation of electric power systems, the integration of distributed generator (DG) and DR program is becoming the most beneficial way to provide ancillary services in power networks [24-26]. Ancillary services can be defined as a set of services required to support the transmission of electric power from supply to demand to maintain power system security and reliability [344]. Ancillary services are classified as active power ancillary service (load frequency control) and reactive power ancillary service (voltage control) [345]. Most of the researches are carried out about the impact of active power ancillary services as the main services in electricity markets at transmission level; for instance, Ref. [346] illustrates how frequency control constraints can be obtained and involved into a market dispatch algorithm. In [347] a new frequency control market is introduced in order to host frequency response reserve offers from both loads and generators. Ref. [348] introduces the flexible frequency operation strategy of power system with high renewable penetration in order to gain the flexibility of the power grids. Absence of reactive power ancillary services may cause voltage instability all over the power network and lead to voltage collapse which is the main reason for blackouts [349]. Supporting the reactive power ancillary services is considered as a part of distribution network operators' (DNOs) activities.

This chapter considers a stochastic approach for the operation of active distribution networks within an active and reactive distribution market environment but covering PVs and demands response. In addition, even the same principle method was applied to maximize the social welfare using market-based active and reactive optimal power flow (OPF) but Scenario-Tree technique was employed to model the uncertainties related to solar irradiance, wind speed and load demands. Further analysis have been performed to investigate the impact of solar and wind power penetration on the active and reactive distribution locational prices (D-LMPs) within the distribution market environment; in which a mixed-integer linear programming (MILP) is applied to recast the proposed model. This study also uses the 16-bus UK generic distribution system (UKGDS) applied in previous chapter.

4.2 Related Research Work

In general, the reactive power markets can be cleared separately or simultaneously from active power markets. In reactive power markets, the market structure, payment mechanism and pricing model are main factors for determining the appropriate components of reactive power market [27]. Recently, most published papers have discussed the impact of reactive ancillary services in transmission systems; for example, in [28], a quadratic reactive power cost model for transmission system has been proposed to optimize reactive power procurement. Pay-as-bid pricing mechanism for reactive power market in the transmission system which takes into account the local nature of reactive power during the clearing of reactive power has been introduced in [322]. In [350] active and reactive power markets at transmission level are implemented to present interaction between energy market and reactive markets.

However, a few papers have discussed the reactive power market at distribution level. For instance, in [351], a settlement procedure for reactive power market for DGs in distribution systems has been proposed for reactive/voltage ancillary services to minimize reactive power payment by DNOs. Ref [352] discusses the application of a sustainable operational scheduling method which systematically focuses on a day-ahead active and reactive power markets at distribution level in order to dispatch active and reactive powers in distribution systems with WTs. The operation of distribution networks within reactive power market still suffers from lack of attention in the existing studies on. In addition, these studies did not consider the joint active and reactive power market model at the distribution level to maximize the social welfare (SW). Table 1 provides a comprehensive comparison of the existing studies and the proposed method. The current work proposes a methodology for operation of distribution network within a novel joint active and reactive power market at distribution level with integration of DR. A stochastic approach is used to evaluate the amount of wind and solar power penetration on the SW and active and reactive distribution locational marginal prices (D-LMPs) taking into account the uncertainties related to wind speed, solar irradiance, and load demand.

Table 4- 1 Comparison of the proposed method with existing ones

Reference	**Transmission or distribution level**	**Renewable-energy**	**Correlation**	**DR**	**Power market**		**SW**
					Active	Reactive	
[342]	Transmission	Yes	Yes	Yes	Yes	No	No
[343]	Transmission	Yes	No	No	Yes	No	No
[24]	Transmission	Yes	No	Yes	Yes	No	No
[25]	Distribution	No	No	Yes	Yes	No	Yes
[346-348]	Transmission	Yes	No	No	Yes	No	No
[27, 28, 322]	Transmission	No	No	No	No	Yes	No
[350]	Transmission	No	No	No	Yes	Yes	No
[351, 352]	Distribution	Yes	No	No	Yes	Yes	No
Proposed	**Distribution**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

4.3 Summarized Contributions to Present Work

To the best of our knowledge, none of the above studies introduced a stochastic approach for the operation of distribution networks within the proposed joint active and reactive power market model by maximizing the social welfare which is the gap that this work aims to fill it.

In summary, the main contributions of this paper are listed as follows:

1. To propose a MILP optimization approach for operation of distribution networks within a proposed joint active and reactive distribution with integration of DR.

2. To design and develop a joint active and reactive electricity market model at distribution level.
3. To model the correlated uncertainties associated with wind speed, solar irradiation and load demand using Scenario-Tree approach.

4.4 Uncertainty Modeling

In addition to the modelling process applied in previous chapter, this section adds the new modelling package of software that includes the solar irradiance modelling. A detailed of such model is explained in the following section.

4.4.1 Solar irradiance modelling

The solar irradiance is modelled using Beta PDF which is described as follows:

$$PDF(s)=\begin{cases}\dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)}\times s^{\alpha-1}\times(1-s)^{\beta-1}, & 0\le s\le 1, 0\le\alpha,\beta\\ 0 & else\end{cases} \tag{4.1}$$

where *s* represents the solar irradiance (kW/m^2). α And β which are the parameters of Beta PDF are derived as follows:

$$\beta=(1-\mu)\times\left(\frac{\mu\times(1-\mu)}{\sigma^2}-1\right) \tag{4.2}$$

$$\alpha=\frac{\mu\times\beta}{1-\mu} \tag{4.3}$$

Where μ and σ are the mean and standard deviation of the random variable. Eqns. (4.4) and (4.5) are used to estimate the output power of PV, the solar irradiance and the cell temperature as follow [353, 354]:

$$P_{pv} = P_{STC}\left\{\frac{G}{1000}\left[1+\delta\left(T_{cell}-25\right)\right]\right\} \tag{4.4}$$

$$T_{cell} = T_{amb} + \left(\frac{NOCT-20}{800}\right)G \tag{4.5}$$

where P_{pv} is the output power in MW, P_{STC} is the power under standard test condition in MW, δ is the power- temperature coefficient in (%/°C), T_{cell} is the cell temperature in °C, T_{amb} is the ambient temperature in °C, $NOCT$ are the national operating cell temperature conditions in *°C*, G ,is the avarrage solar irradiance in (W/m^2).

4.4.2 Modelling approach

In this section, based on "duration curve" [355-358], the model of the correlated uncertainties related to wind speed, solar irradiance and load demand are obtained by the cumulative distribution function (CDF) for each block. The procedure is the following:

- The historical data for hourly demand, wind speed and solar irradiation must be available in order to present the model. Historical data of wind speed and solar irradiance for 8760 hours are described in Fig. 2, which are used in the same period as load demand. Historical data are separated into load demand, wind speed and solar irradiation, respectively, in order to obtain the factorized data.

- The obtained factorized data are used to build the load demand curve which are arranged from higher to lower values keeping the correlation between the different hourly data of load demand, wind speed and solar irradiance as shown in Fig.4-1.
- Time blocks are set to determine the load duration curve and its length varies along the load duration in order to carefully consider the load demand in the model. For each time block load demand, wind speed and solar irradiance are arranged in descending order.
- The CDF of the load demand, wind and PV factors is calculated for each block.
- Each CDF is divided into segments with their corresponding associated probability (i.e. number of demand levels which can achieved in every time block).
- The scenarios are formulated for each time block by combination of the levels of uncertain data. Thus, for each load level *ll*, each scenario *s* comprises an average demand factor $\mu_{ll,s}^{D}$, a maximum level of wind power $\mu_{ll,s}^{w}$ and the maximum level of PV power $\mu_{ll,s}^{\theta}$.
- The total number of scenarios is 108, which was obtained by multiplication of four-time blocks, three load demand levels, three wind speed levels, three solar irradiation levels (4×3×3×3=108).

It should be noted that the model is applicable for all periods of the day.

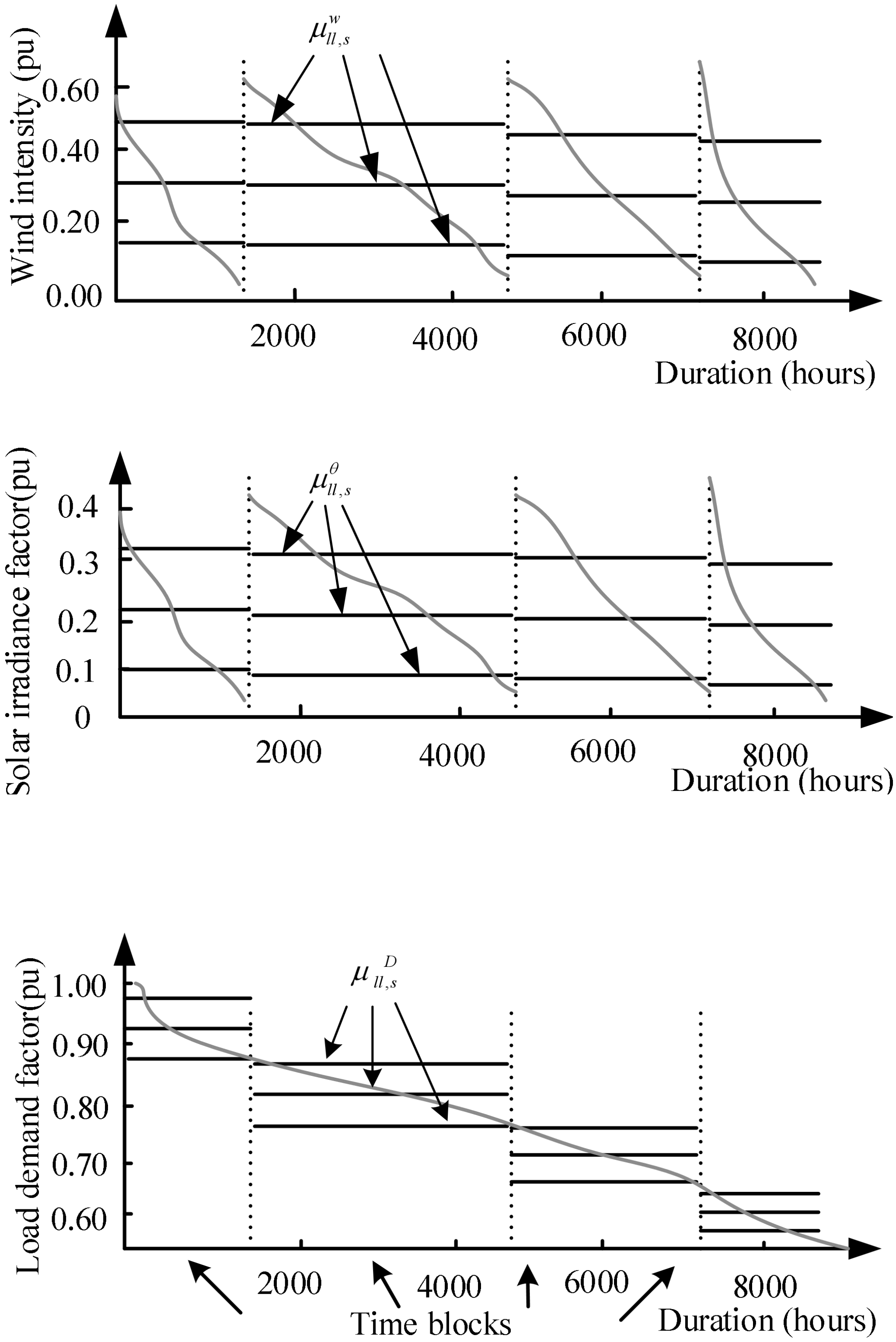


Figure 4-1 Load demand, wind speed, solar irradiance and offer prices of wind and PV curves and levels

