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Article

Optimal Power Flow Incorporating FACTS Devices and Stochastic Wind Power Generation Using Krill Herd Algorithm

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Abstract: This paper deals with investigating the Optimal Power Flow (OPF) solution of power systems considering Flexible AC Transmission Systems (FACTS) devices and wind power generation under uncertainty. The Krill Herd Algorithm (KHA), as a new meta-heuristic approach, is employed to cope with the OPF problem of power systems, incorporating FACTS devices and stochastic wind power generation. The wind power uncertainty is included in the optimization problem using Weibull probability density function modeling to determine the optimal values of decision variables. Various objective functions, including minimization of fuel cost, active power losses across transmission lines, emission, and Combined Economic and Environmental Costs (CEEC), are separately formulated to solve the OPF considering FACTS devices and stochastic wind power generation. The effectiveness of the KHA approach is investigated on modified IEEE-30 bus and IEEE-57 bus test systems and compared with other conventional methods available in the literature.

Keywords: flexible AC transmission systems (FACTS) devices; krill herd algorithm (KHA); optimal power flow (OPF); stochastic wind power generation

1. Introduction

Optimal Power Flow (OPF) plays a significant role in power systems operation and control. The OPF mainly aims to optimize a certain objective function, such as minimizing the generation fuel cost and at the same time, satisfying the load balance constraints and bound constraints [1,2]. Under normal conditions, all devices in power systems should operate within their pre-determined range. Such constraints include the maximum and minimum active and reactive power of the generation units, voltage levels, loadability of power transmission lines, and transformers tap settings. Minimizing the operating costs and increasing the reliability of power systems are two main objectives from the power companies and utilities’ point of view. Basically, the power flow problem focuses on the economic aspect of operating the power systems due to the fact that a slight change in power flow may significantly increase the operating costs of power systems. To do so, an objective function is optimized considering various equality and inequality constraints. Solving the OPF problem precisely leads to proper control, planning, and protection of power systems. The OPF problem can be divided into two major problems: (1) the optimal active power flow problem, and (2) the optimal reactive power.
flow problem. Numerous papers have investigated the OPF problem using conventional optimization methods, such as the Newton Raphson (NR) method, and evolutionary optimization techniques, such as particle swarm optimization (PSO) and artificial bee colony (ABC) optimization algorithms.

Increasing the load demand over the last few decades has created different problems in power systems in terms of power transmission congestion and constraints. Those limitations are mainly due to maintaining the stability and maintaining the voltage range of the power system at its permissible level [3,4]. Distributed Generations (DGs) are one of the best solutions to prevent congestion in the transmission lines [5]. DGs have several advantages, such as reducing energy costs, improving power quality and reliability, and preventing environmental pollutions. Among different DGs, wind power is one of the most popular power generations. However, wind behavior is often unpredictable, as it is a stochastic phenomenon, thereby, needing proper uncertainty modeling. To cope with this challenge, many research studies in the literature have investigated different methods to model the random behavior of the wind power generation, as depicted in Table 1.

| Reference | Uncertainty Model | Solution Method | Objective Functions |
|-----------|-------------------|-----------------|-------------------|
| [6]       | Weibull distribution function | Sequential quadratic programming PSO | Minimizing the total operating costs and minimizing emission |
| [7]       | Incomplete gamma function | Imperialist Competitive Algorithm (ICA) | Minimizing the fuel cost function |
| [8]       | Weibull probability density function | Gbest Guided-ABC | Minimizing the total operating costs |
| [9]       | Weibull probability density function | PSO | Minimizing the total operating and congestion costs |

Another way to enhance the capacity of the transmission systems is by employing Flexible AC Transmission System (FACTS) devices [10]. FACTS devices play a crucial role in improving the flexibility of power transmission and guaranteeing the stability of power systems. FACTS devices are used for improving power flow regardless of the costs of generating power. Two primary goals of using FACTS devices are (1) increasing capacity of transmission systems by controlling some characteristics, such as series/shunt impedances and phase angle; (2) transmitting power through the desired paths. Table 2 shows a summary of the previous research studies related to the FACTS devices. Therefore, the conventional OPF problem, integrated with FACTS devices can open new opportunities for controlling the active and reactive power flow.

To date, numerous papers on the OPF problem with various optimization techniques have been published. However, previous studies have not dealt with the OPF incorporating FACTS devices and stochastic wind power generation at the same time. In this regard, this paper proposes an OPF solution of power system considering FACTS devices and stochastic wind power generation using the krill herd algorithm (KHA). The wind power uncertainty is modeled in the optimization problem using the Weibull probability density function. Minimization of fuel cost, active power losses across the transmission lines, emission, and combined economic and environmental costs (CEEC) are the objective functions.

