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Probabilistic Multi-Objective Optimal Power Flow in an AC/DC Hybrid Microgrid Considering Emission Cost

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Abstract- *As a basic tool in power system control and operation, the optimal power flow (OPF) problem searches the optimal operation point via minimizing different objectives and maintaining the control variables within their applicable regions. In recent years, this problem has encountered many challenges due to the presence of renewable energy sources, which has led introducing of a combinatorial type of power networks known as AC/DC hybrid power systems. In this paper, the OPF problem is proposed in an AC/DC hybrid microgrid, including wind power plants. For the first time, the mentioned problem is considered as a multi-objective optimization problem via minimizing fuel cost and emission. The problem is modeled while considering the power flow equations, the voltage limits in AC and DC buses, the AC voltage angle limits, and the firing angle of the converters. Also, due to the uncertain power generated by wind power plants, the probabilistic OPF problem is modeled by the five-point estimation method. To solve the problem, the "fmincon" function in MATLAB software is used by applying the IP algorithm. The simulation case study on a 13-bus sample MG verifies the effectiveness of the proposed method. The numerical results confirm that increasing the wind farm capacity from 14.54 MW to 113 MW, will be led to increasing the fuel cost from 10% to 61%, in case of including the power losses compared to the condition in which they are neglected. It is also observed that in terms of different weights, the total air pollution including the power losses is 2.30 to 2.40 times higher than the total pollution without electrical losses.*

Keyword: Emission**,** Fuel cost**,** Multi-objective optimization, Optimal power flow (OPF), Power losses, Wind power plants.

1. INTRODUCTION

Over the past decades, microgrids (MGs) have attracted the attention of many researchers as well as power system operators and planers which is owing to their numerous advantages. They have been recognized as a suitable and reliable solution for expanding distributed generation resources (DGRs) into power grids [1-3]. The MG is a combination of electrical, thermal, and DGRs that operates in an integrated manner to supply and deliver the demanded energy to the loads. It can be connected to the main grid only in a single point known as the point of common coupling (PCC) at the distribution voltage level [4].

The mission of the MG is to supply the demand power in islanded, or connected, modes related to the main network [5-6]. However, in each of these cases, the MG, similar to the main network, is controlled and protected through a hierarchical control system and includes primary, secondary, and tertiary control systems [1], [7]. Voltage and frequency controls, known as primary and secondary controls, can be operated under the control of a central MG controller or in a decentralized state [8]. The third stage, as the last stage of the hierarchical structure of the MG control system, is responsible for controlling, protecting, and managing the demand and power exchange between the MG and the main network, as well as managing the MG, economically and optimally [9-10]. In general, MG provides specific control requirements and strategies to maximize the economic benefits and satisfy the load-supply balance [11-12].

MGs are the modern small-scale examples of centralized electrical systems and can achieve several objectives such as fuel cost reduction, carbonaceous emission decrease, reliability optimization, and possibility of applying several energy resources [13]. The main differences between MGs and classical power grids are as follows: in MGs, generation units are located near the loads and supply loads locally, the power losses in MGs are insignificant, and the size of

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power generation sources in MGs is smaller than the capacity of the generating units in classical power plants [14]. In addition, MGs can offer several advantages such as reduction in outages in transmission and distribution systems, possibility of introducing thermal loads and ancillary services into the grids, and possibility of decentralizing energy suppliers [15].

MGs are classified into AC, DC, and hybrid types based on the specifications of distribution lines. Due to the lack of reactive power in DC distribution systems, this type of MGs provides prominent benefits such as reducing power losses, decreasing voltage drops, and increasing electrical capacity of the lines [16]. In addition, some studies have confirmed that DC transmission lines can transmit more electrical power. Therefore, planning, implementing, and operating these networks are more comfortable and straightforward than those of the AC type and need less investment cost [17]. Although the number of DC MGs has increased, many of these networks still use AC distribution lines. As a result, more research is required on DC MG control techniques, standardization, planning, and operation of DC grids. The common choice between these two MGs, known as AC/DC hybrid MGs, can be proposed as an optimal alternative [18-19].

Introducing large-scale renewable energy sources into power systems has posed several challenges to these complex systems. Although the advanced technologies of power generation based on non-renewable sources provide greater efficiency, the availability and inexhaustibility of renewable resources and the limitation in the consumption of fossil fuels are among the important features that have increased the focus of the research topics on hybrid AC/DC networks with renewable resources [20-21]. In fact, an MG is a self-sufficient power system that is used as an efficient solution to provide power and take advantage of local energy sources, such as wind and solar. It generally includes synchronous generators, inverters based on DG units, energy storage systems, and control systems [22]. MGs usually include technologies such as photovoltaic systems (with DC power output) and micro-turbines (high frequency AC power) that require electronic power sources such as DC/AC or DC/AC/DC converters to connect to the electrical system. Given that the MG consists of three main elements, namely DG units, energy storage systems, and loads, the connection of these elements to each other is based on power converters. The converter type may be AC or DC based on MG type. This equipment plays a key role in controlling frequency, voltage, current, and load flow of MGs [23]. Voltage source converters (VSC)-HVDC are the latest type of technology for power transmission based on VSC, the gates or switches of which are made using IGBT transistor and bandwidth modulation and allow the creation of the desired voltage waveform. The main function of the VSC-HVDC is to transfer constant DC power from the rectifier to the inverter. The main structure of a VSC-HVDC consists of passive AC high-pass filters, transformers, converters, fuzzy reactors, DC capacitors, and DC cables. The converters listed in VSC-HVDC are voltage source converters based on IGBT power semiconductors, one of which acts as a rectifier and the other as an inverter. Depending on the application of the system, two converters may be connected to each other back-to-back or via a DC cable [24-25]. With the increasing fuel costs, the issue of ED has become one of the key issues related to the performance of the MGs in both modes of connected to the main network and islanded operation. ED is a non-linear optimization problem that aims to minimize the fuel cost function subject to different equality and non-equality constraints [26].

In order to turn MGs into a possible and practical option in power systems, it is necessary to apply algorithms to its operation analysis in order to meet the environmental constraints in addition to the ED. In this situation, where several objective functions are considered together, any attempt to optimize one objective function may sacrifice the other objectives. Therefore, it is necessary to make a compromise between the objective functions. The technique used to solve these types of problems is multi-objective optimization. One way to solve this type of problem is to consider the pollution function as one of the constraints and, thus, turn the multi-objective problem into a single-objective one. However, in this method, it will be difficult to establish equivalence and compromise between the two objective functions [27]. Other proposed methods are to assign appropriate weight to each of the objective functions and to form a single-objective function or linearize different functions.

1.1. Literature review

The increasing expansion of renewable energy resources (RERs) to electric power systems is a challenging issue which has attracted the attention of power system planners and operators. Although the technology of non-renewable resources offers higher efficiencies, the permanence of RERs and limitation in using fossil fuels are the main reasons that have motivated research on AC/DC hybrid MGs with the presence of RERs [18]. Voltage source converters (VSCs), which are based on MTDC, are known as a practical solution due to their ability to improve flexibility in power flow management [24]. Determining the OPF model in an AC/DC hybrid MG plays a vital role in detecting and evaluating the benefits of VSC-HVDC's steady-state performance [28].

References [29-30] have modeled the OPF problem considering VSC-HVDC, such that the problem can be easily solved by the Newton-Raphson method. In [31-32], an OPF model was performed on an AC/DC hybrid power system considering the impact of VSC-MTDC, while a power converter was regarded as a controllable voltage source. In most of studies, attempts have been made to simplify the power converters while neglecting their electrical losses. References [33-35] focus on different theories and algorithms for solving the OPF problem in an AC/DC hybrid network. In Ref. [36], the OPF problem for typical systems in the presence of VSC-MTDC has been studied while considering controllable variables of the converters (constant DC voltage control and DC voltage drop control) as the constraints of the problem. The investigations show that these variables can seriously alter the final results.

As noted, using distributed generation units (DGs) based on RERs has witnessed rapid growth over recent years. Among all RERs, the electrical energy produced by wind farms has maximum contribution to supplying the demanded load. Generally, any innovation and study on a hybrid power system with the presence of a wind power plant should be based on two fundamental principles: protection and control of load flow for a VSC-MTDC and OPF study, and modeling the mathematical framework [37]. In Refs. [38-39], a hybrid power system has been simulated in the presence of a wind power plant, and the results indicate that optimizing the generation capacity and the appropriate location are essential for optimizing the electrical losses. One of the most critical issues in the control and operation of power systems is the economic load dispatch (ELD). The purpose of this problem is to minimize the fuel cost function for generating a certain amount of electrical power. The ELD must be able to satisfy different constraints governing the generation process. To solve the nonlinear ELD problems, γ iteration and gradient reduction methods have been employed, but the latter has low accuracy and requires a long run time [40]. Nowadays, other important issues such as environmental concerns and need to minimize greenhouse gas emissions have also been raised by power system planners and operators. The main reason for the generation of these gases is the burning of fossil fuels in thermal power plants. Three main categories of emission gases include carbon dioxide (CO_2), oxide sulfur (SO_X), and nitrogen dioxide (NO_X).