Table 4- 2 load demand, WT and PV scenarios

Number Of Scenarios	Demand block	Number of Hours	Demand level	Wind	Solar
1	1	1200	0.967	0.436	0.336
2	1	1200	0.967	0.436	0.167
3	1	1200	0.967	0.436	0.102
4	1	1200	0.967	0.267	0.336
5	1	1200	0.967	0.267	0.167
6	1	1200	0.967	0.267	0.102
7	1	1200	0.967	0.122	0.336
8	1	1200	0.967	0.122	0.167
9	1	1200	0.967	0.122	0.102
10	1	1200	0.921	0.436	0.336
11	1	1200	0.921	0.436	0.167
12	1	1200	0.921	0.436	0.102
13	1	1200	0.921	0.267	0.336
14	1	1200	0.921	0.267	0.167
15	1	1200	0.921	0.267	0.102
16	1	1200	0.921	0.122	0.336
17	1	1200	0.921	0.122	0.167
18	1	1200	0.921	0.122	0.102
19	1	1200	0.875	0.436	0.336
20	1	1200	0.875	0.436	0.167
21	1	1200	0.875	0.436	0.102
22	1	1200	0.875	0.267	0.336
23	1	1200	0.875	0.267	0.167
24	1	1200	0.875	0.267	0.102
25	1	1200	0.875	0.122	0.336
26	1	1200	0.875	0.122	0.167
27	1	1200	0.875	0.122	0.102
28	2	3600	0.873	0.401	0.301
29	2	3600	0.873	0.401	0.223
30	2	3600	0.873	0.401	0.102
31	2	3600	0.873	0.223	0.301
32	2	3600	0.873	0.223	0.223
33	2	3600	0.873	0.223	0.102
34	2	3600	0.873	0.122	0.301
35	2	3600	0.873	0.122	0.223
36	2	3600	0.873	0.122	0.102
37	2	3600	0.831	0.401	0.301
38	2	3600	0.831	0.401	0.223
39	2	3600	0.831	0.401	0.102
40	2	3600	0.831	0.223	0.301
41	2	3600	0.831	0.223	0.223

42	2	3600	0.831	0.223	0.102
43	2	3600	0.831	0.122	0.301
44	2	3600	0.831	0.122	0.223
45	2	3600	0.831	0.122	0.102
46	2	3600	0.789	0.401	0.301
47	2	3600	0.789	0.401	0.223
48	2	3600	0.789	0.401	0.102
49	2	3600	0.789	0.223	0.301
50	2	3600	0.789	0.223	0.223
51	2	3600	0.789	0.223	0.102
52	2	3600	0.789	0.122	0.301
53	2	3600	0.789	0.122	0.223
54	2	3600	0.789	0.122	0.102
55	3	2400	0.793	0.365	0.265
56	3	2400	0.793	0.365	0.223
57	3	2400	0.793	0.365	0.092
58	3	2400	0.793	0.223	0.265
59	3	2400	0.793	0.223	0.223
60	3	2400	0.793	0.223	0.092
61	3	2400	0.793	0.112	0.265
62	3	2400	0.793	0.112	0.223
63	3	2400	0.793	0.112	0.092
64	3	2400	0.755	0.365	0.265
65	3	2400	0.755	0.365	0.223
66	3	2400	0.755	0.365	0.092
67	3	2400	0.755	0.223	0.265
68	3	2400	0.755	0.223	0.223
69	3	2400	0.755	0.223	0.092
70	3	2400	0.755	0.112	0.265
71	3	2400	0.755	0.112	0.223
72	3	2400	0.755	0.112	0.092
73	3	2400	0.717	0.365	0.265
74	3	2400	0.717	0.365	0.223
75	3	2400	0.717	0.365	0.092
76	3	2400	0.717	0.223	0.265
77	3	2400	0.717	0.223	0.223
78	3	2400	0.717	0.223	0.092
79	3	2400	0.717	0.112	0.265
80	3	2400	0.717	0.112	0.223
81	3	2400	0.717	0.112	0.092
82	4	1560	0.682	0.351	0.251
82	4	1560	0.682	0.351	0.251
83	4	1560	0.682	0.351	0.174
84	4	1560	0.682	0.351	0.085
85	4	1560	0.682	0.194	0.251
86	4	1560	0.682	0.194	0.174
87	4	1560	0.682	0.194	0.085
88	4	1560	0.682	0.095	0.251

89	4	1560	0.682	0.095	0.174
90	4	1560	0.682	0.095	0.085
91	4	1560	0.649	0.351	0.251
92	4	1560	0.649	0.351	0.174
93	4	1560	0.649	0.351	0.085
94	4	1560	0.649	0.194	0.251
95	4	1560	0.649	0.194	0.174
96	4	1560	0.649	0.194	0.085
97	4	1560	0.649	0.095	0.251
98	4	1560	0.649	0.095	0.174
99	4	1560	0.649	0.095	0.085
100	4	1560	0.617	0.351	0.251
101	4	1560	0.617	0.351	0.174
102	4	1560	0.617	0.351	0.085
103	4	1560	0.617	0.194	0.251
104	4	1560	0.617	0.194	0.174
105	4	1560	0.617	0.194	0.085
106	4	1560	0.617	0.095	0.251
107	4	1560	0.617	0.095	0.174
108	4	1560	0.617	0.095	0.085

4.5 Distribution Market Model and Formulation

A joint active and reactive market model at the distribution level is proposed in this section. The structure of proposed market is based on bilateral contracts or pool within DNOs control zone, which is shown in Figure 3-1.

Under the proposed distribution market, both price and market clearing quantity are calculated by maximizing SW taking into consideration network constraints with integration of DR. The optimization problem is formulated in the following as the sum of the total consumers' benefits minus the sum of DR cost and the sum of the total generation costs (substation, WTs and PVs).

Maximize SW = (4.6)

$$\left(\sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{l,P} P_{i,s}^{l} + \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{l,Q} Q_{i,s}^{l}\right)$$
$$-\left(\sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{DR,P} P_{i,s}^{DR} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{DR,Q} Q_{i,s}^{DR}\right)$$
$$-\left(\begin{array}{l}\sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,P} P_{i,s}^{ss} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,Q} Q_{i,s}^{ss}\\ +\sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{w,P} P_{i,s}^{w} + \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{pv,p} P_{i,s}^{pv}\\ +\sum_{i=1}^{NB} QPF_i^{w,pv}\end{array}\right)$$

Subject to Kirchhoff's current law, one can obtain the following:

$$\sum P_{i,s}^{ss} + \sum P_{i,s}^{w} + \sum P_{i,s}^{pv} - \sum P_{i,s}^{l} - \sum P_{i,s}^{DR} = f_{i,j,s} - f_{j,i,s} \tag{4.7}$$

$$\sum Q_{i,s}^{ss} + \sum Q_{i,s}^{w} + \sum Q_{i,s}^{pv} - \sum Q_{i,s}^{l} - \sum Q_{i,s}^{DR} = f_{i,j,s} - f_{j,i,s} \tag{4.8}$$

And for Kirchhoff's voltage law, the equation reduced to:

$$u_{i,j}\left[R_{i,j} f_{i,j,s} - (v_{i,s} - v_{j,s})\right] = 0 \tag{4.9}$$

$$u_{i,j}\left[X_{i,j} f_{i,j,s} - (v_{i,s} - v_{j,s})\right] = 0 \tag{4.10}$$

Active and reactive power capacity constraints at substation and WTs has been defined in Eqns. (3.4), (3.5), (3.6) and (3.7). In addition, the active power capacity constraints of PVs could be illustrated as follows:

$$P_{i,s}^{pv,\min} \le P_{i,s}^{pv} \le P_{i,s}^{pv,\max} \tag{4.11}$$

$$Q_{i,s}^{pv,\min} \le Q_{i,s}^{pv} \le Q_{i,s}^{pv,\max} \tag{4.12}$$

Following the above, the voltage and current constraint at each bus can be expressed as follows:

$$V_{i,s}^{\min} \le V_{i,s} \le V_{i,s}^{\max} \tag{4.13}$$

$$-u_{i,j}\,\bar{F}_{i,j,s} \le f_{i,j,s} \le u_{i,j}\,\bar{F}_{i,j,s} \tag{4.14}$$

On top of the above, the DR constraints can bes stated as follows:

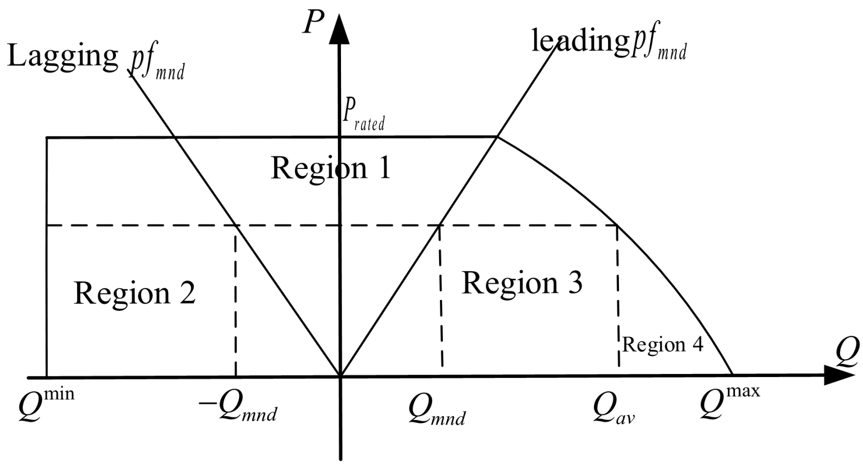
$$0 \le P_{i,s}^{DR} \le P_{i,s}^{DR,\max} \tag{4.15}$$

$$0 \le Q_{i,s}^{DR} \le Q_{i,s}^{DR,\max} \tag{4.16}$$

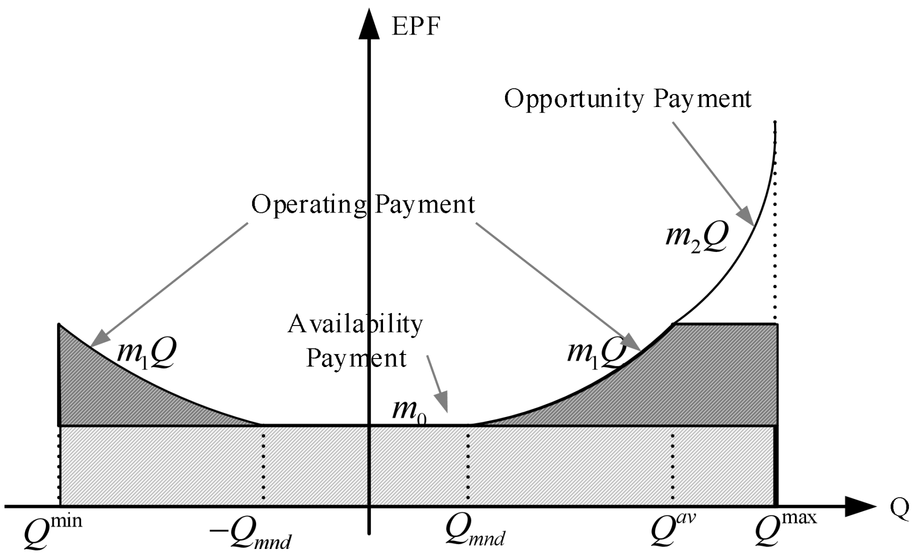
The objective function (4.6) consists of three terms: 1) consumer benefit, 2) DR cost, (3) generation cost (substation and WTs and PVs). In the proposed market, reactive power offer price of substation is assumed to be fixed. The Kirchhoff's current and voltage laws are represented in Eqns.(4.7)-(4.10) respectively. The binary variable $u_{i,j}$ is related with every feeders in order to model its utilization. The active and reactive power which are supplied by PVs are limited by the minimum between their capacities and the maximum power availability in Eqns. (4.11) and (4.12). WTs and PVs' power limits depend on wind speed and solar irradiance. Upper and lower limits in Eqns. (4.13) and (4.14) represent the voltage and current constraints at each bus respectively. DR constraints have been introduced in Equations (4.15) and (4.16).