To the best of the authors’ knowledge, solving the OPF problem considering the minimization of fuel cost, active power losses across transmission lines, emission, and CEEC, incorporating FACTS devices and dealing with the stochastic behavior of wind power generation has not been investigated before. Compared with the other techniques, the proposed method has better performance and achieves more accurate results.
### Table 2. Different methods to model the random behavior of wind power generations.

| Reference | Method | Objective Functions | FACTS Devices |
|-----------|--------|---------------------|---------------|
| [7]       | Micro-genetic algorithm and hybrid method | Minimizing the fuel cost and power losses, Optimal location of FACTS devices | TCSC, TCPAR, UPFC, SVC |
| [8]       | PSAT software analysis | Improving voltage profile, Minimizing power losses | SVC |
| [9]       | Dimensional algorithm using NR load flow | Improving voltage profile, Minimizing power losses and fuel costs | TCSC, TCPAR, SVC, STATCOM |
| [10]      | Genetic Algorithm (GA) and Differential Evolution Algorithm (DEA) | Minimizing the fuel cost and power losses, Optimal location of FACTS devices | UPFC, SVC, TCSC |
| [11]      | Dimensional algorithm | Heat control, Minimizing power losses, Improving power systems stability | UPFC |
| [12]      | GA and DEA | Minimizing the fuel cost and power losses | UPFC |
| [13]      | Artificial Immune Systems (AIS) | Minimizing the fuel cost | TCPS, TCSC |
| [14]      | GA | Minimizing the fuel cost and power losses | TCSC, TCPAR, UPFC |
| [15]      | DEA | Maximizing the loadability of transmission lines, Reducing the transmission lines losses | STATCOM |
| [16]      | Combined Tabu Search (TS) and Simulated Annealing (SA) method | Minimizing the total fuel cost | TCSC, TCPS |
| [17]      | GA | Minimizing the total fuel costs under security constraints | UPFC |
| [18]      | PSO | Reducing the FACTS devices installation costs, Reducing overload | TCSC, UPFC, SVC, TCVR |

The followings are the major contributions of this research study:

- Modeling and including the stochastic nature of wind power generation in the problem formulation.
- Unlike the other research studies, in this paper, the OPF problem incorporating FACTS devices and stochastic wind power generation at the same time is solved.
- The KHA is used to minimize the fuel cost, active power losses across the transmission lines, emission, and CEEC, as the objective functions.

This paper is divided into four sections. In Section 2, the problem formulation is given. The results are presented in Section 3. Finally, the conclusions are presented.

### 2. Problem Formulation

In this part, the OPF problem formulation in the presence of FACTS devices, including thyristor controlled phase shifter (TCPS) as well as thyristor-controlled series compensator (TCSC), and stochastic wind power generation is presented. The frequency distribution is one of the most essential tools for planning and operating in power systems, and its general structure is divided into two parts of the objective function and constraints.

#### 2.1. General Formulation

The general formulation for the constrained optimization problem in this paper is as follows:

$$\min f(u, v)$$

subject to:

$$\begin{align*}
g(u, v) &= 0 \\
h(u, v) &\leq 0
\end{align*}$$

where \( f \) is the objective function that should be minimized, \( g(u, v) \) is the set of equality constraints, and \( h(u, v) \) is the set of inequality constraints. It should be noted that for \( N \) number of components
in power systems, \( u \) is the vector of dependent variables that contains the active power of the slack generator, voltage of the loads \( \left\{ V_{L_1}, \ldots, V_{L_{NPQ}} \right\} \), reactive power generation by the generation units \( \left\{ Q_{G_1}, \ldots, Q_{G_{NPV}} \right\} \), and the lines loadability \( \left\{ S_{L_1}, \ldots, S_{L_{N_L}} \right\} \). Also, \( v \) is the vector of independent variables that contains active power generation by the generation unit except for the slack bus \( \left\{ P_{G_1}, \ldots, P_{G_{NPV}} \right\} \), voltage of the generators \( \left\{ V_{G_1}, \ldots, V_{G_{NPV}} \right\} \), transformers tap settings \( \left\{ T_1, \ldots, T_{NT} \right\} \), and the injected reactive power by the FACTS devices \( \left\{ Q_{C_1}, \ldots, Q_{C_{NC}} \right\} \). It should be noted that \( N_{PQ}, N_{PV}, N_{L}, N_T, \) and \( N_C \) show the maximum number of generation buses, load buses, transmission lines, transformer tap settings, and FACTS devices, respectively.