Reducing the greenhouse gas emissions by applying appropriate solutions is of great importance. In short-term planning, attempts have been made to reduce these gasses while decreasing fuel costs. In such cases where several objective functions are considered concurrently, any attempt to optimize one of the objectives may be at the expense of sacrificing other objectives. Thus, in such cases, we must usually consider a kind of compromise between these objective functions. Also, since there is no specific rule for the perfect preservation of one of the objectives, employing single-objective optimization methods cannot be logical or practical. In this case, we should formulate the problem with several objective functions, known as multi-objective optimization. One method for this purpose is regarding the emission function as one of the constraints; as a result, the multi-objective problem becomes a constrained single-objective problem. However, in this way, establishing equivalence and compromise between the two objective functions will be difficult [41]. Another method is weighing objective functions and linearizing these functions. There are many types of studies on the use of heuristic and meta-heuristic algorithms in this field. In Refs. [42-47], different mathematical, heuristic, and meta-heuristic algorithms have been applied to minimize the fuel cost and environmental emission concurrently with the consideration of different constraints and limitations. In Ref. [48], the interval optimization method, for optimizing different objective functions such as the fuel cost, voltage deviation, and voltage stability, has been proposed on a modified IEEE 112-buse power grid. The output power of the renewable energy source has been determined as the interval variable. The Pareto front and numerical results show that, in comparison with traditional methods, this approach will yield more flexible and convergent results. In Ref. [49], the "fmincon" function in MATLAB software was proposed on a microgrid consisting of RERs and energy storage systems. The mentioned objectives included minimizing the cost of energy and the annualized cost of the system and improving the MG reliability. The results were determined under different parameters, depicting the effectiveness of RERs for optimizing the objectives.

In Ref. [50], an IEEE 30-bus test system considering energy storage subsystems was investigated by applying a multi-objective problem through heuristic algorithms. The multi-objective optimization problem was considered for minimizing the fuel cost and emission, as well as for improving the voltage profile. In Ref. [51], the "PSOGSA" algorithm, for economical-environmental combination optimization, was proposed on three case studies while considering different cost curves and various constraints in a multi-objective framework. In Ref. [52], the positive effects of renewable energy sources such as wind turbines and photovoltaic system on improving the reliability index in the MGs were investigated. Power of renewable resources was modeled using Weibull and beta distribution functions and simulated based on the Monte Carlo method. In Ref. [53], the optimal power flow related to several MGs in the presence of uncertain load and generated power by renewable resources was investigated. The load, solar radiation power, and ambient temperature, as the factors affecting the power generated by the PV system, were modeled using the normal distribution functions and the power generated by wind generators by the Weibull distribution function. Reference [54] presented a multi-objective evolutionary algorithm to solve the combined economic emission dispatch (CEED) problem in the presence of wind energy in order to minimize costs and pollution emitting. In Ref. [48], the interval optimization method was applied to a modified 112 bus IEEE MG to simultaneously optimize the three objective functions of operation cost, voltage deviation, and steady-state voltage stability. The Pareto front method was applied and the obtained results indicated that the obtained solutions from the proposed method had more convergence and flexibility than the classical methods. Due to the uncertainty of the power generation of renewable energy sources, in order to reduce the risk of economic power dispatch methods in MGs, it is necessary to model the uncertainties related to the power generation and demand [55-57]. However, in many references, such as [58-62], while analyzing the OPF performance of AC/DC hybrid MGs, uncertainties related to power generation by renewable energy sources and power demand have been ignored. Contrary to these references, in Ref. [63], the intermittent and indefinite behavior of the generated power of renewable sources was considered. Also in Ref. [64], in addition to considering the uncertainty of renewable power sources, the uncertainty of power prices was considered.

The literature confirms the importance of analyzing the OPF problem in the operation and optimization of MGs, especially in the presence of uncertainties, in AC/DC networks. Given the many benefits of using DGs based on renewable energy sources, especially in reducing the environmental impacts, the need to analyze the problem of OPF for MGs concluding the renewable energy sources is focused on in this paper. For this purpose, the mentioned problem is investigated to minimize the losses, operation costs, and amount of emissions.

1.2. Contributions of the paper

In this paper, the OPF problem is applied to a hybrid AC/DC MG in the presence of a wind power plant. The main novelties of this study are:

- Concurrently minimizing the power losses and fuel cost, and reducing greenhouse gas emissions as the objective functions
- Considering the voltage limits of the AC and DC buses, AC voltage angle limits, firing angle of converters, load-generation balance, and power generation limits, as the problem constraints, for the first time
- Proposing the optimization of multi-objective functions, consisting of two objective functions of fuel cost function and emission function, with controllable parameters of converters as the constraints, for the first time
- Modeling the uncertainty of the power generated by wind sources in the OPF problem by the five-point estimation method while considering different costs of wind power plants
- Applying the "fmincon" function in MATLAB software for the first time for this type of problem

1.3. Paper Organization

The remainder of this paper is structured as follows: Section 2 describes the mathematical modeling of the proposed objective functions and the different constraints and limitations applied to the OPF problem. In Section 3, the solution method is reported. In Section 4, the studied power system is detailed and the simulation case studies in different scenarios are presented through the numerical results. Finally, Section 5 presents the most important conclusions.

2. MATHEMATICAL FORMULATION OF THE OPF PROBLEM

In this section, the formulation applied to the OPF problem in an AC/DC hybrid MG, including the objective functions and constraints, is detailed.

2.1. Objective Functions

In a large power system, the objective functions can be selected as one or some of following functions [50, 65]:

A. Minimizing transmission power losses in the AC/DC network

$$Min\ f(x) = \sum_{j=1}^{n_{bus}} P_j = \sum_{j=1}^{n_{bus}} (P_{gj} - P_{dj}) \quad (1)$$

In which P_{gj} and P_{dj} are the active powers generated and demanded in bus *j*, respectively, n_{bus} is the total number of buses in the power system, and P_j is the active power injected to each bus, which includes power generation (positive) and power consumption (negative).

B. Minimizing fuel cost

Typically, the fuel cost function for power generation in a power plant is viewed as a quadratic nonlinear function in terms of active generation capacity. The total fuel cost of system is equal to total cost of all individual units. C_j is the fuel cost function of the jth generator, and P_{gj} is the generator's generation capacity [66-67]:

$$\sum_{j=1}^{n_{bus}} C_j(P_{gj}) = \sum_{j=1}^{n_g} (a_j + b_j.P_{gj} + c_j.P_{gj}^2) \quad (2)$$

In which $a_j(\$/h), b_j(\$/Mwh)$, and $c_j(\$/MW^2h)$ are the cost function's coefficient for each generator, and n_g denotes the number of fossil fuel generators.

In this paper, this function is regarded as Eq. (3):

$$\min\ f_2 = \sum_{j=1}^{5} prob_j.\mathrm{Cos}\,t_j \quad (3)$$

$$\mathrm{Cos}\,t_j = \sum_{j=1}^{n_g} C_j(P_{gj}) + C_{Wind} = \sum_{j=1}^{n_g} (a_j + b_j.P_{gj} + c_j.P_{gj}^2).t_j + C^{op,wind}.P_{Wind}.t_j \quad (4)$$

Where $Prob_j$ indicates the probability percentage of the operating cost in the jth scenario, C_{Wind} $(\$/h)$ represents the cost of the wind power plant, $C^{op,wind}(\$/MWh)$ is the operation cost of the wind power plant and is assumed to be equal to 0, 5, 10, 15, for different cases, and P_{Wind} is the power of the wind generator in MW. Moreover, t_j represents time duration and is equal to 1 hour.

C. Minimizing emission

The goal of emission minimization is to reduce the emission caused by fossil fuels. Several factors influence the amount and rate of greenhouse gas emission, but the main factor in the amount of these gases is the active power generated by thermal power plants. Generally, this relation is a nonlinear quadratic function in terms of the generated active power of thermal power plants.

$$Min\ Emission_j = \sum_{j=1}^{n_g} (\alpha_j + \beta_j.P_{gj} + \gamma_j.P_{gj}^2) \quad (5)$$

where $Emission_j$, P_{gj} are the emission function and the generation capacity of generator j, respectively, while $\alpha_j(kg/h)$, $\beta_j(kg/Mwh)$, and $\gamma_j(kg/MW^2h)$ are the coefficients of air emission due to the consumption of fossil fuels and CO_x production in the j-generator.

In this paper, the objective function of emission is expressed as follows:

$$Min\ f = \sum_{j=1}^{5} \mathrm{Pr}\,ob_j.Emission_j \quad (6)$$

This equation calculates the total emission of generation units in the presence of wind turbines. $\mathrm{Pr}\,ob_j$ is the probability of operating cost in scenario j.