4.6 Offer structure for reactive power

Based on the capability curve of WTs and PVs shown in Fig. (4-2a), reactive power payment structure is divided into four regions[352, 359] as follows:



a) capability curve of renewable DGs



b) reactive power offer structure

Figure 4- 2 a) Reactive power capability curve, b) reactive power offer structure

Region 1($-Q_{mnd}$ to Q_{mnd}), Region 2(Q^{min} to $-Q_{mnd}$), Region 3 (Q_{mnd} to Q_{av}) and Region 4 (Q_{mnd} to Q^{max}): when WTs and PVs operate in region 1, it should receive only the payment (m_0) which is called availability payment. In regions

2 and 3, WTs and PVs should receive the availability and losses payments, because WTs and PVs in these regions will lose extra active power losses.

In region 4, the reactive power payment function should contain three payments, which are availability payment, losses payment and opportunity payment as the WTs and PVs lose the opportunity to sell active power. Eqn. (4.17) defines the maximum available reactive power, which is supply by WTs and PVs. The capability curve of WTs and PVs is defined in Eqn. (4.18). Based on the above classification of reactive power production payment, the reactive power payment (QPF) of WTs and PVs in these regions can be formulated as in Eqn. (4.19). Note that the opportunity offer of Q is a quadratic function, given by [360] :

$$Q = \left\{ \begin{array}{l} \sqrt{\left(V_t\, I_c\right)^2 - \left(P^{w,pv}\right)^2} \\ \sqrt{\left(\dfrac{V_t\, V_c}{X_c}\right)^2 - \left(P^{w,pv}\right)^2} - \dfrac{V_t^2}{X_c} \end{array} \right\} \tag{4.17}$$

$$QPF = \left\{ \begin{array}{ll} m_0 & -Q_{mnd} \le Q_i^{w,pv} \le Q_{mnd} \\ \frac{1}{2} m_1 \left((Q_1)^2 - (Q_{mnd})^2 \right) & Q_1 \le Q_i^{w,pv} \le -Q_{mnd} \\ \frac{1}{2} m_1 \left((Q_2)^2 - (Q_{mnd})^2 \right) & Q_{mnd} \le Q^{w,pv} \le Q_2 \\ \left(\begin{array}{l} \frac{1}{2} m_1 \left((Q_{av})^2 - (Q_{mnd})^2 \right) + \\ \frac{1}{2} m_2 \left((Q_3)^2 - (Q_{av})^2 \right) \end{array} \right) & Q_{mnd} \le Q^{w,pv} \le Q_{av}, Q_{av} \le Q^{w,pv} \le Q_3 \end{array} \right\} \tag{4.18}$$

$$QPF = Z_0 m_0 + Z_1 \frac{1}{2} m_1 \left((Q_1)^2 - (Q_{mnd})^2 \right)$$
$$+ Z_2 \frac{1}{2} m_1 \left((Q_2)^2 - (Q_{mnd})^2 \right)$$
$$+ Z_3 \left[\frac{1}{2} m_1 \left((Q_{av})^2 - (Q_{mnd})^2 \right) + \frac{1}{2} m_2 \left((Q_3)^2 - (Q_{av})^2 \right) \right] \quad (4.19)$$

where Z_0,Z_1,Z_2 and Z_3 are the binary variables which determine the compensation region of WTs and PVs. If the accepted unit is operated in region 1, then Z_o=1 and Z_1=Z_2=Z_3=0, in region 2, Z_0=Z_1=1 and Z_2=Z_3=0, in region 3, Z_0=Z_2=1 and Z_1=Z_3=0, in region 4, Z_0=Z_2=Z_3=1 and Z_1=0. Fig.4.b illustrates the QPF as function of reactive power generated by WTs and PVs. In addition, the equality and inequality constraints of WTs and PVs are given as follow:

$$Z_0, Z_1, Z_2, Z_3 \in \{0,1\} \quad (4.20)$$

$$-Z_0 Q_{mnd}^{w,pv} \le Q_0^{w,pv} \le Z_0 Q_{mnd}^{w,pv} \quad (4.21)$$

$$Z_1 Q_{\min}^{w,pv} \le Q_1^{w} \le -Z_1 Q_{mnd}^{w,pv} \quad (4.22)$$

$$Z_2 Q_{mnd}^{w,pv} \le Q_2^{w,pv} \le Z_2 Q_{av}^{w,pv} \quad (4.23)$$

$$Z_3 Q_{av}^{w,pv} \le Q_3^{w,pv} \le Z_3 Q_{\max}^{w,pv} \quad (4.24)$$

$$Q_{mnd}^{w,pv} = P^{W,PV} \tan\left(\cos^{-1}\left(pf_{mnd} \right) \right) \quad (4.25)$$

$$Q^{w,pv} = Q_0^{w,pv} + Q_1^{w,pv} + Q_2^{w,pv} + Q_3^{w,pv} \quad (4.26)$$

$$Z_1 + Z_2 + Z_{3,} \le Z_0 \quad (4.27)$$

Hence, in order to minimize the reactive power dispatch impact on the initial active power dispatch of WTs and PVs, a cap on the reduction in the active power is imposed, as follows,

$$\Delta P_i^{w,pv} \leq x_i^{w,pv} P_i^{w,pv,\text{int}} \tag{4.28}$$

where, $x_i^{w,pv}$ is the considered cap on reduction in the active power of WTs and PVs.

Note that the total reactive payment function QPF is nonlinear. In order to keep the problem linear, the quadratic function in (4.19) is linearized by piecewise linearization approach as in Eqns. (4.31) to (4.35) in below section.

4.7 Linearization Proposed Model

The proposed optimization problem is nonlinear, therefore, finding the global optimal solution it hard to obtain. The below linearization model was first proposed by Haffner et al. [361] which have been successfully implemented in [356]. The linearized network model is an adapted version of the dc model that is based on two assumptions: (i) all current injections and flows have the same power factor, and (ii) the per-unit voltage drop across a branch is equal to the difference between the per-unit magnitudes of the nodal voltages at both ends of the branch. Assumption (i) allows expressing Kirchhoff's current law as a set of linear scalar equalities in terms of current magnitudes. In addition, assumption (ii) allows formulating Kirchhoff's voltage law for branches in use as a linear expression relating the magnitudes of currents, nodal voltages, and branch impedances. The equivalent integer linear reformulation is shown in (4.29) and (4.30), where, M is a large enough positive constant and its impact is similar to Eqn. (4.7) and (4.8), that can be presented by:

$$-M(1-u_{i,j}) \le R_{i,j} f_{i,j,s} - (v_{i,s} - v_{j,s}) \le M(1-u_{i,j}) \quad (4.29)$$

$$-M(1-u_{i,j}) \le X_{i,j} f_{i,j,s} - (v_{i,s} - v_{j,s}) \le M(1-u_{i,j}) \quad (4.30)$$

$u_{i,j}$ is binary utilization variables for all feeders (substation, WTs and PV).

The linearization of the nonlinear formulation of QPF is carried out using piecewise linearization approach [362]. Equations (4.31)-(4.35) describe the linearization process as follows:

$$Q^2 = \sum_{l=1}^{L} (2l-1) \frac{Q^{max}}{L} \Delta Q_l \quad (4.31)$$

$$Q = Q^{(+)} - Q^{(-)} \quad (4.32)$$

$$Q^{(+)} \ge 0; \quad Q^{(-)} \ge 0 \quad (4.33)$$

$$Q^{(+)} + Q^{(-)} = \sum_{l=1}^{L} Q_l \quad (4.34)$$

$$\Delta Q_l \ge \Delta Q_{l+1} \quad (4.35)$$

In equation (4.31), the quadratic variable is linearized through piecewise linear approximation considering L number of segments. Q is divided into two parts, forward variable and reverse auxiliary flow variables so that it will only use the first quadrant of the quadratic curve as explained in equation (4.32). It is worthy to note that these variables cannot be nonzero and non-negative simultaneously as imposed by (4.33). Equation (4.34) guarantees that the step flow variables ΔQ_l equal to the flow. Equation (4.35) guarantees the successive filling of the partitions.