The constraints of the OPF problem include active and reactive power of the generation units, transformer tap settings, and the loading of the power transmission lines.

2.2. FACTS Devices Modeling

2.2.1. TCSC Modeling

Figure 1 shows the static of a TCSC connected between bus \( p \) and \( q \) [20,21].

![Figure 1. Model of TCSC connected between \( p^{th} \) bus and \( q^{th} \) bus.](image)

The power flow equations from bus \( p \) to bus \( q \), including TCSC, are as follows [21]:

\[
P_{pq} = V_q^2 G_{pq} - V_p V_q G_{pq} \cos(\delta_p - \delta_q) - V_p V_q B_{pq} \sin(\delta_p - \delta_q) \tag{3}
\]

\[
Q_{pq} = -V_q^2 B_{pq} - V_p V_q G_{pq} \sin(\delta_p - \delta_q) + V_p V_q B_{pq} \cos(\delta_p - \delta_q) \tag{4}
\]

where

\[
G_{pq} = \frac{R_{pq}}{R_{pq}^2 + (X_{pq} - X_{Cpq})^2} \tag{5}
\]

\[
B_{pq} = \frac{R_{pq}}{R_{pq}^2 + (X_{pq} - X_{Cpq})^2} \tag{6}
\]

where \( P_{pq} \) and \( Q_{pq} \) are the active and reactive power flow from bus \( p \) to bus \( q \) with TCPS, respectively, \( G_{pq} \) and \( B_{pq} \) are the conductance and susceptance of transmission line between bus \( p \) and bus \( q \), respectively, \( \delta_p \) and \( \delta_q \) are the voltage angles at the \( p^{th} \) bus and \( q^{th} \) bus, respectively, \( R_{pq} \) and \( X_{pq} \) denote the resistance and reactance of the transmission line between bus \( p \) and bus \( q \), respectively, and lastly, \( X_{Cpq} \) represents the reactance of the TCSC located in the transmission line between bus \( p \) and bus \( q \).

Similarity, the power flow equations from bus \( q \) to bus \( p \), including TCSC, are as follows:

\[
P_{qp} = V_p^2 G_{pq} - V_q V_p G_{pq} \cos(\delta_p - \delta_q) + V_p V_q B_{pq} \sin(\delta_p - \delta_q) \tag{7}
\]

\[
Q_{qp} = -V_p^2 B_{pq} + V_q V_p G_{pq} \sin(\delta_p - \delta_q) + V_p V_q B_{pq} \cos(\delta_p - \delta_q) \tag{8}
\]
where \( P_{qp} \) and \( Q_{qp} \) are the active and reactive power flow from bus \( q \) to bus \( p \) with TCPS, respectively.

### 2.2.2. TCPS Modeling

Figure 2 demonstrates the static of a TCPS connected between bus \( p \) and \( q \), having a complex taping ratio of 1 : 1 and \( \varphi \) and series admittance of \( Y_{pq} = G_{pq} - jB_{pq} \) [20].

![TCPS model connected between \( p^{th} \) bus and \( q^{th} \) bus.](image)

The power flow equations from bus \( p \) to bus \( q \), including the TCPS, are as follows:

\[
P_{pq} = \frac{V_p^2 G_{pq}}{\cos^2(\varphi)} - \frac{V_p V_q}{\cos(\varphi)} \left[ G_{pq} \cos(\delta_p - \delta_q + \varphi) + B_{pq} \sin(\delta_p - \delta_q + \varphi) \right] 
\]

(9)

\[
Q_{pq} = -\frac{V_p^2 B_{pq}}{\cos^2(\varphi)} - \frac{V_p V_q}{\cos(\varphi)} \left[ G_{pq} \sin(\delta_p - \delta_q + \varphi) - B_{pq} \cos(\delta_p - \delta_q + \varphi) \right] 
\]

(10)

where \( P_{pq} \) and \( Q_{pq} \) are the active and reactive power flow from bus \( p \) to bus \( q \) with TCPS, respectively. In addition, \( \varphi \) shows the phase shift angle of TCPS.