The problems related to minimizing the fuel cost and emissions can be investigated individually. Usually, the OPF based on the cost minimization reduces the fuel cost, but increases the amount of emission. On the contrary, OPF based on emission minimization of emission reduces contamination by minimizing the pollutant emission. However, the fuel cost is increased with this goal. Given these effects, one has to make compromises between two objectives at a given point of operation. In this case, the objective function changes as follows:

$$Min\ f(F_{\cos t}, E_{\cos t}) \quad (7)$$

Equation (7) is a general equation and should be balanced as follows:

$$Min\ \varphi = F_{\cos t} + h * E_{\cos t} \quad (8)$$

$F_{\cos t}$ and $E_{\cos t}$ are the same as those in Equations (3) and (6). The penalty factor of h composes the cost and the emission functions. h is the coefficient which converts the emission to the cost function. The penalty factor of h_j is the ratio of the maximum fuel cost to the maximum emission in the *j*th generation unit:

$$h_j = \frac{a_j + b_j.P_{gj}^{\max} + c_j.P_{gj}^{\max 2}}{\alpha_j + \beta_j.P_{gj}^{\max} + \gamma_j.P_{gj}^{\max 2}} (\$/lb),\ j = 1, 2, ..., n_g \quad (9)$$

After determining the amount of h, the problem is optimized according to Equation (8) [42], [50], [68]. In this paper, minimizations of power losses, cost, and emission are chosen as the objective functions. Variable "x" is an optimization variable and can be any parameter such as the voltage limit in an AC or DC bus, the AC voltage angle limit, the firing angle of the converter, and the power generation limit.

2.2. Modeling different constraints

In a multi-terminal HVDC hybrid network, there are four group constraints for controlling the uncertain power flow. These constraints can be categorized based on a set of equality and inequality constraints, including the limitations of power conversion in the converter, DC power flow constraints, AC power flow constraints, and wind turbine uncertainty modelling.

2.2.1. Power conversion constraints in the converters

The power generated by the wind turbines is an AC power form converted into HVDC power after generation, and is transmitted through submarine cables and transformers. This DC power transmitted through AC converters converts into AC power grid and feeds the ground AC network. Therefore, two DC terminals should be thoroughly analyzed [69].

If the rectifier terminal of the AC to DC is summarized as "r" and the inverter terminal DC to AC is summarized as "i", Kirchhoff rules are shown separately for the rectifier and inverter as follows:

The rectifier's equations:

$$U_{d,0,r} = Kn_r U_{AC,r} \quad (10)$$

$$U_{d,r} = U_{d,0,r} \cos\alpha_r - R_r I_{d,r} \quad (11)$$

$$P_r = U_{d,r} I_{d,r} \quad (12)$$

$$Q_r = U_{d,r} I_{d,r} \tan\varphi_r \quad (13)$$

In which, n is the transformer ratio, $K = (3\sqrt{2})/\pi$.

The inverter's equations:

$$U_{d,0,i} = Kn_i U_{AC,i} \quad (14)$$

$$U_{d,i} = U_{d,0,i} \cos\gamma_i - R_i I_{d,i} \quad (15)$$

$$P_i = U_{d,i} I_{d,i} \quad (16)$$

$$Q_i = U_{d,i} I_{d,i} \tan\varphi_i \quad (17)$$

which $U_{d,0,r}, U_{d,0,i}$ are the ideal per-phase no-load DC voltages after the conversion of AC voltage at the rectifier and inverter terminals, respectively. R_r, R_i are the equivalent resistances of the rectifier and inverter, respectively. α_r, γ_i are the rectifier and inverter firing angles, and φ_r, φ_i determine the power factor at the rectifier and inverter terminals.

The direct current of the line between the rectifier and the inverter is specified by:

$$I_{DC} = I_{DC,r} = I_{DC,i} = I_{DC} = \frac{U_{d,r} - U_{d,i}}{R_{DC}} \quad (18)$$

where R_{DC} is the DC line resistance. Conventionally, from the power flow point of view, a converter acts as a power injector point for both AC and DC systems. Therefore, a general structure is considered for both AC and DC networks at the connection point of the two networks. The active power injected–into AC and DC systems must satisfy the power constraint as follows:

$$P_{AC,m} + P_{DC,m} + P_{loss,m} = 0 \quad (19)$$

$P_{AC,m}$, $P_{DC,m}$, $P_{loss,m}$ represent the active power injected into the AC and DC systems and the active power losses in the *m*th converter, respectively. The power losses are modeled as a quadratic equation in terms of the converter current:

$$P_{loss,m} = a_m + b_m I_{C,m} + c_m I_{Cm}^2 \quad (20)$$

in which a_m, b_m, c_m are the coefficients of the power losses of VSC and dependent to power electronic device functionality. The equation of the converter's current is obtained as follows:

$$I_{Conv,m} = \frac{\sqrt{P_{Conv,m} + Q_{Conv,m}}}{U_{Conv,m}} \quad (21)$$

One of the most important constraints governing the converters is:

$$-I_{Conv,m,max} \le I_{Conv,m} \le I_{Conv,m,max} \quad (22)$$

In this paper, the converters are considered as lossless equipment. In the steady-state condition, the *m*th VSC converter is modeled as a controlled voltage source from the perspective of the AC system, which produces voltage $\vec{U}_{AC,m}$ and injects power $\vec{S}_{AC,m} = P_{AC,m} + jQ_{AC,m}$ into *n*th node.

$$\begin{aligned} P_{AC,m} &= U_{AC,m}^2 G_{AC,mn} \\ &- U_{AC,m} U_{AC,n} G_{AC,mn} \cos(\delta_{AC,m} - \delta_{AC,n}) \\ &- U_{AC,m} U_{AC,n} B_{AC,mn} \sin(\delta_{AC,m} - \delta_{AC,n}) \end{aligned} \quad (23)$$

$$\begin{aligned} Q_{AC,m} &= -U_{AC,m}^2 B_{AC,mn} \\ &- U_{AC,m} U_{AC,n} G_{AC,mn} \sin(\delta_{AC,m} - \delta_{AC,n}) \\ &+ U_{AC,m} U_{AC,n} B_{AC,mn} \cos(\delta_{AC,m} - \delta_{AC,n}) \end{aligned} \quad (24)$$

$$P_{AC,m} - P_{AC,n} - P_{loss,AC,mn} = 0 \quad (25)$$

$$Q_{AC,m} - Q_{AC,n} = 0 \quad (26)$$

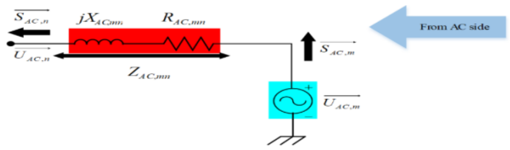

Fig. 1. VSC configuration from the AC system

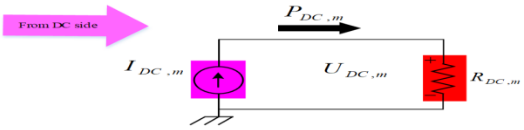

Fig. 2. VSC configuration from the DC system

In which $G_{AC,mn} + jB_{AC,mn} = 1/Z_{AC,mn}$ is the admittance of the AC transmission line between m and n nodes if it is seen from the AC system side of each phase [70].

2.2.2. DC load flow constraints

From the perspective of the DC system, the converter system can be viewed as a controllable current source with the constant value of $I_{DC,m}$. The total active power injected by the mth converter into the DC system is obtained by:

$$I_{DC,m} = \sum_{n=1}^{n_{DC}} Y_{DC,mn}\left(U_{DC,m} - U_{DC,n}\right) \tag{27}$$

$$P_{DC,m} = U_{DC,m} I_{DC} + P_{loss,DC,mn} \tag{28}$$

In addition to the constraint shown as Equation (22), there are two more inequality constraints for the converters:

$$U_{DC,m,min} \le U_{DC,m} \le U_{DC,m,max} \tag{29}$$

$$I_{DC,m,min} \le I_{DC,m} \le I_{DC,m,max} \tag{30}$$

2.2.3. AC load flow constraints

The most important constraints of the AC load flow are as follows:

$$\sum_{k\in m} P_{Gk} - \sum_{k\in m} P_{Lk} - \sum_{k\in m} P_{Conv,k} = \sum_{n=1}^{n_{AC}} U_{AC,m} U_{AC,n} G_{AC,mn} \cos\left(\delta_{AC,m} - \delta_{AC,n}\right) + \sum_{n=1}^{n_{AC}} U_{AC,m} U_{AC,n} B_{AC,mn} \sin\left(\delta_{AC,m} - \delta_{AC,n}\right) \tag{31}$$

$$\sum_{k\in m} Q_{Gk} - \sum_{k\in m} Q_{Lk} - \sum_{k\in m} Q_{Conv,k} = \sum_{n=1}^{n_{AC}} U_{AC,m} U_{AC,n} G_{AC,mn} \sin\left(\delta_{AC,m} - \delta_{AC,n}\right) - \sum_{n=1}^{n_{AC}} U_{AC,m} U_{AC,n} B_{AC,mn} \cos\left(\delta_{AC,m} - \delta_{AC,n}\right) \tag{32}$$

where $P_{Conv,k}$, $Q_{Conv,k}$ denote the active and reactive generated powers by the converter if the VSC is connected to the *k*th node; and P_{Lk} , Q_{Lk} represent the active and reactive power consumption at *k*th node [71].