4.8 Case study for the Current Work

As noted earlier in this chapter the case study was already detailed in the previous chapter; however, in this chapter it is assumed that two WTs of 630kW are installed at the buses 6 and 11 and one PV unit of 220kW at the bus 13. The assumed limits for voltage were between V_{max}= 1.06 p.u and V_{min}=0.94 p.u. WTs and PV power factor was assumed to be 0.95 lagging. The total peak demand for active is 38.2MW and 7.7 MVAr for reactive power. The active and reactive offer price of the substation are 150 £/MWh and 70 £/MVArh. Table 4-2 provides the characteristics of load demand, wind speed and solar irradiance scenarios. Bid prices for active and reactive load demands are presented in Tables 4-3 and 4-4 respectively. It is assumed that for each load at maximum demand there are three blocks [326, 363]

Table 4- 3 Load active power bid prices

Bus No.	Bid price list for active power		
	Blocks (MW@£/MWh)		
	b_1	b_2	b_3
2	2.52@280	1.84@260	1.06@250
3	1.15@260	0.63@250	0.15@230
4	0.03@260	0.02@250	0.01@240
5	9.15@250	6.10@240	3.15@230
6	1.85@240	0.67@230	0.256@230
7	0.93@250	0.56@220	0.41@220
9	0.23@220	0.19@220	0.14@220
10	1.43@220	0.90@210	0.37@200
11	1.52@210	0.89@200	0.44@200
12	0.44@220	0.22@200	0.14@190
13	0.67@200	0.22@190	0.12@170
14	0.37@190	0.14@180	0.07@170

Table 4- 4 Load reactive power bid prices

Bus No.	Bid price list for reactive power		
	Blocks MVAr@£/MVArh		
	b_1	b_2	b_3
2	0.600@200	0.300@230	0.190@200
3	0.210@180	0.120@205	0.060@195
4	0.004@180	0.0035@210	0.0025@200
5	2.110@170	1.200@120	0.430@180
6	0.210@160	0.140@195	0.050@185
7	0.200@170	0.110@185	0.080@175
9	0.060@140	0.030@180	0.020@180
10	0.225@140	0.185@175	0.150@155
11	0.300@135	0.200@155	0.080@160
12	0.080@140	0.070@165	0.030@145

13	0.100@120	0.070@145	0.030@135
14	0.060@115	0.040@153	0.020@130

4.8.1 Active power quantity and the offer prices of WTs and PVs

In order to calculate the active power price for WTs and PVs, financial data of WTs and PVs are summarized in Table 4-5 [157, 230, 363, 364]. The annual cost of calculating offer price of WTs and PVs is explained as follows [157]:

$$Ann\_Cost = \frac{r(1+r)^n}{(1+r)^n - 1} \times Inst\_Cost \qquad (4.36)$$

where n is the depreciation period in year, r is the interest rate in (%), Inst_Cost and Ann_cost are the installation cost and the annual cost for depreciation, respectively. The capacity factor (the ratio of average power output to the rated power output) is evaluated according to the WTs and PVs data and their capability curve. The active power offer price of WTs and PVs is calculated by dividing the annual cost by the number of equivalent hours.

Table 4- 5 Financial statement for approximating active power offer price of WTs and PVs

Size	**WTs**	**PVs**
Installation cost (£/kW)	1200	1400
Number of equivalent hours (h)	4000	4000
Interest rate (%)	3	3
Depreciation time (years)	3	3
Capacity factor (%)	46	46

Annual cost (£/kW-year)	168.81	229.77
Active Offer Price (£/MWh)	**35.16**	**41.03**

4.8.2 Calculation of the reactive power and energy adjustment offer prices of WTs and PVs

According the offer structure of reactive power, a reactive offer prices are listed in Table 4-6.

Table 4- 6 Reactive power offer prices of WTs and PVs

	Qmax (kVAr)	Qmin KVAr	m_0 (£)	m_1 (£/MVar)	m_2 (£/MVar h)^2	m_{adj} £/MVar	X %
WTs	630	-220	0.082	0.015	0.35×10^{-3}	0.068	30
PVs	270	-60	0.068	0.013	0.42×10^{-3}	0.072	30

4.9 Simulation Results

In order to investigate the impact of DR program on dispatched active and reactive power, SW and active and reactive D-LMPs, two different cases are taken into account as presented in Table 4-7. For each case, total dispatched active, reactive power, active and reactive D-LMPs and SW are examined. Figs. 4-3 and 4-4 respectively show the total dispatched active and reactive power for cases A and B at each candidate bus. It is seen that the highest and lowest dispatched active and reactive power are related to buses 11 and 13, respectively. This is mainly due to voltage and thermal constrains at each bus, and active and reactive bid prices. It is evident that in case B, with DR integration, the total active and reactive power dispatched by WTs and PV is higher in comparison with those in case A.

Fig 4-5 shows the SW for both cases. It is seen that the SW is higher in case B compared to case A. This mainly due to DR integration and the higher dispatched active and reactive power in case B which allows increasing the SW.

The total active and reactive D-LMPs at candidate buses and both cases are shown in Figs. 4-6 and 4-7, respectively. The highest active and reactive D-LMPs are related to bus 13 and the lowest active and reactive D-LMPs to bus 11. This is because of the highest and lowest dispatched active and reactive power at these buses. It also observed that the active and reactive D-LMP decreases in case B by implementation DR program.