Likewise, the power flow equations from bus \( q \) to bus \( p \), including the TCPS, are as follows:

\[
P_{qp} = \frac{V_q^2 G_{pq}}{\cos^2(\varphi)} - \frac{V_p V_q}{\cos(\varphi)} \left[ G_{pq} \cos(\delta_p - \delta_q + \varphi) - B_{pq} \sin(\delta_p - \delta_q + \varphi) \right] 
\]

(11)

\[
Q_{qp} = -\frac{V_q^2 B_{pq}}{\cos^2(\varphi)} - \frac{V_p V_q}{\cos(\varphi)} \left[ G_{pq} \sin(\delta_p - \delta_q + \varphi) + B_{pq} \cos(\delta_p - \delta_q + \varphi) \right] 
\]

(12)

where \( P_{qp} \) and \( Q_{qp} \) are the active and reactive power flow from bus \( q \) to bus \( p \) with TCPS, respectively.

### 2.3. Wind Power Generation Modeling

The technology of wind turbines to generate electricity from wind can be divided into two major groups: (1) constant speed wind turbine, and (2) variable speed wind turbine. Fixed speed wind turbines are easy to install, more durable, and more affordable, while variable speed wind turbines should be installed according to the strategic and geographical conditions. Figure 3 shows the output power curve of a typical wind turbine. In Figure 3, \( v_{ci} \) and \( v_{co} \) are the cut-in wind speed and cut-out wind speed, respectively, \( v_r \) is the rated wind speed, and \( v_w \) is the wind speed flowing into the wind turbine.
2.4. Objective Functions

Since the wind speed is variable, the Weibull distribution is often considered as the probability density function that can be used to approximately model the behavior of the wind with a reasonable error. The Weibull distribution function to calculate the probability of the wind speed is as follows [22,23]:

\[
f(v) = \left(\frac{k}{\kappa}\right)^{k-1} \frac{v^{k-1}}{\kappa^{k}} e^{-\left(\frac{v}{\kappa}\right)^{k}}
\]

where \(v\) shows the wind speed, and \(k\) (shape factor) and \(\kappa\) (scale factor) are the wind speed parameters that vary depending on the region in which the wind blows.

It should be noted that to evaluate the power output of wind power, the problem has a general wind scenario, which initially generates a random number of wind speeds. Then, based on the Weibull distribution function considering the shape factor and scale factor, the probability of occurrence of those wind speeds is determined. Next, a certain number of wind speeds that most probably occur is selected. Finally, the average power of the wind farm is calculated.

### 2.4.1. Minimization of Fuel Cost

Fuel cost minimization with a quadratic function is considered as the first objective function, as follows [24]:

\[
\min F_C = \sum_{p=1}^{N_{PV}} \left[a_p + b_p P_{G_p} + c_p P_{G_p}^2\right] \tag{14}
\]

where \(F_C\) is the total fuel cost of the generation units in ($/h), \(a_p\), \(b_p\), and \(c_p\) are the fuel cost coefficients of the \(p^{th}\) generation unit, \(N_{PV}\) shows the total number of generation units, and \(P_{G_p}\) denotes the generated active power by the \(p^{th}\) generation unit.

Considering the valve-point effect, Equation (15) can be rewritten as follows:

\[
\min F_C = \sum_{p=1}^{N_{PV}} \left[a_p + b_p P_{G_p} + c_p P_{G_p}^2\right] + d_p \sin\left(c_p\left(P_{G_p}^{min} - P_{G_p}\right)\right) \tag{15}
\]

where \(d_p\) and \(c_p\) are the fuel cost coefficients to model the valve-point effect, and \(P_{G_p}^{min}\) denotes the minimum active power generated by the \(p^{th}\) generation unit.

Figure 3. The output power curve of a typical wind turbine.
2.4.2. Minimization of Active Power Losses across the Transmission Lines

This objective function can be formulated as follows:

\[
\min P_{\text{Loss}} = \sum_{k=1}^{N_L} \left( G_k \left( V_p^2 + V_q^2 - 2 V_p V_q \cos(\delta_p - \delta_q) \right) \right)
\]

(16)

where \( P_{\text{Loss}} \) is the total active power losses across the transmission lines in (MW), \( G_k \) is the conductance of the \( k^{th} \) transmission line connected between bus \( p \) and bus \( q \), \( N_L \) is the total number of transmission lines, \( V_p \) and \( V_q \) are the voltage magnitudes of bus \( p \) and bus \( q \), respectively, and \( \delta_p \) and \( \delta_q \) are the voltage angles of bus \( p \) and bus \( q \), respectively.