2.2.4. Wind turbine uncertainty modeling

The Weibull probability distribution function is usually adopted to model the uncertainty of wind speed, as an effective method. This distribution function is a three-parametric function, but for wind speed, it can be expressed in a two-parametric one [72]:

$$f\left(v|\lambda,k\right) = \left(\frac{k}{\lambda}\right)\left(\frac{v}{\lambda}\right)^{k-1} e^{-\left(\frac{v}{\lambda}\right)^k} \tag{33}$$

In which *v* is the wind speed in (m/s), k>0 is the dimensionless shape parameter, and λ>0 is the scale parameter with the same wind speed unit. There are several methods for determining the Weibull distribution parameters, one of the most common of which is the method of moments [72-73]:

$$\bar{v} = \lambda.\Gamma\left(1+\frac{1}{k}\right), \; k = \left(\frac{0.9874}{\sigma/\bar{v}}\right)^{1.0983} \tag{34}$$

$\bar{v}$ is the average wind speed. Generally, in POP F analysis, the distribution of wind turbine output is required, instead of wind speed distribution. Variable-speed wind turbines are described with a specific curve, called the characteristic curve, which indicates the relationship between wind speed and wind turbine output. For simplification, a linear approximation method is applied as follows:

$$Y = \begin{cases} 0 & X \le V_{ci} \text{ or } X \ge V_{co} \\ \alpha + \beta X & V_{ci} \le X \le V_{n0} \\ M & V_{no} \le X \le V_{co} \end{cases} \tag{35}$$

where *Y* is the wind power, *X* is the actual wind speed, *M* is the maximum wind turbine power, α and β are the linear parameters, V_{ci} , V_{co} , V_{no} are the low cut-off, high cut-off, and the natural wind speeds, respectively. To reduce the computational complexity in the POPF analysis, the continuous probability distribution of the wind source is replaced with a discrete distribution, known as the point estimation method (PEM). The main idea is to divide continuous random variable values into some finite quantities. Therefore, instead of using a continuous PDF, a discrete five-point probability function is applied in studies. The 10-year wind data in City of Madison are used as an example. The rated output of the wind power unit is assumed to be 113 MW wind power, which yields with the penetration of 40%. The cut-off, rated, and high cut-off speeds are assumed to be 5.3, 40, and 5.13 m/s, respectively. The parameters are summarized in Table 1 [50]: also, it was assumed that for maximum power of wind 113 MW, K=2.5034, λ=10.0434, α=-39.55, and β=11.3 [67]. In this paper, the "fmincon" function in MATLAB software and "interior-point" algorithm have been proposed as a useful method for nonlinear optimization problems [74].

Table 1. Five-point discrete estimation of produced wind power

Wind (MW)	0	14.54	55.79	98.12	113
Probability (%)	6.89	20.44	40.48	19.92	12.27

3. SOLUTION METHOD

Optimization problems, regardless of their structure, fall into two general categories: single-objective and multi-objective problems. First, it is necessary to extract the mathematical structure of the studied problem. To derive the mathematical model of an optimization problem, the following four steps must be fully identified and defined:

1. Define a set of variables of $[x_1, x_2, x_3, \ldots]$ as the decision variables or optimization variables.
2. Describe a function (s) called the objective function (s), which should be optimized (minimized or maximized), in which the decision variables are applied and a real value is returned, depending on the type of problem.
3. Define an allowable or feasible range for each of the decision variables.
4. Determine a set of equal and unequal constraints applying to decision variables and limiting the objective function (s).

General structure of a single objective problem is as:

$$\min f(x), \quad X = [x_1, x_2, \ldots, x_k]$$
$$subject\ to \begin{cases} g_i(x) \le 0 & i = 1, 2, \ldots, N_{ueq} \\ h_i(x) = 0 & i = 1, 2, \ldots, N_{eq} \end{cases} \quad (36)$$

In which $f(x)$ is the objective function that should be minimized, over the vector of X, $g_i(x)$, and $h_i(x)$ are the equal and non-equal sets of constraints [75].

In multi-objective optimization problems, where different objectives are considered, arranging the set of solutions becomes very complicated. These objective functions are usually disproportionate and often contradictory. Multi-objective optimization problems with conflicting objective functions result in an optimal response set. The reason for the large number of optimal solutions is that by considering all the objective functions simultaneously, no solution can optimize all the objective functions. This set of solutions is called the Pareto optimal set [76]. In general, multi-objective optimization problems can be defined as follows:

$$\min \vec{f}(\vec{x}) = \left\{ f_1(\vec{x}), f_2(\vec{x}), \ldots, f_n(\vec{x}) \right\}$$
$$subject\ to \begin{cases} \vec{g}(\vec{x}) \le 0 \\ \vec{h}(\vec{x}) = 0 \end{cases} \quad (37)$$

where $\vec{x}$ is the vector of decision variables and $\vec{f}(\vec{x})$ is a set of objective functions that must be minimized. Functions $\vec{h}(\vec{x}), \vec{g}(\vec{x})$ represent a set of equal and unequal constraints that define the possible and feasible regions of the next discrete or continuous n-dimensional response space.

One of the multi-objective optimization methods is weighted sum optimization. Using this method, one weight is assigned to each of the objective functions and the importance and value of each of the objectives in different weights are examined. In general, this method is implemented as follows:

$$\min f_{ws}(x) = \sum_{i=1}^{m} w_i f_i(x) \quad (38)$$

In this paper, two objective functions of operation cost and pollution in different weights are considered and to solve the optimization problem, "fmincon" function in MATLAB software by using the interior point (IP) algorithm is applied. By using this function, a minimum of a nonlinear constrained multi-objective function can be obtained. In fact, the “fmincon” optimization function examines the solutions in such a way that the minimum values of all the variables are found. In general, the “fmincon” function is structured in MATLAB as follows:

$$\min_x f(x), \text{subject to} \begin{cases} c(x) \le 0 \ , & c_{eq}(x) = 0 \\ A.x \le b \ , & A_{eq}.x = B_{eq} \\ l_b \le x \le u_b \end{cases} \quad (39)$$

$c(x), c_{eq}(x)$ describe the non-linear non-equal, and equal constraints. A , and b define the relevant coefficients for linear non-equal constraints. A_{eq}, B_{eq} determine the relevant coefficients for linear equal constraints. l_b , and u_b describe the lower and upper limits of decision variable x. Generally, Fmincon is defined in the following form:

$$[x,\ fval] = fmincon(fun, x_0,\ A, b,\ A_{eq}, B_{eq}, l_b, u_b,\ nonlcon) \quad (40)$$

The IP algorithm, which is known as barrier method, is appropriate for solving a chain and order of approximate minimization problems. For $\mu > 0$, the approximate problem is as follows:

$$\min_{x,s} f_\mu(x, s) = \min_{x,s} f(x) - \mu \sum_i \ln(s_i),$$
$$subject\ to\ h(x) = 0 \ , \ g(x) + s = 0 \quad (41)$$

There are s_i slack variables equal to the number of inequality constraints, g. For remaining $\ln(s_i)$ to be finite and archetypal, $s_i > 0$. The minimum value of f_μ approaches minimum value of f, while μ decreases to zero. Eq. (40) is a chain of linear constrained problems. This algorithm is more suitable for solving the complex problems, with a large number of variables [77-79].

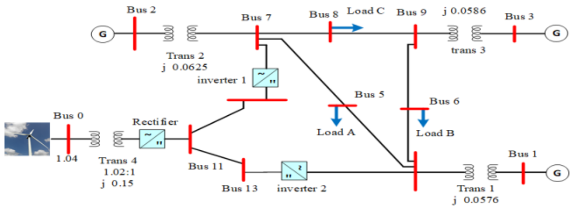

Fig. 3. Multi-terminal hybrid AC/DC network and wind farm [80]

Table 2. The line impedance and shunt admittance of each line

Line between the buses	impedance z (pu)	$B_c/_2$ (pu)
4-5	0.010+j 0.161	j 0.088
4-6	0.017+j 0.092	j 0.079
5-7	0.032+j 0.161	j 0.153
6-9	0.039+j 0.179	j 0.179
7-8	0.0085+j 0.072	j 0.745
8-9	0.0119+j 0.1008	j 0.1045
11-12	0.04	-
11-13	0.05	-
Converter	0.0001+j 0.1643	-

Table 3. Bus data

Bus Number	Bus type
Bus 1	Slack Bus
Bus 2,3,10	PV Bus
Bus 5,6,8	PQ Bus
Bus 11,12,13	DC Bus

Table 4. VSC constraints and control variables

Constraint and control variables
$0.9 \leq V_{AC,DC} \leq 1.1$
$-0.8 \leq \theta_{AC} \leq 0.8$
$5 \text{ deg} \leq \alpha_{rec10}, \gamma_{inv12}, \gamma_{inv13} \leq 60 \text{ deg}$

Table 5. Cost and emission function's coefficients and the capacity of each generator

	Cost function's coefficients			Emission function's coefficients			Generation limits (MW)	
Bus	a_i	b_i	c_i	α_i	β_i	γ_i	Min	Max
1	150	5	0.11	22.983	-0.9	0.0126	10	250
2	600	1.2	0.085	29	-0.1	0.0034	10	300
3	335	1	0.1225	22.05	-1.249	0.013	10	270

4. SIMULATION ZASE STUDIES

Figure 3 displays the single-line diagram of the AC/DC hybrid system. The system consists of 10 AC buses, three DC buses, and VSC-MTDC converters. The system data are as follows: $Load_A = 1.25 + j0.5\ (pu)$, $Load_B = 0.9 + j0.3\ (pu)$, $Load_C = 1 + j0.35\ (pu)$, $Base\ MVA: 100\ MVA$

4.1. Simulation Results

4.1.1. Power Loss Minimization

Considering Eq. (1) and the relevant constraints mentioned in the previous section, minimizing overall power losses in studied system is reported as follows:

4.1.2. Total Cost Minimization

Considering Equations (3) and (4) and the coefficients of fuel cost functions and generation constraints of each unit, fuel cost minimization is considered as the objective function. The cost of wind power generator is assumed to be C=0, 5, 10, and 15 $^{\$}/_{MWh}$. It should be noted that all costs are presented in terms of ($/h), Pr. is the probability, and P_{gi}, P_d, are in pu.