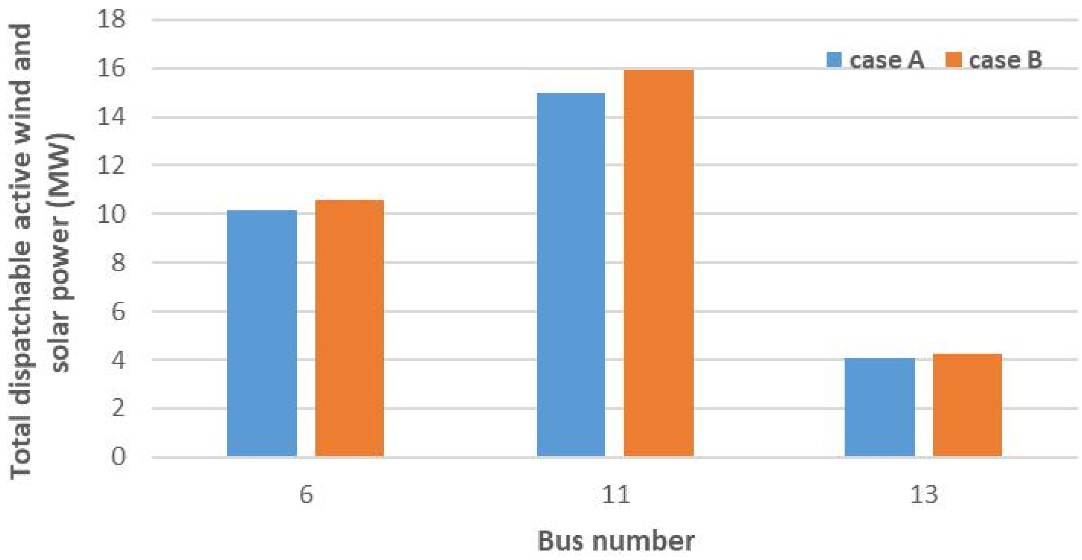


Figure 4- 3 Total dispatched active power at candidate buses

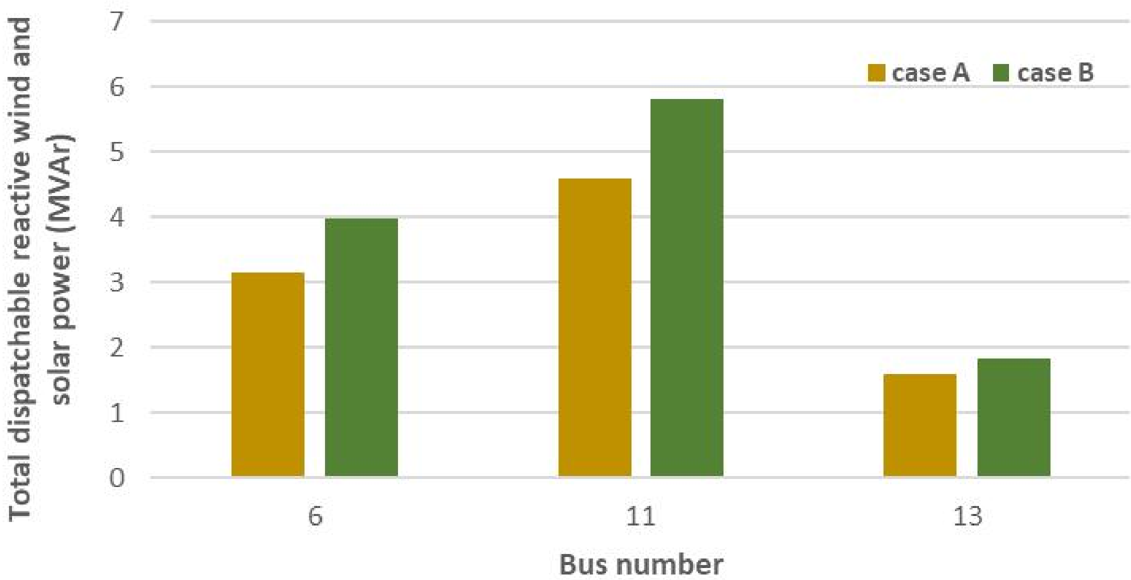


Figure 4- 4 Total dispatched reactive power at candidate buses

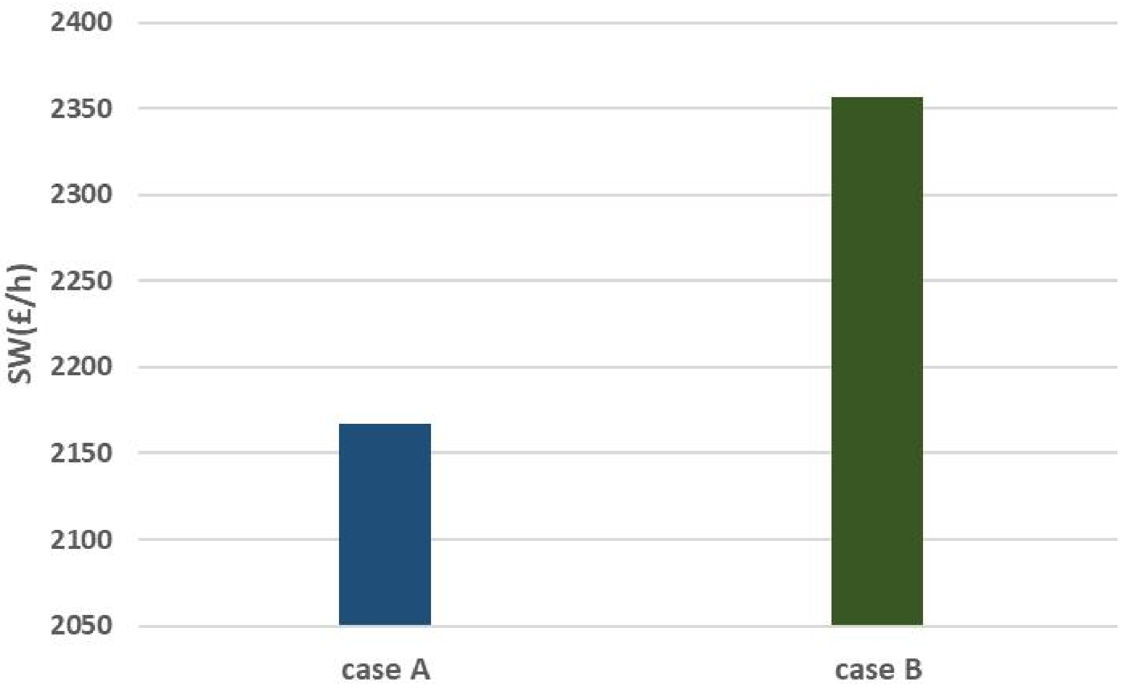


Figure 4- 5 Social welfare

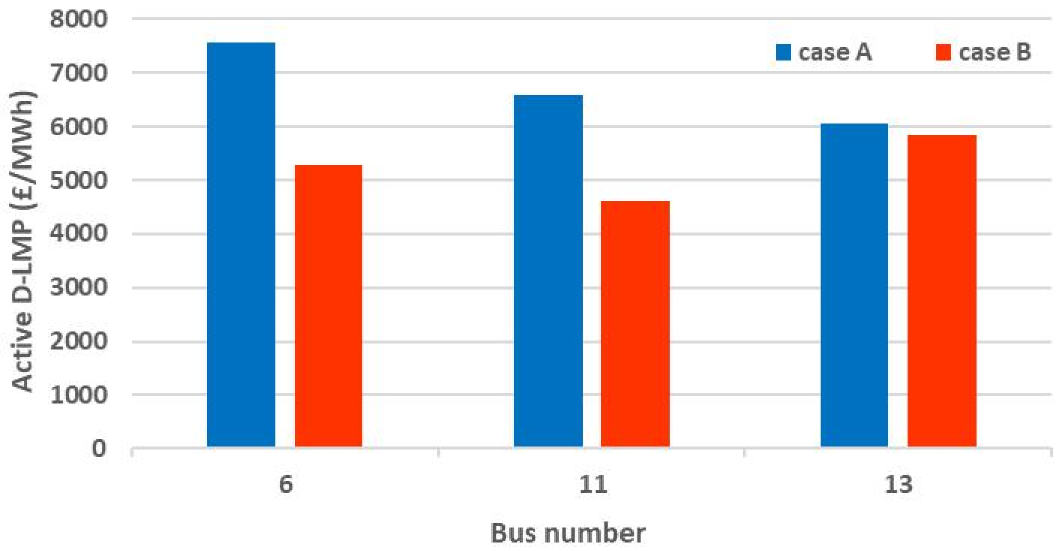


Figure 4- 6 Total active D-LMP at candidate buses

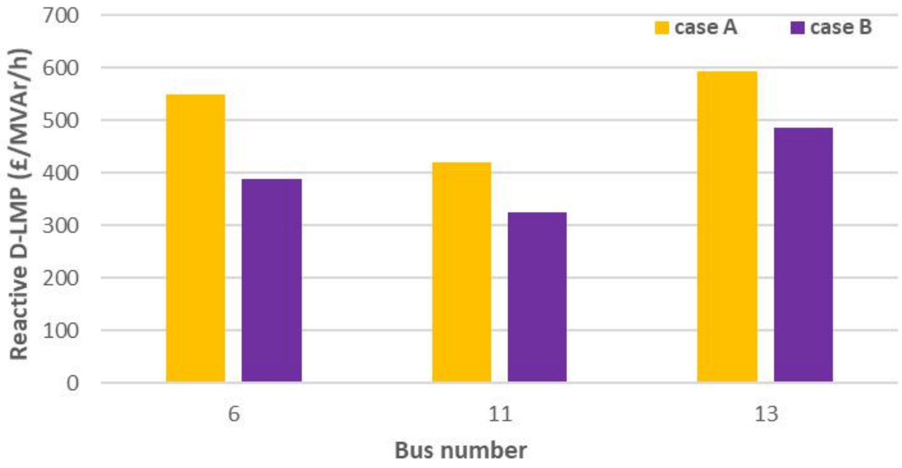


Figure 4- 7 Total reactive D-LMP at candidate buses

4.10 Conclusions

A novel approach for the operation of distribution networks within a joint active and reactive distribution with integration of demand response has been proposed. The market-based active and reactive optimal power flow was used to maximize the social welfare in order to determine the optimal capacity of WTs and PVs. In order to evaluate the amount of wind and solar power penetration on the social welfare and on active and reactive locational marginal prices, a stochastic method was used taking into account the uncertainties related to wind speed, solar irradiance and load demand. Scenario-tree was applied to model the uncertainties related to the wind speed, solar radiation and load demand.

The new proposed method could be recommended to support the distribution network operators to assess the impact of wind and solar power generation penetration on a given network in terms of technical and economic effects.

The method will also help DNOs install wind turbines and PVs at a more advantageous location in terms of cost reduction and consumers' benefits.

The proposed methodis able to provide an accurate real time pricing which paves the way to operate the proposed market more efficiently thus leads to load demand and prices reduction. This envisages the participation of distribution network operators and active consumers in the distribution market environment, and making use of active and reactive distribution location marginal prices.

Chapter 5 Active Distribution Network Operation: A Market-based Approach

5.1 Introduction

Integration of renewable distributed generators (RDGs) (e.g. photovoltaic cells (PVs) and wind turbines (WTs)) have been considered as one of the issues for the power distribution system [365]. The intermittent generation of PVs and WTs introduce both technical and commercial challenges which include, voltage stability, voltage violation and power losses to distribution network operators (DNOs) [22]. Addressing these challenges, the DNOs need to consider the development of new methodologies and models to deal with the uncertainty associated with WTs and PVs [366]. Active network management (ANM) schemes at distribution level including coordinated voltage control (CVC) of on-load tap changers (OLTCs) and adaptive power factor control (PFC) offer a feasible solution for DNOs for optimal operation for network assets with a high penetration of RDGs at the same time considering uncertainties related to output power of WTs and PVs, market constraints, and power flows schedule with the interface to the transmission system [367]. ANM seek to decrease the deviation in voltage and power losses and reactive power compensators [368]. In general, ANM can be defined as smart control techniques based on real time measurement of voltage and current which provides benefits in facilitating the increasing integration of RDGs [369].

Demand response (DR) is another additional option, which provide economic reliability benefits and mitigate the impact of RDGs uncertainties. DR is defined as the ability of consumers to change their consumption behaviour patterns of electricity in order to improve the reliability of system [343].
Under the decentralized electric power systems scheme, at all times, the boundaries of frequency and voltage limits must be sustained within a specified limit in order to fullfil the required safety and security standards.

In order to solve this problem, a set of special services are required to ensure a stable and safe operation of the electric supply [370]. These are known as ancillary services because they complement the energy product and provide open access transmission, supply reactive demand, control system voltage and support system security [371]. One of the primary objectives of DNOs is to provide these ancillary services which are classified as active power services which deal with load frequency regulation, and reactive power services which include voltage control [345, 371]. Usually, the voltage instability in the power network is due to non existence of reactive power ancillary services, which may lead to the collapse of the power system and this is the main reason for the power outage [349].

Therefore, this chapter proposes a novel technique for operation of distribution networks with considering active network management (ANM) schemes and demand response (DR) within a joint active and reactive distribution market environment. Additionally, this work explores the impact of wind and solar power penetration on the active and reactive distribution locational prices (D-LMPs) within the distribution market environment with integration of ANM schemes and DR. The abovementioned 16-bus UK generic medium voltage distribution system is used to demonstrate the effectiveness of the proposed method.

5.2 Related Research Work

Previous research has focused on the active power ancillary services at the transmission level. For instance, in [346] two new frequency control constraints are introduced namely, the minimum frequency constraint, and the rate of change of frequency constraint and are illustrated how these constraints can be included in a market dispatch formulation are introduced. A new market model for implementation a primary frequency response of ancillary service into pool-based restructured power markets is proposed in [372], a day-ahead energy market which includes a primary frequency reserve from generators and fast frequency response reserve from load resources is introduced [373].

Other studies have addressed the mitigation of the impact of reactive ancillary services in transmission systems. Reference [322] has proposed a day-ahead market for reactive power based on pay-as-bid pricing mechanism in the transmission system considering the reactive power behavior during the market clearing period, and multi-objective optimization technique based on reactive power market clearing which consider voltage stability is presented [359, 374].

A new stochastic model based on the decoupled day-ahead active and reactive power markets at distribution level has been proposed with considering active network management (ANM) schemes in order to scheduling the active and reactive power in distribution system with RDGs [360], the reactive power market settlement procedure for DGs in distribution network for reactive power ancillary services which minimize the DNOs reactive power payment and enhance the voltage profile for DGs [324], another model is the combination of ANM with DR program to minimize the costs which are beneficial to both economy and environment [351].

Therefore, establishing a joint active and reactive power market at distribution level is considered to be a successful technique for efficiently managing and hosting a large amount of RDGs in distribution networks [375].

However, none of the literature studies introduced the joint active and reactive power market model at the distribution level and assessed the impact of active and reactive power on the amount of active and reactive power that can be injected/absorbed to/from the grid from WTs and PV with integration of ANM schemes and DR program. The gap that this work tries to fill is to investigate the impact of DR and ANM schemes on active and reactive power generated by RDGs within a novel electricity market.

Table 5-1 is a summary of all the references and differences between them and the state of the art.

Table 5- 1 Comparison of existing literature with proposed model

Reference	Transmission or distribution level	Renew -able energy	Correlation	DR	Power market		ANM	SW Max.
					active	reactive		
[346, 372, 373]	Transmission	✓	×	×	✓	×	×	×
[322, 359, 374]	Transmission	×	×	×	×	✓	×	×
[360]	Distribution	✓	×	×	✓	✓	✓	×
[324]	Distribution	✓	×	×	×	✓	×	×
[351]	Distribution	✓	×	✓	✓	×	✓	×
Proposed	**Distribution**	✓	✓	✓	✓	✓	✓	✓

5.3 Contributions to the State of the Art of ANM

The main aim of this work is to maximize SW using market-based active and reactive OPF considering ANM schemes and DR programs. In addition, the impact of wind and solar power penetration on the SW and on active and reactive D-LMPs is investigated.

The voltage and reactive power control can be an alternative to the increase of the participation of the DGs in the distribution networks, since the active and reactive power management can be smartly coordinated by external control in order to eliminate both under voltage and over voltage violations in the distribution networks [376]. In order to achieve an optimum voltage profile over the distribution feeders and optimum reactive power flows in the system, Active Network Management (ANM) including on load tap changer (OLTC) transformers, DGs power factor control and demand response can play an important role to decrease the deviation in voltage and reactive power compensators [377].

On the other hand, the electrical distribution system became more active to comply with the connection of large amount of DGs. Demand response (DR) program is an attractive way to address this issue as it can respond quickly with respect to the variation of DGs [378].

Integration of ANM and DR in the distribution system creates opportunities to more efficiently balance supply and demand [379]. In addition, they are a key means for the smooth incorporation of RDGs into power systems, and it considers distribution system operators (DSOs) as the agents for integration of RDGs into the electricity market that can maximize the share of renewable energy system in overall energy consumption[380]. Also, with ANM schemes, DNOs will be capable of optimizing use of their assets by dispatching generation, controlling OLTCs and voltage regulators and managing reactive power [381].

This work proposes a joint active and reactive optimal power flow in order to evaluate the amount of active and reactive power that can be injected/absorbed to/from the grid from WTs and PVs is proposed to offer a means of measuring the impact of ANM schemes and DR programs on connectable active and reactive power capacity which generated by wind and

PVs. In addition, to effectively handling the time-variation of multiple renewable sites and demand, it also considers ANM to allow maximum absorption of WTs and PVs generation capacity while respecting voltage statutory limits and thermal constraints. ANM schemes including coordinated voltage control (CVC) of on-load tap changers (OLTCs) are embedded within the formulation.

Another innovative contribution of the proposed method, the contribution of DNOs in a joint active/reactive distribution market including a day-ahead and a real-time intraday schedule of WTs, PVs and load demand according to the market price is evaluated. The implementation of a distribution-level market based on active and reactive D-LMPs provides opportunities for real-time pricing that necessitates the implementation of innovative technologies, such as smart grids [324].