2.4.3. Minimization of Emission

The third objective function is to minimize the total emission, which is formulated as follows:

\[
\min E(P_G) = \sum_{k=1}^{N_G} \left[ 10^{-2} \left( \alpha_p + \beta_p P_{Gp} + \gamma_p P_{Gp}^2 + \eta_p e^{\lambda_p P_{Gp}} \right) \right]
\]

(17)

where \( E(P_G) \) is the total emission due to the generation of the \( p^{th} \) generation unit in (ton/h), \( \alpha_p, \beta_p, \gamma_p, \eta_p, \) and \( \lambda_p \) are the emission coefficients of the \( p^{th} \) generation unit.

2.4.4. Minimization of the Combined Economic and Environmental Costs

The last objective function is to minimize the CEEC according to Equations (15) and (17):

\[
\min \text{CEEC} = F_C + \Phi E(P_G) = \sum_{p=1}^{N_G} \left( \alpha_p + \beta_p P_{Gp} + \gamma_p P_{Gp}^2 + \eta_p e^{\lambda_p P_{Gp}} \right) + \Phi \sum_{p=1}^{N_G} \left( \alpha_p + \beta_p P_{Gp} + \gamma_p P_{Gp}^2 + \eta_p e^{\lambda_p P_{Gp}} \right)
\]

(18)

where CEEC denotes the combined economic and environmental costs, and \( \Phi_p \) is the penalty factor, and can be obtained as follows:

\[
\Phi = \frac{a_p \left( \frac{P_{p}}{G_p} \right)^2 + b_p P_{p} + c_p}{\alpha_p \left( \frac{P_{p}}{G_p} \right)^2 + \beta_p P_{p} + \gamma_p}
\]

(19)

The pollution charge coefficient for each unit is defined as the amount of fuel cost divided by the amount of pollution at its maximum output active power (\( P_{Gp}^{\text{max}} \)).

2.5. Constraints

In this section, different constraints are defined [24].

2.5.1. Load Flow Constraints

\[
P_{\text{wt}} + \sum_{p=1}^{N_B} (P_{Gp} - P_{Ip}) + \sum_{p=1}^{N_{\text{PV}}} P_{pk} = \sum_{p=1}^{N_B} \sum_{q=1}^{N_B} V_p \left| V_{pq} \right| \cos(\theta_{pq} + \delta_p - \delta_q)
\]

(20)

\[
\sum_{p=1}^{N_B} (Q_{Gp} - Q_{Ip}) + \sum_{p=1}^{N_{\text{PV}}} Q_{pk} = -\sum_{p=1}^{N_B} \sum_{q=1}^{N_B} V_p \left| V_{pq} \right| \sin(\theta_{pq} + \delta_p - \delta_q)
\]

(21)

where \( P_{Gp} \) and \( Q_{Gp} \) are the generated active and reactive power at bus \( p \), respectively, \( P_{Ip} \) and \( Q_{Ip} \) are the consumed active and reactive power at bus \( p \), respectively, \( P_{pk} \) and \( Q_{pk} \) are the injected active and
reactive power by the TCPSs at bus $p$, respectively, $P_{wt}$ indicates the generated active power by the wind turbine, $|Y_{pq}|$ and $\theta_{pq}$ are the magnitude and phase of the admittance of the transmission line between bus $p$ and bus $q$, $N_B$ shows the total number of buses, and $N_{TPCS}$ denotes the total number of TCPSs.

2.5.2. Active and Reactive Power of the Generation Units

$$P_{min}^G \leq P_G^p \leq P_{max}^G$$

(22)

$$Q_{min}^G \leq Q_G^p \leq Q_{max}^G$$

(23)

where for $p = 1, \ldots, N_{PV}$ ($N_{PV}$ is the total number of generators), $P_{min}^G$ and $P_{max}^G$ are the minimum and maximum limits of the active power of the $p^{th}$ generator, respectively, and $Q_{min}^G$ and $Q_{max}^G$ are the minimum and maximum limits of the reactive power of the $p^{th}$ generator, respectively.

2.5.3. Voltage at Each Bus

$$V_{min}^L \leq V_L^p \leq V_{max}^L$$

(24)

where for $p = 1, \ldots, N_{PQ}$ ($N_{PQ}$ is the total number of loads), $V_{min}^L$ and $V_{max}^L$ are the minimum and maximum level of the voltage at the $p^{th}$ load center, respectively.

2.5.4. Transformer Tap Settings

$$T_{min}^p \leq T_p \leq T_{max}^p$$

(25)

where for $p = 1, \ldots, N_T$ ($N_T$ is the total number of transformers), $T_{min}^p$ and $T_{max}^p$ are the minimum and maximum tap settings limits of the $p^{th}$ transformer, respectively.