Table 6. Optimal values obtained from minimizing losses

Wind (MW)	0	14.54	55.79	98.12	113
Pr. (%)	6.89	20.44	40.48	19.92	12.27
P_{loss}(pu)	2.8596	2.7143	2.3017	1.8784	1.7296

Table 7. Optimal values obtained from the cost minimization

Wind (MW)	0	14.54	55.79	98.12	113
Pr. (%)	6.89	20.44	40.48	19.92	12.27
P_{g1}	0.8656	0.8201	0.6909	0.5583	0.5116
P_{g2}	1.3438	1.2848	1.1176	0.9460	0.8857
P_{g3}	0.9406	0.8997	0.7836	0.6646	0.6227
P_d	3.15	3.0046	2.5921	2.1688	2.02
$Cost_i$ (C=0)	5216	4873.7	3981.9	3188.6	2939.1
	Total Cost				3963.2
$Cost_i$ (C=5)	5216	4946.4	4260.8	3679.2	3504.1
	Total Cost				4258
$Cost_i$ (C=10)	5216	5019.1	4539.8	4169.8	4069.1
	Total Cost				4552.9
$Cost_i$ (C=15)	5216	5091.8	4818.7	4660.4	4634.1
	Total Cost				4847.7

Table 8. Optimal values obtained from the cost minimization while considering the losses

Wind (MW)	0	14.54	55.79	98.12	113
P (%)	6.89	20.44	40.48	19.92	12.27
P_{g1}	2.4268	0.8116	0.1008	0.1000	0.5225
P_{g2}	0.5740	1.8436	2.0293	1.9186	0.9217
P_{g3}	1.1796	1.1691	1.0750	0.3780	٠.7598
P_{loss}^{*}	103.0343	81.9700	61.3043	22.7830	18.3940
$Cost_i$ (C=0)	10948	7117	6413.7	4718	3262.2
	Total Cost				6145.4
$Cost_i$ (C=5)	10948	7189.7	6692.7	5208.6	3827.2
	Total Cost				6440.2
$Cost_i$ (C=10)	10948	7262.4	6971.6	5699.2	4392.2
	Total Cost				6735.1
$Cost_i$ (C=15)	10948	7335.1	7250.6	6189.8	4957.3
	Total Cost				7029.9

* in terms of MW.

4.1.3. Fuel cost minimization considering power losses

To minimize the fuel cost considering the losses, we consider the cost function obtained from the previous section with the equality and inequality constraints mentioned as the objective function. As illustrated in the previous section, the results by taking different costs for the wind generator into account are obtained as follows:

4.1.4. Fuel cost and emission minimization neglecting power losses

Based on what has already been said about two fuel cost and emission functions, the desired objective function is obtained using Equation (9) and by determining h and placing it in Eq. (8). Different weights are assigned to each objective function and the obtained new objective function is minimized in the form of $Minimize\ \varphi = w_1.F_{cost} + w_2.h * E_{cost}$. The results are summarized in the following tables by changing the power generated by the wind power plant as well as altering the operating cost of the wind generator. The results of the two- and single-objective functions are related to the conditions with $c^{op,wind}$=0$^{\$}/_{MWh}$.

Table 9(a). Optimal values obtained from minimizing cost and emission considering $P_{wind} = 0$ (MW), Pr.=6.89%

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
P_{g1}	0.8656	0.7984	0.7387
P_{g2}	1.3438	1.4543	1.5611
P_{g3}	0.9406	0.8973	0.8502
f_{val}	359.3842	249.0900	136.4111
f_1	359.3842	360.6015	364.0605
f_2	141.2903	137.5785	136.4111
$Emission_i(kg/h)$	2050.7	1996.8	1979.8
$Cost_i$ (C=0)	5216	5233.7	5283.9
$Cost_i$ (C=5)	5216	5233.7	5283.9
$Cost_i$ (C=10)	5216	5233.7	5283.9
$Cost_i$ (C=15)	5216	5233.7	5283.9

Table 9(b). Optimal values obtained from the cost and emission minimization considering $P_{wind} = 14.54$ (MW), Pr.=20.44%

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
P_{g1}	0.8201	0.7633	0.7131
P_{g2}	1.2848	1.3771	1.4661
P_{g3}	0.8997	0.8642	0.8254
f_{val}	996.1862	682.0828	363.0465
f_1	996.1862	998.7058	1005.9
f_2	373.1478	365.4599	363.0465
$Emission_i(kg/h)$	1825.6	1788	1776.2
$Cost_i$ (C=0)	4873.7	4886	4921
$Cost_i$ (C=5)	4946.4	4958.7	4993.7
$Cost_i$ (C=10)	5019.1	5031.4	5066.4
$Cost_i$ (C=15)	5091.8	5104.1	5139.1

Table 9(c). Optimal values obtained from the cost and emission minimization considering $P_{wind} = 55.79$ (MW), Pr.=40.48%

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
P_{g1}	0.6909	0.6637	0.6404
P_{g2}	1.1176	1.1579	1.1968
P_{g3}	0.7836	0.7705	0.7549
f_{val}	1611.9	1065	516.2534
f_1	1611.9	1612.8	1615.6
f_2	520.1666	517.1759	516.2534
$Emission_i(kg/h)$	1285	1277.6	1275.3
$Cost_i$ (C=0)	3981.9	3984.3	3991
$Cost_i$ (C=5)	4260.8	4263.2	4270
$Cost_i$ (C=10)	4539.8	4542.2	4548.9
$Cost_i$ (C=15)	4818.7	4821.1	4827.8

Table 9(d). Optimal values obtained from the cost and emission minimization considering $P_{wind} = 98.12$ (MW), Pr.=19.92%

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
P_{g1}	0.5583	0.5615	0.5658
P_{g2}	0.9460	0.9330	0.9204
P_{g3}	0.6646	0.6743	0.6826
f_{val}	635.1649	405.2631	175.2569
f_1	635.1649	635.2186	635.3683
f_2	175.4731	175.3076	175.2569
$Emission_i(kg/h)$	880.8889	880.0583	879.8039
$Cost_i$ (C=0)	3188.6	3188.8	3189.6
$Cost_i$ (C=5)	3679.2	3679.4	3680.2
$Cost_i$ (C=10)	4169.8	4170	4170.8
$Cost_i$ (C=15)	4660.4	4660.6	4661.4

Table 9(e). Optimal values obtained from the cost and emission minimization considering $P_{wind} = 113$ (MW), Pr.=12.27%

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
P_{g1}	0.5116	0.5256	0.5396
P_{g2}	0.8857	0.8540	0.8232
P_{g3}	0.6227	0.6404	0.6572
f_{val}	360.6223	227.6808	94.3881
f_1	360.6223	360.8007	361.3138
f_2	95.1021	94.5610	94.3881
$Emission_i(kg/h)$	775.0783	770.6680	769.2596
$Cost_i$ (C=0)	2939.1	2940.5	2944.7
$Cost_i$ (C=5)	3504.1	3505.5	3509.7
$Cost_i$ (C=10)	4069.1	4070.5	4074.7
$Cost_i$ (C=15)	4634.1	4635.5	4639.7

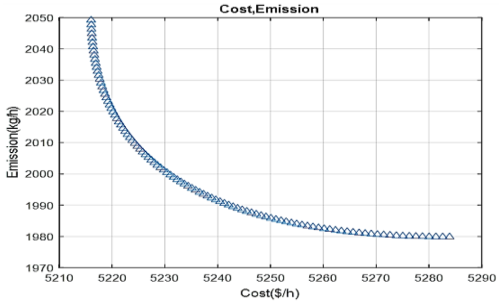

Fig. 4. Curve obtained from the results of optimizing cost and emission functions of Table 9(a)

The constant values with the changes in the operation cost of the wind generator are the result of the emission function and the generating capacity power of the generators. It should be noted that $f_{val}$is the same as the result of the two-objective function. The results of Table 9(a) are plotted in Fig. 4. If the results of the fuel cost and emission functions derived from the tables are plotted for other cases, the curves will be like Figure (4). It is observed that emission decreases as fuel costs increase. A comparison of the tables shows that with an increase in the power generated by the wind generator, the cost of production (which includes the cost of wind generators) and the emission generated by the fossil fuels are reduced. Also, the first and second objective functions, which include the probability of the presence of the wind farm, vary with the probability percentage. Ultimately, by increasing the power generated by the wind generator, the power generated, thermal units decrease. By summing up the total results of different generating powers of the wind generator and the unique probability percentages, the following results can be achieved:

4.1.5. Minimizing fuel cost and emission considering power losses

By considering the conditions mentioned in Section 4.1.4., with modeling the power losses, the following results are obtained:

Similar to the previous section, the results of two- and single-objective functions correspond to the condition $c^{op,wind}$=0$\$/_{MWh}$. The values which remain constant by changing the operating cost of the wind generator are the result of the emission function and generation of thermal power plants.