Mixed- integer linear optimization program (MILP) is used to clear the proposed joint active and reactive distribution market. MILP is applied because: 1) the mathematical model is robust; 2) the computational behaviour of a linear solver is more efficient than nonlinear ones; and 3) using classical optimization techniques, convergence can be guaranteed. The steady-state operation of a radial electrical distribution network is complicated to model linearly hence, an alternative current (ac) flow is approximated through linear expressions.

Non-linear technique has several drawbacks, including slow convergence, complexity, and difficulties involved in handling constraint and in adapting to different problem. In addition, it is non-convex therefore finding a global solution for problem is challenging.

In this work the proposed nonlinear model is converted to MILP model. Owing to the convexity, the proposed model can guarantee convergence of optimality and can be solved efficiently with commercial solver. Also linearization technique is very convenient for handling the constraints, providing global optimal solution.

This work proposes a stochastic method to assess the amount of wind and solar power peneteration on the social welfare (SW) and on active and reactive distribution location marginal prices (D-LMP) within a novel distribution market model taking into account the uncertainties related to wind speed, solar irradiance and load demand with integration of ANM and DR. The main contributions of this work are highlighted as follows:

1. To design a joint active and reactive electricity market model at distribution level with active ANM schemes.
2. To introduce a novel formulation for optimal operation of distribution networks within a proposed joint active and reactive distribution with the integration of ANM schemes and DR using mixed-integer linear programming (MILP).
3. Modelling the uncertainties associated with load demand, wind speed, and solar irradiation abovementioned uncertainties using Scenario-Tree approach.

5.4 Objective function

The equations used to represent the operation of a radial electrical distribution network [185]. The model is applied under the following assumptions:

1. The loads are modeled as constant active and reactive power.
2. In branch *i,j* the node *i* is closer to the substation node than node *j*.
3. The active and reactive power losses on branch *ij* are concentrated in origin node *i*.
4. The electrical distribution system is balanced and represented by a single-phase equivalent.

Objective function (5.1) maximizes SW which includes three terms. The first term represents the consumer benefit ($P_{i,s}^{l}$ and $Q_{i,s}^{l}$ are active and reactive power for load at bus *i* at scenario *s*, $C_{i}^{l,P}$ and $C_{i}^{l,Q}$ are bid prices for active and reactive power load at bus *i*). The second term represents the cost of DR ($P_{i,s}^{DR}$ and $Q_{i,s}^{DR}$ are active and reactive power for demand response at bus *i* at scenario *s*, $C_{i}^{DR,P}$ and $C_{i}^{DR,Q}$ are bid prices for active and reactive power demand response at bus *i*). Finally, the third term represents the generation cost for both active and reactive power of substation, WTs and PVs ($P_{i,s}^{ss}$, $P_{i,s}^{w}$, $P_{i,s}^{PV}$, $Q_{i,s}^{ss}$, $Q_{i,s}^{PV}$ and $Q_{i,s}^{w}$ are active power and reactive power of substation, WTs and PVs at bus *i*. $C_{i}^{ss,P}$, $C_{i}^{w,P}$, $C_{i}^{PV,P}$, $C_{i}^{ss,Q}$, $C_{i}^{w,Q}$ and $C_{i}^{pv,Q}$ are offer prices for active and reactive power of substation, WTs and

PVs at bus *i*). π_s refers to the probability of the scenarios. In addition, QPF in the third term refers to the reactive power payment of WTs and PVs, which is nonlinear. Piecewise linearization approach is used to linearize the quadratic function in (5.1) [362](seelinearization section).

$$\begin{aligned}
&\text{Maximize SW=}\\
&\left(\sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{l,P} P_{i,s}^{l} + \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{l,Q} Q_{i,s}^{l}\right)\\
&-\left(\sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{DR,P} P_{i,s}^{DR} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{DR,Q} Q_{i,s}^{DR}\right)\\
&-\left(\begin{aligned}&\sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,P} P_{i,ss}^{ss} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss} Q_{i,s}^{ss} + \sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{w,P} P_{i,s}^{w}\\ &+\sum_{i=1}^{NB}\sum_{s=1}^{NS}\pi_s C_i^{pv,p} P_{i,s}^{pv} + \sum_{i=1}^{NB} QPF_i^{w,pv}\end{aligned}\right)
\end{aligned} \tag{5.1}$$

5.5 Constraints

To support the objective function in the previous section, the two constraint should be invoked in the system, these are quality and inequality constraints. These can be defined respectively by the following equations:

$$\begin{aligned}
&\sum_{i=1}^{NB}\sum_{s=1}^{NS} P_{i,s}^{ss} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} P_{i,s}^{w} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} P_{i,s}^{pv} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} P_{i,s}^{DR} - \sum_{i=1}^{NB}\sum_{s=1}^{NS} P_{i,s}^{l} =\\
&\sum_{i=1}^{NB}\sum_{j=1}^{NB}\sum_{s=1}^{NS}(P_{i,j,s} + R_{i,j} I_{i,j,s}^{sq})
\end{aligned} \tag{5.2}$$

$$\begin{aligned}
&\sum_{i=1}^{NB}\sum_{s=1}^{NS} Q_{i,s}^{ss} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} Q_{i,s}^{w} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} Q_{i,s}^{pv} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} Q_{i,s}^{DR} - \sum_{i=1}^{NB}\sum_{s=1}^{NS} Q_{i,s}^{l} =\\
&\sum_{i=1}^{NB}\sum_{j=1}^{NB}\sum_{s=1}^{NS}(Q_{i,j,s} + X_{i,j} I_{i,j,s}^{sq})
\end{aligned} \tag{5.3}$$

$$V_i^{sq} - V_j^{sq} - 2\left[R_{i,j}(P_{i,j}) + X_{i,j}\left(Q_{i,j}\right)\right] - Z_{i,j}^2 I_{i,j}^{sq} = 0 \tag{5.4}$$

$$T_{ss,i} V_{ss}^{sq} - V_j^{sq} - 2\left[R_{i,j}\left(P_{j,i}\right) + X_{i,j}\left(Q_{j,i}\right)\right] - Z_{i,j}^2 I_{i,j}^{sq} = 0 \tag{5.5}$$

$$V_i^{sq} I_{i,j}^{sq} = P_{ij}^2 + Q_{ij}^2 \tag{5.6}$$

$$\left(V_i^{\min}\right)^2 \le V_{i,s}^{sq} \le \left(V_i^{\max}\right)^2 \tag{5.7}$$

$$I_{i,j,s}^{sq} \le \left(I^{\max}\right)^2 y_{i,j,s} \tag{5.8}$$

$$T_{i,j}^{\min} \le T_{i,j} \le T_{i,j}^{\max} \tag{5.9}$$

In more details, the above constraints can be categorized into two main groups:

a) Equality constraints including power flow equations: constraints (5.1)-(5.7) apply Kirchhoff's voltage law. Constraints stated in Eqns. (5.1)-(5.2) ensure the active and reactive power balances in system nodes. Equations (5.3)-(5.6) are related to the active, reactive and apparent power flows and the current flow, where, $V_{i,s}^{sq}$ is the square of voltage magnitude, $I_{i,j,s}^{sq}$ is the square of current magnitude. It is assumed that the lines with OLTC is modelled as series impedance R+jX with an ideal transformer with a variable turns ratio *T* as shown in Fig (5.1).

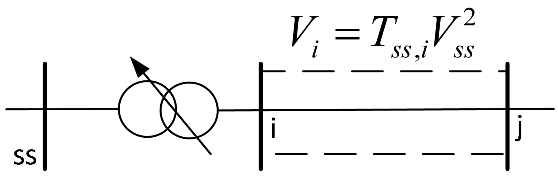


Figure 5- 1 Line model

b) Inequality constraints: constraint (5.7) determines the acceptable range of square voltage magnitude in nodes, while constraint (5.8) is the current flow limit in branch *i,j*.

Constraint (5.9) represents the limits of tap ratio in the OLTC.

5.6 Linearization

To avoid nonlinearity, the linearization process described in [362, 382] is used.

1. The component QPF is carried out in section (4.7).
2. $T_{ss,i} V_{ss}^{sq}$ is nonlinear in eqn. (5.5). The same above linearization method is provided as follows:

$$\kappa_{ss,i} = \frac{T_{ss,i} - u_{ss,i}}{2} \tag{5.10}$$

$$\omega_{ss,i} = \frac{T_{ss,i} - u_{ss,i}}{2} \tag{5.11}$$

where $\omega_{ss,i} - \kappa_{ss,i} = T_{ss,i} u_{ss}$ (5.12)

$$\kappa_{ss,i} = \kappa^{+}_{ss,i} - \kappa^{-}_{ss,i} \tag{5.13}$$

$$\kappa^{+}_{ss,i} - \kappa^{-}_{ss,i} = \sum_{f} \Delta\kappa_{ss,i,f} \tag{5.14}$$

$$\kappa^2_{ss,i,f} = \sum_f (2f-1)\Delta\kappa^{\max}_{ss,i} \Delta\kappa_{ss,i,f} \tag{5.15}$$

$$0 \le \kappa_{ss,i,f} \le \Delta\kappa^{\max}_{ss,i} \tag{5.16}$$

$$\text{where} \qquad \Delta\kappa^{\max}_{ss,i} = \frac{\kappa^{\max}_{ss,i}}{F} \tag{5.17}$$

$$\omega_{ss,i} = \omega^+_{ss,i} - \omega^-_{ss,i} \tag{5.18}$$

$$\omega^+_{ss,i} - \omega^-_{ss,i} = \sum_f \Delta\omega_{ss,i,f} \tag{5.19}$$

$$\omega^2_{ss,i,f} = \sum_f (2f-1)\Delta\omega^{\max}_{ss,i} \Delta\omega_{ss,i,f} \tag{5.20}$$

$$0 \le \omega_{ss,i,f} \le \Delta\omega^{\max}_{ss,i} \tag{5.21}$$

$$\text{where} \qquad \Delta\omega^{\max}_{ss,i} = \frac{\omega^{\max}_{ss,i}}{F} \tag{5.22}$$

3. $V_i^{sq} I_{i,j}^{sq} = P_{ij}^2 + Q_{ij}^2$: both the left and right sides are nonlinear and both should be linearized separately [383]. Note that V_i^{sq} and $I_{i,j}^{sq}$ are variables that represent the square magnitude values of voltages and currents, respectively.

   - $V_j^{sq} I_{i,j}^{sq}$: The product of two variables is linearized by discretizing V_i^{sq} in small intervals. However, this leads to an increase in the number of binary variables and computation time. Since the voltage magnitude is within small range in electrical distribution systems, a constant value V_{nom}^{sqr} is selected and substituted for

V_j^{sq} in equation (5.6) for the first iteration. Then, the model is run again and V_j^{sq} takes the value resulting from the first iteration. Note that V_j^{sq} hardly changes after the second iteration.