2.5.5. Transmission Lines Loading

$$S_{min}^L \leq S_L^p \leq S_{max}^L$$

(26)

where for $p = 1, \ldots, N_L$ ($N_L$ is the total number of transmission lines), $S_{min}^L$ and $S_{max}^L$ are the apparent power flow and maximum apparent power flow of the $p^{th}$ transmission line, respectively.

2.5.6. TCSC Reactance Constraints

$$X_{min}^T \leq X_T^p \leq X_{max}^T$$

(27)

where for $p = 1, \ldots, N_{TCSC}$ ($N_{TCSC}$ is the total number of TCSCs), $X_{min}^T$ and $X_{max}^T$ are the minimum and maximum reactance of the $p^{th}$ TCSC, respectively.

2.5.7. TCPS Phase Shift

$$\phi_{min}^T \leq \phi_T^p \leq \phi_{max}^T$$

(28)

where for $p = 1, \ldots, N_{TPCS}$ ($N_{TPCS}$ is the total number of TCPSs), $\phi_{min}^T$ and $\phi_{max}^T$ are the minimum and maximum phase shift angle of the $p^{th}$ TCPS, respectively.
2.6. Solution Method

The KHA is based on the herding behavior of krill swarms in response to the specific biological and environmental processes [25]. In this paper, the KHA is used to solve the OPF problem incorporating stochastic wind power generation and FACTS devices considering uncertainty. The followings are the steps to implement the KHA.

Step 1: Start

Step 2: Check the data structure

Step 3: Initialization

Step 4: Fitness evaluation and check for constraints

Step 5: Motion calculation
   - Induced motion
   - Foraging motion
   - Physical diffusion

Step 6: Implementation of the genetic operator

Step 7: Check the results based on updating the krill individual position in the search space

Step 8: If the best results are achieved then
   Go to Step 9
   Otherwise
   Go to Step 4

Step 9: End

3. Simulation Results

To demonstrate the applicability and validity of the proposed method, two different test systems, (1) IEEE 30-bus test system, and (2) IEEE 57-bus test system are analyzed [26,27]. In addition, a wind farm consisting of 20 $\times$ 2 MW wind turbines is considered. It should be noted that the number of iterations for all simulated cases is set to 500. The highlighted rows in all tables show the corresponding values for the specific objective functions.

3.1. Case 1: IEEE 30-Bus Test System

The IEEE 30-bus test system consists of 21 load centers with an overall power consumption of 4283 MW. It has six generators at buses 1, 2, 5, 8, 11, and 13. Totally, nine reactive power control devices are located at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29. In addition, the range of voltage in this case study is considered between 0.95 and 1.05 p.u. There are 41 transmission lines. The tap changers are located in transmission lines 6–9, 6–10, 4–12, and 28–27. According to [13], two TCSCs are installed in transmission lines 3–4, 19–20 with 50% (minimum) and 100% (maximum) series line reactances, and two TCPS are also placed on transmission lines 5–7 and 10–22 with $-5^\circ$ (minimum) and $+5^\circ$ (maximum) phase shift angles. In addition, the wind farm is placed on bus 22 [27]. In this section, two case studies, considering the wind farm in power systems and neglecting it are carried out.

3.1.1. Minimization of Fuel Cost

The simulation results without considering the valve-point effect, with and without wind farm (as indicated by $P_{\text{wind}}$), are provided in Table 3. The simulation results considering the valve-point effect, with and without wind farm, are also given in Table 4. Tables 3 and 4 show that the presence of a wind farm in the case study reduces the generation capacity of other generation units and decreases the fuel costs and emission. Additionally, the results of Particle Swarm Optimization with Aging Leader and
Challengers (ALC-PSO), DEA, and Real-Coded Genetic Algorithm (RCGA) are presented to evaluate and compare the performance and accuracy of KHA [28].

Table 3. Results for fuel cost minimization without considering the valve-point effect for the Test System 1.