Table 10. General results of Tables 8(a-e)

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
$Emission_i(kg/h)$	1305.2	1290.1	1285.4
$Cost_i$ (C=0)	3963.2	3968.2	3982.2
$Cost_i$ (C=5)	4258	4263	4277
$Cost_i$ (C=10)	4552.9	4557.8	4571.8
$Cost_i$ (C=15)	4847.7	4852.6	4866.6

Table 11(a). Optimal values obtained from cost and emission minimization of considering losses, $P_{wind} = 0$ (MW), Pr.=6.89%

Results	$w_1 = 1, w_2 = 0$	$w_1 = 0.5, w_2 = 0.5$	$w_1 = 0, w_2 = 1$
P_{g1}	2.4268	2.4034	2.3662
P_{g2}	0.5740	0.5286	0.6271
P_{g3}	1.1796	1.2418	1.3049
P_{loss}^*	103.0343	102.3843	114.8189
f_{val}	754.3208	707.2506	656.4472
f_1	754.3208	754.7993	761.5337
f_2	661.3174	659.7019	656.4472
$Emission_i(^{kg}/_h)$	9598.2	9574.8	9527.5
$Cost_i$ (C=0)	10948	10955	11053
$Cost_i$ (C=5)	10948	10955	11053
$Cost_i$ (C=10)	10948	10955	11053
$Cost_i$ (C=15)	10948	10955	11053

Table 11(b). Optimal values obtained from cost and emission minimization considering losses, $P_{wind} = 14.54$ (MW), Pr.=20.44%

Results	$w_1 = 1, w_2 = 0$	$w_1 = 0.5, w_2 = 0.5$	$w_1 = 0, w_2 = 1$
P_{g1}	0.8116	0.8530	0.8820
P_{g2}	1.8436	1.9186	1.9708
P_{g3}	1.1691	1.0547	0.9745
P_{loss}^*	81.9700	82.1649	82.2714
f_{val}	1454.7	1049.7	637.1028
f_1	1454.7	1459.2	1467.7
f_2	455.6415	640.2473	637.1028
$Emission_i(^{kg}/_h)$	3207.6	3132.3	3116.9
$Cost_i$ (C=0)	7117	7139	7180.5
$Cost_i$ (C=5)	7189.7	7211.7	7253.2
$Cost_i$ (C=10)	7262.4	7284.4	7325.9
$Cost_i$ (C=15)	7335.1	7357.1	7398.6

Table 11(c).Optimal values obtained from cost and emission minimization considering losses, $P_{wind} = 55.79$ (MW), Pr.=40.48%

Results	$w_1 = 1, w_2 = 0$	$w_1 = 0.5, w_2 = 0.5$	$w_1 = 0, w_2 = 1$
P_{g1}	1.0083	0.1742	0.32279
P_{g2}	2.0293	2.1432	2.2224
P_{g3}	1.0750	0.9063	0.7893
P_{loss}^*	61.3043	63.1681	64.7428
f_{val}	2596.3	1889.6	1148.3
f_1	2596.3	2616.6	2656.6
f_2	1232.2	1162.5	1148.3
$Emission_i(^{kg}/_h)$	3044.1	2871.8	2836.6
$Cost_i$ (C=0)	6413.7	6463.9	6562.8
$Cost_i$ (C=5)	6692.7	6742.9	6841.8
$Cost_i$ (C=10)	6971.6	7021.8	7120.7
$Cost_i$ (C=15)	7250.6	7300.8	7399.7

Table 11(d). Optimal values obtained from cost and emission minimization considering losses, $P_{wind} = 98.12$ (MW), Pr.=19.92%

Results	$w_1 = 1, w_2 = 0$	$w_1 = 0.5, w_2 = 0.5$	$w_1 = 0, w_2 = 1$
P_{g1}	0.1000	0.1000	0.1000
P_{g2}	1.9186	1.8746	1.8461
P_{g3}	0.3780	0.5229	0.6162
P_{loss}^*	22.7830	32.8622	39.3470
f_{val}	939.8246	674.6924	408.7072
f_1	939.8246	945.2081	954.3836
f_2	431.2987	412.1767	408.7072
$Emission_i(^{kg}/_h)$	2165.2	2069.2	2051.7
$Cost_i$ (C=0)	4718	4745	4791.1
$Cost_i$ (C=5)	5208.6	5235.6	5281.7
$Cost_i$ (C=10)	5699.2	5726.2	5772.3
$Cost_i$ (C=15)	6189.8	6216.8	6262.9

Table 11(e). Optimal values obtained from cost and emission minimization considering losses, $P_{wind} = 113$ (MW), Pr.=12.27%

Results	$w_1 = 1, w_2 = 0$	$w_1 = 0.5, w_2 = 0.5$	$w_1 = 0, w_2 = 1$
P_{g1}	0.5225	0.5357	0.5450
P_{g2}	0.9217	0.9404	0.9235
P_{g3}	0.7598	0.7326	0.7135
P_{loss}^*	18.3940	18.8643	19.1933
f_{val}	400.2871	256.5596	112.5461
f_1	400.2871	400.4551	400.7742
f_2	113.2390	112.6642	112.5461
$Emission_i(^{kg}/_h)$	922.8930	918.2087	917.2464
$Cost_i$ (C=0)	3262.3	3263.7	3266.3
$Cost_i$ (C=5)	3827.3	3828.7	3831.3
$Cost_i$ (C=10)	4392.3	4393.7	4396.3
$Cost_i$ (C=15)	4957.3	4958.7	4961.3

Table 12. General results of Tables 11(a-e)

Results	$w_1 = 1$, $w_2 = 0$	$w_1 = 0.5$, $w_2 = 0.5$	$w_1 = 0$, $w_2 = 1$
$Emission_i(^{kg}/_h)$	3093.7	2987.3	2963
$Cost_i$ (C=0)	6145.4	6176.3	6241
$Cost_i$ (C=5)	6440.3	6471.1	6535.9
$Cost_i$ (C=10)	6735.1	6765.9	6830.7
$Cost_i$ (C=15)	7029.9	7060.8	7125.5

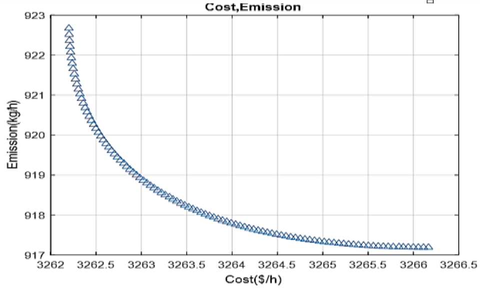

Fig. 5. The curve obtained from the results of cost and emission functions of Table 11(e)

The results of Table 11(e) are plotted in Fig. 5. By summarizing the results of tables, the following results are obtained, as Table 12.

By comparing the results of Tables 6-12 and Figures 4-5, some important notes can be easily obtained:

- By increasing the power generation of wind generators, the loss of transmission lines will be reduced.
- In the case that the objective function is selected as the fuel cost minimization when the operating cost of the wind power plant is considered to be constant, as the power generated by the wind power plants is increased, the fuel cost (including the operating cost of wind generators) and the power generated by the other generators will be reduced. If we assume the wind generator's capacity to be constant and increase the cost of operation for these generators, the fuel cost will be raised. If the objective function is assumed to be cost minimization while considering the power losses, the fuel cost will be increased (compared to the case where power losses are neglected). Nevertheless, by considering a constant cost for wind power plants, the fuel cost will be reduced as the generated power by the wind power plants is raised.
- According to Table 7, if the goal is to minimize the fuel cost neglecting the losses, considering a constant operating cost of the wind generator, by increasing the generation capacity of the wind generator, the fuel cost (including the operating cost of the wind generator) and the generating capacity of power plant generators will be reduced. By considering the constant generating capacity for wind generators, an increase in the operating cost of the wind generator will lead to an obvious increase in the cost of fuel. Meanwhile, the generating capacity of other

generators will remain constant. If the objective is to minimize the costs by considering losses, the cost of fuel (compared to the case where losses are neglected) will increase. Comparing Tables 7 and 8 shows that, in the case where the generating capacity of the wind farm is zero, the fuel cost in the case of considering losses is almost twice as much as in the case where losses are neglected. In other cases, in which the generation production capacity of the wind farm increases from 14.54 MW to 113 MW, the fuel cost, if losses are taken into account, is from 10% to 61% higher than the condition neglecting losses. According to Table 8, in terms of the fixed cost of the wind farm, the fuel cost decreases with the increase of generation capacity by the wind farm. It can be seen that by reducing the operating cost of wind generator from $c^{op,wind}$=15 $/MWh to $c^{op,wind}$=0 $/MWh, the total cost in the case of considered losses is 45% to 55 % of the total cost of production in the absence of losses. In fact, with the increase in the operating cost of the wind generator, the rate of increase in the total cost, taking into account the losses, decreases compared to the case where the losses are not taken into account. For example, if the cost of a wind generator is considered 0 $/MWh, the total cost of production with losses is 55% higher than the total cost without losses. The total cost of production in terms of losses for 15 $/MWh is 45% more than the total cost without losses.