- $P_{ij}^2 + Q_{ij}^2$: the linearization of both terms on the right side of (5.6) is carried out by a piecewise linear approximation, as follows:

$$P_{ij}^2 + Q_{ij}^2 = \sum(m_{i,j}\Delta P_{i,j}) + \sum(m_{i,j}\Delta Q_{i,j}) \quad (5.23)$$

$$P_{i,j}^+ - P_{i,j}^- = P_{i,j} \quad (5.24)$$

$$Q_{i,j}^+ - Q_{i,j}^- = Q_{i,j} \quad (5.25)$$

$$P_{i,j}^+ + P_{i,j}^- = \sum \Delta P_{i,j} \quad (5.26)$$

$$Q_{i,j}^+ + Q_{i,j}^- = \sum \Delta Q_{i,j} \quad (5.27)$$

$$0 \le \Delta P_{i,j} \le \Delta S_{i,j} \quad (5.28)$$

$$0 \le \Delta Q_{i,j} \le \Delta S_{i,j} \quad (5.29)$$

$$P_{i,j}^+ \le V_{nom} I_{i,j}^{\max} o_{i,j}^{P+} \quad (5.30)$$

$$P_{i,j}^- \le V_{nom} I_{i,j}^{\max} o_{i,j}^{P-} \quad (5.31)$$

$$Q_{i,j}^+ \le V_{nom} I_{i,j}^{\max} o_{i,j}^{Q+} \quad (5.32)$$

$$Q^{-}_{i,j} \le V_{nom} I^{\max}_{i,j} o^{Q-}_{i,j} \tag{5.33}$$

Eqn. (5.23) is a linear approximation of $P^2_{ij} + Q^2_{ij}$ .To ensure that $P^{+}_{i,j} + P^{-}_{i,j}$ and $Q^{+}_{i,j} + Q^{-}_{i,j}$ are equal to the sum of all values in separated blocks, Eqn. (5.24) and (5.27) are represented. Both upper and lower bounds of the variable are represented Eqns. (5.28) and (5.29). Constraints (5.30)-(5.33) are introduced for active and reactive power. Parameters $I^{\max}_{i,j}$ and V_{nom} are Maximum current flow in branch i,j and a nominal voltage of the distribution network. In addition, $o^{P+}_{i,j}$, $o^{P+}_{i,j}$, $o^{P-}_{i,j}$, $o^{Q+}_{i,j}$ $o^{Q-}_{i,j}$ are binary variables to avoid considering forward and backward power flow simultaneously. Note that the slope $m_{i,j}$ and the variation $\Delta S_{i,j}$ are constant parameters which are defined as follow:

$$m_{i,j} = (2r-1)\Delta S_{i,j} \tag{5.34}$$

$$\Delta S_{i,j} = (V_{nom} I^{\max}_{i,j}) / R^{tot} \tag{5.35}$$

As shown in (5.23)–(5.27), the right side of (5.6) can be replaced with the right side of (5.23) to form a linear equation. The linear form of (5.6) is shown as following which V^{sq}_{i} is constant and $\sum(m_{i,j}\Delta P_{i,j})$ and $\sum(m_{i,j}\Delta Q_{i,j})$ are a linear approximation of P^2_{ij} and Q^2_{ij} ;

$$V^{sq}_{i} I^{sq}_{i,j} = \sum(m_{i,j}\Delta P_{i,j}) + \sum(m_{i,j}\Delta Q_{i,j}) \tag{5.36}$$

The linearization processes performed in the proposed method is illustrated in Fig.5-2.

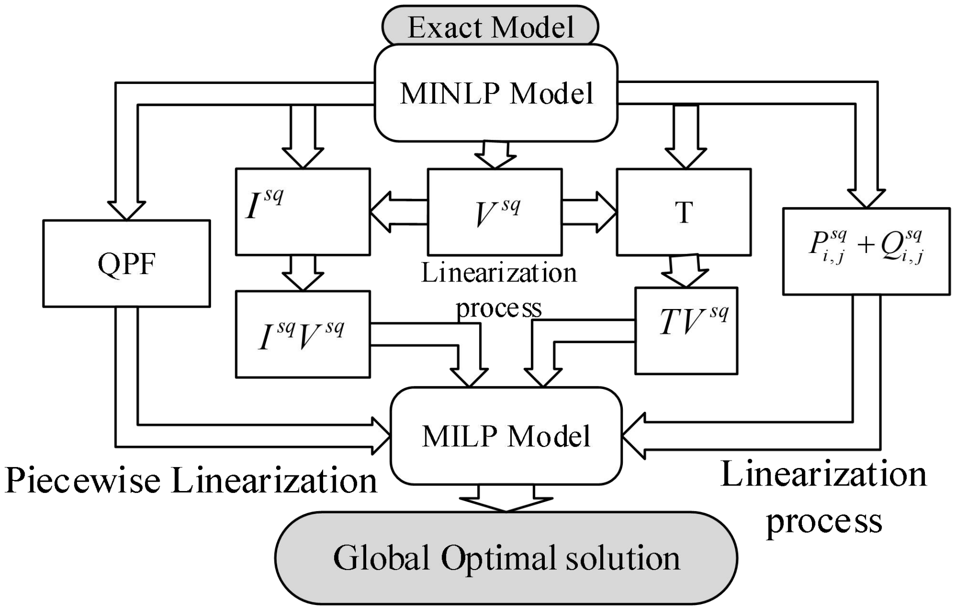


Figure 5- 2 Illustration the linear processes performed in the proposed distribution market

Linear model is used as a benchmark against which the approximate nonlinear model can be compared. In this regard, first the linear model is solved and the global optimal solution of the problem is found. This solution is then used as a benchmark for assessing the solution accuracy of the nonlinear model. Note that, the accuracy evaluation of the MILP model was conducted based on the error in the SW. In addition, the error computation time is used, as shown in Eq. (5.37), as an index for evaluation of the performance of the proposed model. Note that the error indicates the deviation of the nonlinear model from the global solution which is found by linear model, it is noted that the error is 0.23% in the SW. In addition, The computational time required for solving the nonlinear and linear models are respectively 1.484 and 0.938 min.

$$Error = \frac{t^{nonlinear} - t^{linear}}{t^{linear}} \times 100\% \tag{5.37}$$

Where $t^{nonlinear}$ and t^{linear} denote the time associated with the nonlinear and linear models, respectively.

5.7 Case Study

In order to assess the impact of wind and solar power penetration on active and reactive D-LMPs with ANM schemes and DR, three WTs and two PVs units are installed in the distribution network. The candidate buses for WTs are buses 5, 10, and 13 with the nominal capacity of 660,440 and 880 kW, respectively and PVs are 2 and 11 with the nominal capacity of 660 and 440 kW, respectively. The upper and lower limit of voltage at each is assumed to be 1.06 and 0.94 p.u.

5.8 Simulation Results

It is worth mentioning that, the correlation between uncertainties characterizing associated with load demand, wind speed, and solar irradiation has been considered by using Scenario-Tree approach. For the presentwork, jointly considering four-time blocks, three load demand levels, three wind speed levels, three solar irradiation levels, which are leading to 108 different scenarios. The same correlation among load demand and wind and PV power production is considered in all the location of the system. Table 4-2 provides the characteristics of load demand, wind speed and solar irradiance scenarios.

This section discusses the results from three case studies shown in Table 5-2, which shall facilitate to study the impact of ANM schemes and DR on SW, dispatched active and reactive power, and active and reactive D-LMPs. For each case, the SW, the total dispatched active and reactive power for WTs and PVs, and the total active and reactive D-LMPs at candidate buses are examined.

Figs. 5-3 and 5-4 represent the total dispatched active and reactive power supplied by WTs and PVs for each cases at candidate buses. It is evident that buses 11 and 13 have the lowest and highest dispatched active and reactive power respectively supplied by WTs and PVs. This is due to active and reactive bid prices and voltage thermal limits at each bus. At the same time, it can be observed in these figures that in case C (with ANM schemes and DR), the total dispatched active and reactive power of WTs and PV is higher when compared with those in case A and B by up to 20% for active power and up to 13% for reactive power. Fig. 5-5, shows the SW for three cases. It is seen that case C has the highest SW when compared with both SW in case A and B. This is mainly due to the higher dispatched active and reactive power in case C with integration of ANM schemes and DR which allows increasing the SW.

Table 5- 2 Cases

Case	ANM	DR
A	×	×
B	✓	×
C	✓	✓

Table (5-3) and Fig (5-6) show the total active and reactive D-LMPs at candidate buses in all cases. It indicates that a highest active D-LMPs is related to bus 11 and lowest active D-LMP is related to bus 13; this is due to the highest and lowest dispatched active and reactive WTs and PVs power at these buses. It should be noted that the active and reactive D-LMPs in case C is decreased if compared with those in case A and B by up to 1.5% and 6%, respectively. This mainly due to ANM schemes and DR program. To further clarify the impact of ANM schemes and DR on the system voltages, Figs. 5-7 is introduced. As shown in Fig.5-7 bus 13 has the highest voltage this related to the highest reactive power in bus 13.

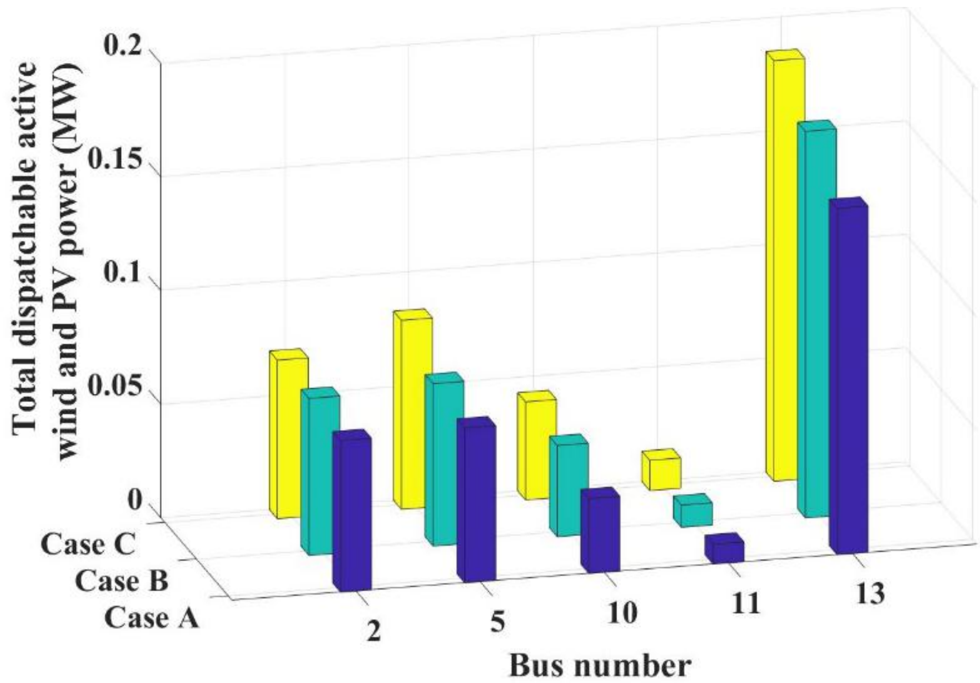


Figure 5- 3 Total dispatched active wind and PV power at candidate buses in all cases.