| Control Variable | Without Wind Farm | With Wind Farm |
|------------------|-------------------|----------------|
|                  | KHA               | ALC-PSO        | DEA            | RCGA           | KHA           |
| $P_{G1}$ (MW)    | 179.755           | 185.240        | 180.260        | 192.460        | 137.526       |
| $P_{G2}$ (MW)    | 47.8185           | 46.3300        | 49.3200        | 48.3800        | 41.9122       |
| $P_{G3}$ (MW)    | 18.5154           | 20.8800        | 20.8200        | 19.5400        | 19.3311       |
| $P_{G4}$ (MW)    | 16.0965           | 15.6400        | 17.6100        | 11.6000        | 15.5927       |
| $P_{G5}$ (MW)    | 10.0000           | 11.1200        | 11.0500        | 10.0000        | 20.9956       |
| $P_{G6}$ (MW)    | 19.3238           | 12.5800        | 12.6900        | 12.0000        | 17.7110       |
| Total Generation (MW) | 291.509       | 291.790        | 291.750        | 294.000        | 253.067       |
| Fuel Cost ($/h)  | 779.393           | 796.930        | 797.290        | 803.840        | 683.646       |
| Emission (ton/h) | 0.42496           | 0.39020        | 0.37560        | 0.00000        | 0.28904       |
| Power Losses (MW)| 8.10960           | 8.39000        | 8.35000        | 10.6000        | 4.08011       |
| Computation Time (s) | 184.400       | 479.200        | 487.300        | 265.800        | 188.100       |

According to the obtained results, the values of objective function without considering the valve-point effect and without wind farm using ALC-PSO, DEA, and RCGA are 17.537, 17.897, and 24.447 $/h more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 683.646 $/h, which is 95.747 $/h less than the case without the wind farm.

In addition, the values of objective function considering the valve-point effect and with wind farm using ALC-PSO, DEA, and RCGA are 1.74, 2.39, and 6.88 $/h more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 676.762 $/h, which is 147.388 $/h less than the case without the wind farm.

3.1.2. Minimization of Active Power Losses across the Transmission Lines

Table 4 shows the best control variable settings for the minimization of the active power losses across the transmission lines of the IEEE 30-bus test system using KHA. According to Table 4, the presence of a wind farm in power systems reduces the active power losses across the transmission lines.

Table 4. Results for fuel cost minimization considering the valve-point effect for the Test System 1.

| Control Variable | Without Wind Farm | With Wind Farm |
|------------------|-------------------|----------------|
|                  | KHA               | ALC-PSO        | DEA            | RCGA           | KHA           |
| $P_{G1}$ (MW)    | 191.690           | 199.850        | 199.130        | 198.810        | 130.246       |
| $P_{G2}$ (MW)    | 34.4058           | 38.2000        | 38.3200        | 38.9600        | 39.4530       |
| $P_{G3}$ (MW)    | 15.0000           | 20.1600        | 20.1700        | 19.1600        | 32.9699       |
| $P_{G4}$ (MW)    | 10.0000           | 11.1500        | 11.4300        | 10.6400        | 29.5335       |
| $P_{G5}$ (MW)    | 19.2954           | 10.1300        | 10.4300        | 13.5600        | 11.8032       |
| $P_{G6}$ (MW)    | 21.0191           | 12.6600        | 12.6600        | 12.0300        | 12.0000       |
| Total Generation (MW) | 291.410       | 292.150        | 292.140        | 293.160        | 256.005       |
| $P_{wind}$ (MW)  | 0.00000           | 0.00000        | 0.00000        | 0.00000        | 32.6020       |
| Fuel Cost ($/h)  | 824.150           | 825.890        | 826.540        | 831.030        | 676.762       |
| Emission (ton/h) | 0.44373           | 0.44124        | 0.43830        | 0.43660        | 0.30525       |
| Power Losses (MW)| 8.01050           | 8.75000        | 8.74000        | 9.76000        | 5.20370       |
| Computation Time (s) | 185.700       | 503.120        | 505.600        | 714.800        | 189.000       |

According to the obtained results, the values of objective function without considering the valve-point effect and without wind farm using ALC-PSO, DEA, and RCGA are 17.537, 17.897, and 24.447 $/h more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 683.646 $/h, which is 95.747 $/h less than the case without the wind farm.

In addition, the values of objective function considering the valve-point effect and with wind farm using ALC-PSO, DEA, and RCGA are 1.74, 2.39, and 6.88 $/h more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 676.762 $/h, which is 147.388 $/h less than the case without the wind farm.