- By comparing Tables 7 and 8, it can be observed that in the case of non-generated power by the wind power plant, the fuel cost, while considering the electrical losses, is approximately twice the case where there is no loss. Also, when the wind power generation is decreased from 113 MW to 14.54 MW, the fuel cost will be increased form 10% to 61% when considering the losses compared to no-losses cases.
- If the objective function is selected as the simultaneous minimization of fuel cost and emission costs, the power generated from the first to the third thermal generators, as well as the fuel cost and emission costs, will be reduced as the wind power generation is increased. In corresponding weights, and in cases where the power generated by the wind generator is constant, by increasing the operating cost of the wind generator, the generated power of the other generators and emission remain unchanged, while the fuel cost is increased. If the objective is to minimize the costs of fuel and emission while considering the power losses, then the cost of fuel and emission will undoubtedly increase a little less than the conditions where the power losses are not taken into account. By increasing the generated power of the wind power plant, the fuel and emission costs, as well as power losses, are reduced.
- According to Tables 9 (a) to 9 (e), if the objective is to simultaneously minimize fuel costs and pollution without loss, at applied weight corresponding to the objective functions, by increasing the generating capacity by the wind generator, the generating capacity by the first to third generators, the fuel cost and generation as well as pollution are reduced. In this case, at the corresponding weight and with the increase of generation capacity by the wind generator, the fuel cost and generation are 2.54 to 3.8 times of the pollution. If we consider the power generated by the wind generator to be constant, at the corresponding weight, with the increase in the operating cost of the wind generator, the generating power of other generators and the pollution remain constant, but the fuel cost increases. According to Tables 11 (a) to 11 (e), if the objective is to minimize the fuel costs and pollution by considering losses, they will experience an increase in fuel costs and pollution compared to the case where losses are neglected. By increasing generation capacity by wind generator, the cost of fuel and pollution as well as transmission line losses will be reduced and will be close to their minimum solutions. In this case, at the corresponding weight and with the increase in generation capacity by the wind generator, the fuel cost and production are 1.14 to 3.6 times of the pollution. Comparing two Tables 10 and 12 demonstrates that if the cost of wind generator decreases from 15 $/MWh to 0 $/MWh, the total cost in terms of losses and pollution is 45% to 55% more than the total cost in terms of pollution neglecting losses. It is also observed that by applying different weight, the total pollution in terms of losses is 2.30 to 2.40 times of the total pollution without losses.
- According to Figures 4-5, emission will be reduced by increasing the fuel and emission costs.

5. CONCLUSION

MGs are the small-scale examples of the centralized electrical system, which are used for different aims such as the minimization of power losses, fuel cost, and GHG emissions. They can also provide the possibility of using distributed energy resources based on renewable energy energies. Using wind power plants has been increased because of their high efficiency, low cost of electricity generation, and high ability in generating large-scale power. In this paper, while considering the uncertainty of the wind power plant and the VSC-MTDC converters, the probabilistic optimal power flow in an AC/DC hybrid system was investigated via the "fmincon" function of MATLAB by applying the "interior point" algorithm. The uncertainty of the wind power plant was modeled using the method of moments by applying the five-point estimation method. The system was analyzed in different scenarios while taking different network constraints into account. The results showed that, by increasing the generated power of wind power plants, the transmission losses, fuel cost, GHG emission, and power generated by thermal units were decreased. It was concluded that the MG performance was improved in the presence of converters and wind power plants.

REFERENCES

[1] D. Olivares et al. “Trends in microgrid control”, *IEEE Trans. Smart Grid*, vol. 54, pp. 1905-19, 2014.
[2] W. Shi et al., “Real-time energy management in microgrids”, *IEEE Trans. Smart Grid*, vol. 81, pp. 228-38, 2015.
[3] W. Hu, P. Wang and H. Gooi, “Toward optimal energy management of microgrids via robust two-stage optimization”, *IEEE Trans. Smart Grid*, vol. 92, pp. 1161-74, 2016.
[4] B. Panigrahi et al., “Multi-objective fuzzy dominance based bacterial foraging algorithm to solve economic emission dispatch problem”, *Energy*, vol. 35, pp. 4761-70, 2010.
[5] R. Hamidi et al., “Distributed cooperative control system for smart microgrids”, *Electr. Power Syst. Res.*, vol. 130, pp. 241-250, 2016.
[6] L. Vasquez et al., “Optimal energy management within a microgrid: a comparative study”, *Energies*, vol. 118, pp. 1-22, 2018.
[7] J. Guerrero et al., “Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids”, *IEEE Trans. Ind. Electron.*, vol. 60, pp. 1263-70, 2012.
[8] A. Kaur, J. Kaushal and P. Basak, “A review on microgrid central controller”, *Renew. Sustain. Energy Rev.*, vol. 55, pp. 338-45, 2016.
[9] A. Bidram and A. Davoudi, “Hierarchical structure of microgrids control system”, *IEEE Trans. Smart Grid*, vol. 3, pp. 1963-76, 2012.
[10] L. Minchala-Avila et al., “A review of optimal control techniques applied to the energy management and control of microgrids”, *Procedia Comput. Sci.*, vol. 52, pp. 780-87, 2015.
[11] F. Katiraei et al., “Microgrids management”, *IEEE Power Energy Mag.*, vol. 6, pp. 54-65, 2008.
[12] Z. Shuai et al., “Microgrid stability: Classification and a review”, *Renew. Sustain. Energy Rev.*, vol. 58, pp. 167-179, 2016.
[13] H. Moradi, A. Abtahi and M. Esfahanian, “Optimal operation of a multi-source microgrid to achieve cost and emission targets”, *IEEE Power Energy Conf.*, 2016.
[14] L. Dulău and D. Bică, “Optimization of generation cost in a microgrid considering load demand”, *Proc. Manuf.*, vol. 32, pp. 390-396, 2019.
[15] M. Zia, E. Elbouchikhi and M. Benbouzid, “Microgrids energy management systems: A critical review on methods, solutions, and prospects”, *Appl. Energy*, vol. 222, pp. 1033-55, 2018.
[16] R. Asad and A. Kazemi, “A quantitative analysis of effects of transition from ac to dc system, on loads and generation”, *IEEE Smart Grid Conf.*, 2012.
[17] S. Bahrami, V. Wong and J. Jatskevich, “Optimal power flow for AC-DC networks”, *IEEE Int. Conf. Smart Grid Commun.*, 2014.
[18] M. Zolfaghari, M. Abedi and G. Gharehpetian, “Power flow control of interconnected AC-DC microgrids in grid-connected hybrid microgrids using modified UIPC”, *IEEE Trans. Smart Grid*, vol. 10.6, pp. 6298-07, 2016.
[19] M. Rezvani and S. Mehraeen, “A new approach for steady-state analysis of a hybrid AC-DC microgrid”, *IEEE Texas Power Energy Conf.*, 2019.
[20] T. Adefarati and R. Bansal, “Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources”, *Appl. Energy*, vol. 206, pp. 911-33, 2017.
[21] A. Einaddin, A. Yazdankhah and R. Kazemzadeh, “Power management in a utility connected micro-grid with multiple renewable energy sources”, *J. Oper. Autom. Power Eng.*, vol. 5, pp. 1-10, 2017.
[22] K. Oureilidis and C. Demoulias, “A fault clearing method in converter-dominated microgrids with conventional protection means”, *IEEE Trans. Power Electron.*, vol. 31 pp. 4628-40, 2015.
[23] J. Lopes, A. Madureira and C. Moreira, “A view of microgrids”, *Wiley Interdiscip. Rev.: Energy Environ.*, vol. 2, pp. 86-103, 2013.
[24] Y. Xuan, N. Li and Z. Xu, “A new control strategy with fault ride through capability for VSC based offshore high power oil pump motor power supply system”, *IEEJ Trans. Electr. Electron. Eng.*, vol. 11, pp. 655-64, 2016.
[25] Z. Li et al., “An optimal power flow algorithm for AC/DC hybrid power systems with VSC based MTDC considering converter power losses and voltage droop control strategy”, *IEEJ Trans. Electr. Electron. Eng.*, vol. 13, pp. 1690-98, 2018.
[26] E. Elattar, “Modified harmony search algorithm for combined economic emission dispatch of microgrid incorporating renewable sources”. *Energy*, vol. 159, pp. 496-507, 2018.
[27] S. Brodsky and R. Hahn, “Assessing the influence of power pools on emission constrained economic dispatch”, *IEEE Trans. Power Syst.*, vol. 1, pp. 57-62, 1986.
[28] M. Banaei, “Multi-stage DC-AC converter based on new DC-DC converter for energy conversion”, *J. Oper. Autom. Power Eng.*, vol. 4, pp. 42-53, 2016.
[29] A. Martinez et al., “Modeling of VSC-based HVDC systems for a Newton-Raphson OPF algorithm”, *IEEE Trans. Power Syst.*, vol. 22, pp. 1794-1803, 2007.
[30] A. Martínez, C. Esquivel and C. Camacho, “Voltage source converter based high-voltage DC system modeling for optimal power flow studies”, *Electr. Power Compon. Syst.*, vol. 40, pp. 312-20, 2012.
[31] M. Baradar, M. Hesamzadeh and M. Ghandhari, “Modelling of multi-terminal HVDC systems in optimal power flow formulation”, *IEEE Electr. Power Energy Conf.*, pp. 170-175, 2012.