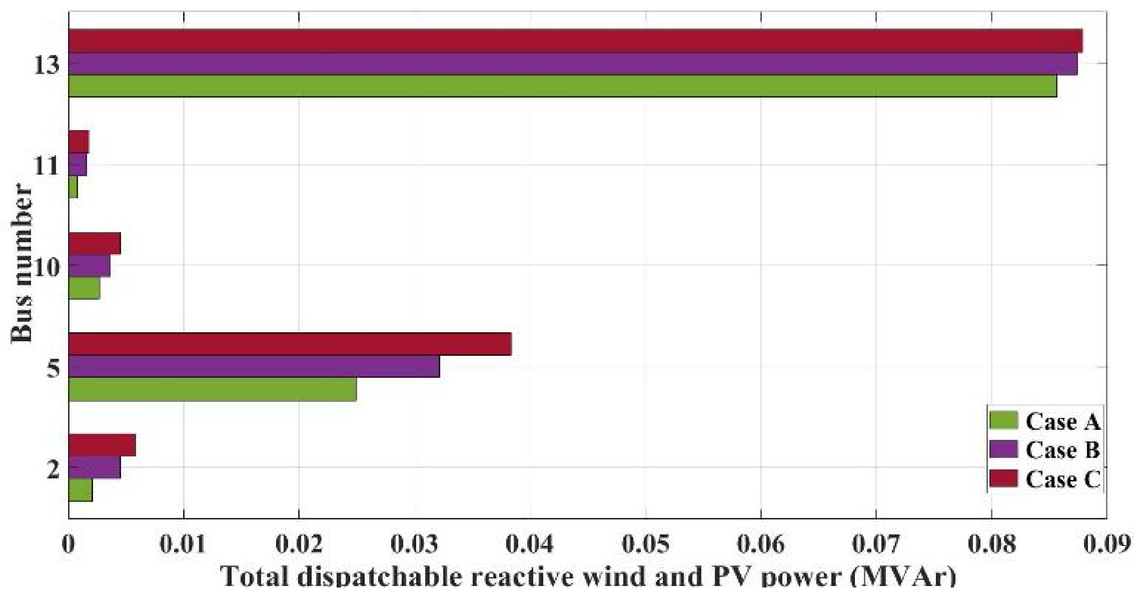


Figure 5- 4 Total dispatched reactive wind and PV power at candidate buses in all cases

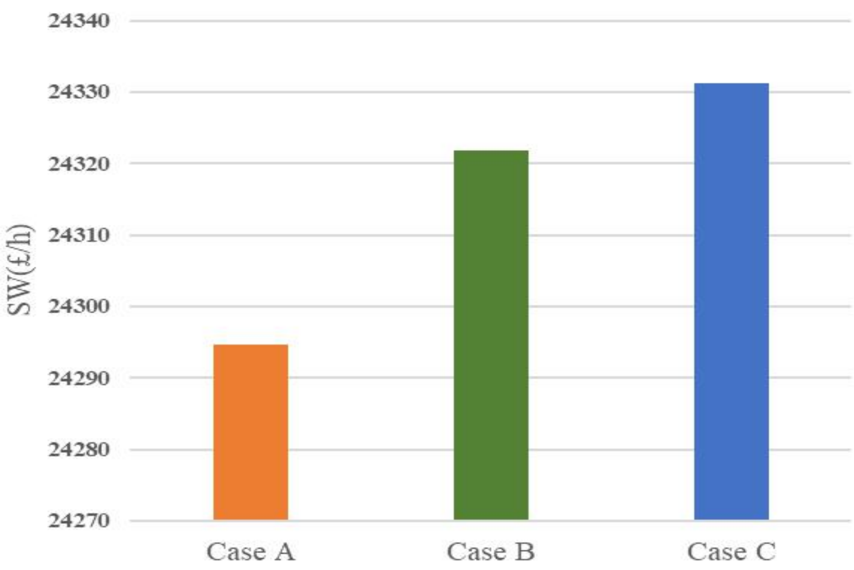


Figure 5- 5 Social welfare for each case.

Table 5- 3 Total active D-LMP at candidate buses for all cases

	Bus No.	Total active D-LMP((£/MWh)
Case A	2	8850.143
	5	9252.783
	10	9499.11
	11	9892.786
	13	8206.665
Case B	2	8752.238
	5	9201.512
	10	9370.11
	11	9820.03
	13	8103.081
Case C	2	8711.999
	5	9116.291
	10	9330.038
	11	9649.589
	13	8003.495

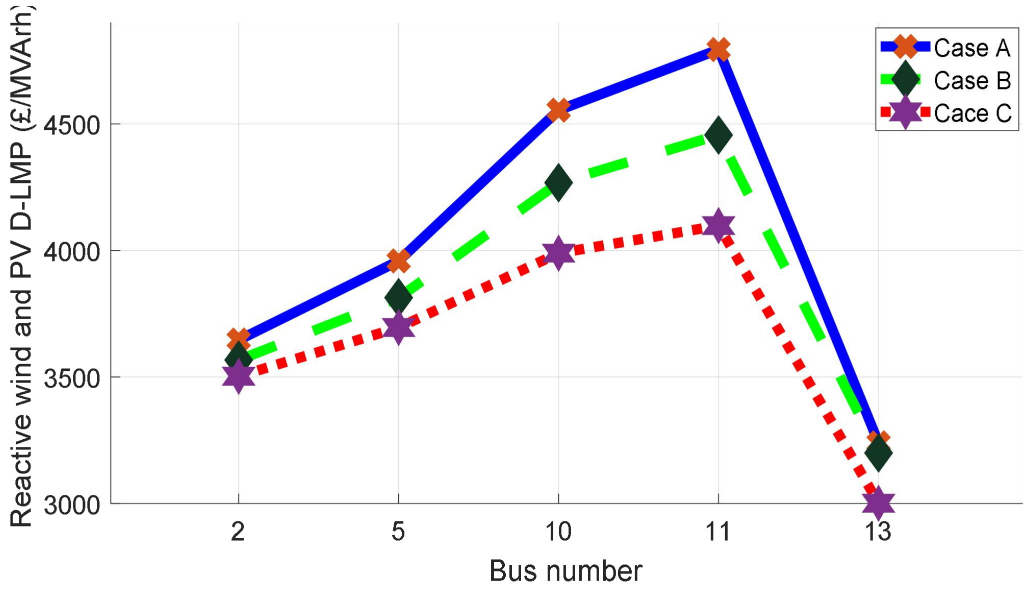


Figure 5- 6 Total reactive D-LMP at candidate buses for all cases

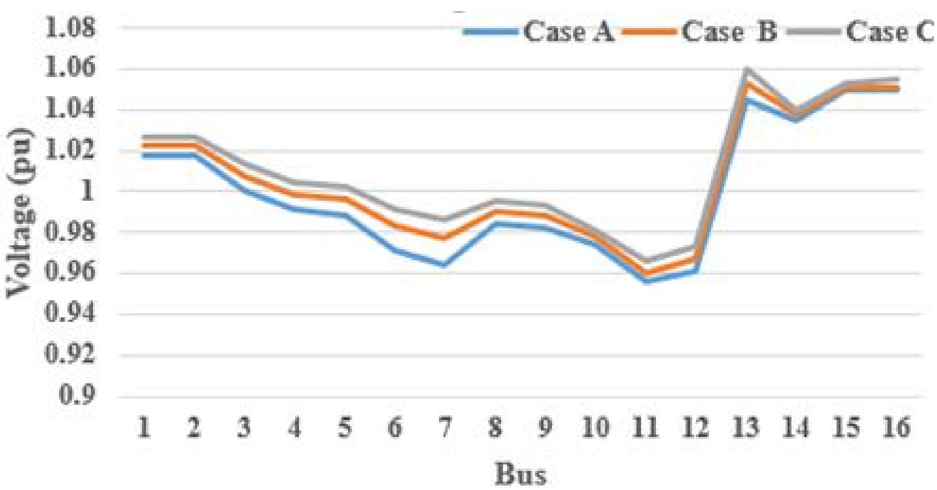


Figure 5- 7 voltage profile for the system

Chapter 6 Conclusions and Recommendations for Further Work

6.1 Conclusion

The thesis starts with a comprehensive literature review covering the penetration of DGs to minimize the cost, improve voltage profile, minimize the loss, maximize the benefits, etc. It was concluded that previous works have not studies the modelling of uncertainties related to the renewable energy resource and load demand. It was also confirmed from the comprehensive review carried out that no study has considered the joint active and reactive power simultaneously in the distribution market environment.

The proposed method addresses the abovementioned research gaps by proposing a stochastic method for operation of active distribution networks within a joint active and reactive distribution market environment

The outcomes of the this thesis can be used as tool for distribution network operators to assess the impact of wind and solar power generation penetration.

A summarized conclusion of each chapter is illustrated as follows:

Chapter 2: This chapter has summarized the state of the art of research methodologies for modelling uncertainties and optimization methods applied to the distribution networks. It was concluded with clear evidence that no previous work has considered the joint active and reactive power market model in distribution newtwork operation.

Chapter 3: A stochastic method to assess the amount of active and reactive power that can be injected/absorbed into/from the grid by WTs has been presented. The impact of wind power penetration on the social welfare (SW) and active and reactive distribution-locational marginal prices (D-LMPs) within a distribution market environment considering uncertainties associated with load demand and wind speed have been investigated to confirm the operation of the proposed market model.

Chapter 4: The PV has been added in this chapter in addition to the subject of chapter three. A full program was updated for studying the uncertainties modelling for WT, PV and load demands. The Scenario-Tree technique has been investigated to employ uncertainties model associated with solar irradiance, wind speed and load demands.

The offer structure of the reactive power price was studied in this model and it was concluded that the variations of the offer price has direct influence on the SW. It was noticeable from the achieved results that DR integration leads to increase in the social welfare and total dispatched active and reactive power and consequently decrease in active and reactive distribution locational marginal prices.

Chapter 5: A novel technique for the operation of distribution networks with considering active network management (ANM) schemes and demand response (DR) within a joint active and reactive distribution market environment has been proposed. Three case studies have been investigated, against the SW, these include, case 1) Without ANM and DR, case 2) ANM niof these three cases studies, that increasing active and reactive power capcity up to 20% for active power and up to 13% for reactive power; confirm to reduce the LMP by 1.5% and 6% respectively.

6.2 Recommendations for Further Work

The proposed market model could be easily considered and extended for further work to include new research areas, such as:

- A new approach to use chance-constrained model to solve the nonlinear optimization problem in which this can be easily integrated with the GAMS software. This type of constraint supports the combinations of multiple inequalities to be applied for OPF under uncertainty in order to evaluate the probabilities of holding the inequality constraint and quantify the constraint violation.

- Another idea to include the security constraints into the proposed current method. One may use the security constraint (N-1) of a distribution system when a fault occurs at any feeder or maintenance is required; this approach could enhance the fault or maintenance at any part of the power system by isolating this fault quickly and then the power supply be able to restore to customers through some switch operations. It should be noticed that N-1 security of DGs is newly process to the operational constraint of distribution system with DGs.

- A good idea to investigate the bi-level optimisation algorithm in further evaluating the joint active and reactive power. In fact the suggestion is to include SW and total costs including their constriants between them.

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