[32] R. Wiget and G. Andersson, "Optimal power flow for combined AC and multi-terminal HVDC grids based on VSC converters", *IEEE Power Energy Soc. Meet.*, 2012.

[33] M. Baradar, M. Hesamzadeh and M. Ghandhari, "Second-order cone programming for optimal power flow in VSC-type AC-DC grids", *IEEE Trans. Power Syst.*, vol. 28.4, pp. 4282-91, 2012.

[34] S. Rodrigues et al., "Optimal power flow control of VSC-based multiterminal DC network for offshore wind integration in the north sea", *IEEE J. Emerg. Selected Topics Power Electron.*, vol. 1, pp. 260-8, 2013.

[35] M. Aragüés-Peñalba et al., "Optimal power flow tool for mixed high-voltage alternating current and high-voltage direct current systems for grid integration of large wind power plants", *IET Renew. Power Gener.*, vol. 9, pp. 876-81, 2015.

[36] J. Cao et al., "Minimization of transmission loss in meshed AC/DC grids with VSC-MTDC networks", *IEEE Trans. Power Syst.*, vol. 28, pp. 3047-55, 2013.

[37] M. Aragues-Penalba et al., "Optimal power flow tool for hybrid AC/DC systems", *IET Int. Conf. AC and DC Power Transm.*, 2015.

[38] D. Dhua, S. Huang and Q. Wu, "Optimal power flow modelling and analysis of hybrid AC-DC grids with offshore wind power plant", *Energy Proc.*, vol. 141, pp. 572-9, 2017.

[39] D. Kotur and P. Stefanov, "Optimal power flow control in the system with offshore wind power plants connected to the MTDC network", *Int. J. Electr. Power Energy Syst.*, vol. 105, pp. 142-150, 2019.

[40] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis", *Renew. Sustain. Energy rev.*, vol. 42, pp. 569-96, 2015.

[41] S. Brodsky and R. Hahn, "Assessing the influence of power pools on emission constrained economic dispatch", *IEEE Power Eng. Rev.* vol. PER-6.2, pp. 30-31, 1986.

[42] P. Venkatesh, R. Gnanadass and N. Padhy, "Comparison and application of evolutionary programming techniques to combined economic emission dispatch with line flow constraints", *IEEE Trans. Power syst.*, vol. 18, pp. 688-97, 2003.

[43] M. Bhoye et al., "An emission constraint economic load dispatch problem solution with microgrid using JAYA algorithm", *Int. Conf. Energy Efficient Technol. Sustain.*, pp. 497-502, 2016.

[44] S. Alfredo, "Evolutionary multi objective environmental economic dispatch: stochastic & deterministic approaches", *MSc. thesis, Italy: university of del salento*, 2019.

[45] T. Gildenhuys et al., "Optimization of the operational cost and environmental impact of a multi-microgrid system", *Energy Proc.*, vol. 158, pp. 3827-32, 2019.

[46] V. Sarfi, I. Niazazari and H. Livani, "Multiobjective fireworks optimization framework for economic emission dispatch in microgrids", *North American Power Symp.*, pp. 1-6, 2016.

[47] F. Gazijahani, A. Abadi and J. Salehi, "Optimal multi-objective operation of multi microgrids with considering uncertainty", *Power Syst. Conf.*, pp. 228-35, 2016.

[48] Y. Li et al., "Multi-objective optimal dispatch of microgrid under uncertainties via interval optimization", *IEEE Trans. Smart Grid*, vol. 10, pp. 2046-58, 2017.

[49] T. Adefarati, C. Ramesh and J. Jackson, "Reliability and economic evaluation of a microgrid power system", *Energy Proc.*, vol. 142, pp.43-48, 2017.

[50] V. Jani and H. Abdi, "Optimal allocation of energy storage systems considering wind power uncertainty", *J. Energy Storage*, vol. 20, pp. 244-53, 2018.

[51] J. Radosavljević, "A solution to the combined economic and emission dispatch using hybrid PSOGSA algorithm", *Appl. Artif. Intell.*, vol. 30, pp. 445-74, 2016.

[52] Z. Liu et al., "Wind-solar micro grid reliability evaluation based on sequential monte carlo", *IEEE Int. Conf. Probab. Methods Appl. Power Syst.*, 2016.

[53] N. Nikmehr and S. Ravadanegh, "Optimal power dispatch of multi-microgrids at future smart distribution grids", *IEEE Trans. Smart Grid*, vol.6, pp.1648-57, 2015.

[54] J. Zhan et al., "Impacts of wind power penetration on risk constrained economic dispatch", *IEEE PES Asia-Pacific Power Energy Eng. Conf.*, 2013.

[55] A. Maulik and D. Das, "Optimal operation of a droop-controlled DCMG with generation and load uncertainties", *IET Gener. Transm. Distrib.*, vol. 12, pp. 2905-17, 2018.

[56] T. Niknam, F. Golestaneh and A. Malekpour, "Probabilistic energy and operation management of a microgrid containing wind/photovoltaic/fuel cell generation and energy storage devices based on point estimate method and self-adaptive gravitational search algorithm", *Energy*, vol. 43, pp. 427-37, 2012.

[57] S. Bahrami and M. Amini, "A decentralized trading algorithm for an electricity market with generation uncertainty", *Appl. Energy*, vol. 218, pp. 520-32, 2018.

[58] P. Baboli et al., "Energy management and operation modelling of hybrid AC–DC microgrid", *IET Gener. Transm. Distrib.*, vol. 8, pp. 1700-11, 2014.

[59] M. Hosseinzadeh and F. Salmasi, "Power management of an isolated hybrid AC/DC micro-grid with fuzzy control of battery banks", *IET Renew. Power Gener.*, vol. 9, pp. 484-93, 2015.

[60] M. Hosseinzadeh and F. Salmasi, "Robust optimal power management system for a hybrid AC/DC micro-grid", *IEEE Trans. Sustain. Energy*, vol. 6, pp. 675-87, 2015.

[61] P. Li et al., "Optimal operation of AC/DC hybrid microgrid under spot price mechanism", *IEEE Power Energy Soc. Meet.*, 2016.

[62] C. Qi et al., "A decentralized optimal operation of AC/DC hybrid distribution grids", *IEEE Trans. Smart Grid*, vol. 9, pp. 6095-105, 2017.

[63] L. Peng et al., "Double-uncertainty optimal operation of hybrid AC/DC microgrids with high proportion of intermittent energy sources", *J. Modern Power Syst. Clean Energy*, vol. 5, pp. 838-49, 2017.

[64] A. Hussain, V. Bui and H. Kim, "Robust optimal operation of AC/DC hybrid microgrids under market price uncertainties", *IEEE Access*, vol. 6, pp. 2654-67, 2017.

[65] "OFFSHORE WIND VISION" http://offshorewind. works/wp-content/uploads/2015/11/151106_offshore _ Wind _vision_FINAL. Pdf.

[66] J. Zhu, "Optimization of power system operation", *John Wiley & Sons*, 2017.

[67] S. Wen et al., "Economic allocation for energy storage system considering wind power distribution", *IEEE Trans. Power Syst.*, vol. 30, pp. 644-52, 2014.

[68] T. Thakur et al., "A particle swarm optimization solution to NO2 and SO2 emissions for environmentally

constrained economic dispatch problem", *IEEE/PES Transm. Distrib. Conf. Expos.*, 2006.

[69] A. Panosyan and B. Oswald, "Modified Newton-Raphson load flow analysis for integrated AC/DC power systems", *Int. Univ. Power Eng. Conf.*, vol. 3, pp. 1223-27, 2004.

[70] S. Cole, J. Beerten and R. Belmans, "Generalized dynamic VSC MTDC model for power system stability studies", *IEEE Trans. Power Syst.*, vol. 25, pp. 1655-62, 2010.

[71] M. Khan et al., "A load flow analysis for AC/DC hybrid distribution network incorporated with distributed energy resources for different grid scenarios", *Energies*, vol. 11, pp. 367, 2018.

[72] A. Azad et al., "Analysis of wind energy conversion system using Weibull distribution", *Proc. Eng.*, vol. 90, pp. 725-32, 2014.

[73] Q. Fu, D. Yu and J. Ghorai, "Probabilistic load flow analysis for power systems with multi-correlated wind sources", *IEEE Power Energy Soc. Meet.*, 2011.

[74] R. Waltz et al., "An interior algorithm for nonlinear optimization that combines line search and trust region steps", *Math. Program.*, vol. 107, pp. 391-408, 2006.

[75] S. Rao, "Engineering optimization: theory and practice", *John Wiley & Sons*, 2019.

[76] K. Deb, "Multi-objective optimization", *Search methodologies*, pp. 403-449, 2014.

[77] A. Kidwell, "Optimization under parameter uncertainties with application to product cost minimization", 2018.

[78] R. Byrd, E. Mary and J. Nocedal, "An interior point algorithm for large-scale nonlinear programming' *SIAM J. Optim.*, vol. 9, 877-900, 1999.

[79] Mathworks Global Optimization Toolbox User's Guid. MATLAB Global Optimization Toolbox User's Guid, R2017, 2017.

[80] "Test Case P.M. Anderson Power System" http://fglongatt.org/OLD/Test_Case_Anderson.html.