As shown in Table 5, the values of objective function without wind farm using ALC-PSO, DEA, and RCGA are 0.0587, 0.0687, and 0.1487 MW more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 1.76710 MW, which is 1.1542 MW less than the case without the wind farm.
Table 5. Results for minimizing the active power losses across the transmission lines for the Test System 1.

| Control Variable | Without Wind Farm | With Wind Farm |
|------------------|-------------------|----------------|
|                  | KHA | ALC-PSO | DEA | RCGA | KHA |
| $P_{G_1}$ (MW)   | 98.0937 | 74.6900 | 77.5900 | 77.5800 | 15.7459 |
| $P_{G_2}$ (MW)   | 53.5641 | 67.3000 | 67.3000 | 69.5800 | 80.0000 |
| $P_{G_3}$ (MW)   | 50.0000 | 50.0000 | 50.0000 | 49.9800 | 50.0000 |
| $P_{G_4}$ (MW)   | 35.0000 | 34.6600 | 34.8500 | 34.9600 | 35.0000 |
| $P_{G_5}$ (MW)   | 16.5549 | 27.2600 | 27.0400 | 23.6900 | 30.0000 |
| $P_{G_6}$ (MW)   | 32.8586 | 32.2200 | 32.3600 | 30.4300 | 40.0000 |
| Total Generation (MW) | 286.071 | 286.130 | 285.140 | 286.220 | 250.745 |
| $P_{wind}$ (MW)  | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 34.4212 |
| Fuel Cost ($/h)  | 992.050 | 992.180 | 992.300 | 985.210 | 918.639 |
| Emission (ton/h) | 0.21091 | 0.21090 | 0.21090 | 0.21440 | 0.21031 |
| Power Losses (MW) | 2.92130 | 2.98000 | 2.99000 | 3.07000 | 1.76710 |
| Computation Time (s) | 170.150 | 482.100 | 497.400 | 711.700 | 174.300 |

3.1.3. Minimization of Active Power Losses across the Transmission Lines

Table 6 shows the best control variable settings for the emission minimization of the IEEE 30-bus test systems using KHA. Table 6 shows that the presence of a wind farm in power systems decreases the emission.

Table 6. Results for emission minimization for the Test System 1.

| Control Variable | Without Wind Farm | With Wind Farm |
|------------------|-------------------|----------------|
|                  | KHA | ALC-PSO | DEA | RCGA | KHA |
| $P_{G_1}$ (MW)   | 51.3924 | 64.5200 | 63.5000 | 63.9800 | 45.9204 |
| $P_{G_2}$ (MW)   | 80.0000 | 66.9000 | 67.9200 | 67.7500 | 51.6969 |
| $P_{G_3}$ (MW)   | 50.0000 | 50.0000 | 50.0000 | 50.0000 | 50.0000 |
| $P_{G_4}$ (MW)   | 35.0000 | 35.0000 | 35.0000 | 35.0000 | 35.0000 |
| $P_{G_5}$ (MW)   | 30.0000 | 30.0000 | 30.0000 | 29.9600 | 30.0000 |
| $P_{G_6}$ (MW)   | 40.0000 | 40.0000 | 40.0000 | 40.0000 | 40.0000 |
| Total Generation (MW) | 286.392 | 286.420 | 286.420 | 286.690 | 252.617 |
| $P_{wind}$ (MW)  | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 33.3285 |
| Fuel Cost ($/h)  | 1012.75 | 1014.24 | 1015.10 | 1015.80 | 906.068 |
| Emission (ton/h) | 0.20469 | 0.20475 | 0.20480 | 0.20490 | 0.19587 |
| Power Losses (MW) | 2.92130 | 2.98000 | 2.99000 | 3.07000 | 1.76710 |
| Computation Time (s) | 170.150 | 482.100 | 497.400 | 711.700 | 174.300 |

According to the obtained results, the values of objective function without wind farm using ALC-PSO, DEA, and RCGA are 0.00006, 0.00011, and 0.00021 ton/h more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 0.19587 ton/h, which is 0.00882 ton/h less than the case without the wind farm.

3.1.4. Minimization of Combined Economic and Environmental Costs

Table 7 demonstrates the best control variable settings for the CEEC minimization of the IEEE 30-bus test systems using KHA. According to the obtained results, the presence of a wind farm in power systems decreases the CEEC.

As shown in Table 7, the values of objective function without wind farm using ALC-PSO and DEA are 1.64 and 5.29 more than KHA, respectively. Considering such conditions in the presence of the wind farm, the value of the objective function using KHA is 1095.72, which is 137.08 less than the case without the wind farm.
Table 7. Results for emission minimization for the Test System 1.

| Control Variable | Without Wind Farm | ALC-PSO | DEA | With Wind Farm |
|------------------|-------------------|--------|-----|---------------|
| $P_{G_1}$ (MW)   | 126.476           | 115.230| 107.980| 110.376       |
| $P_{G_2}$ (MW)   | 66.4293           | 56.5700| 58.5700| 63.8014       |
| $P_{G_8}$ (MW)   | 29.8519           | 31.8800| 32.3800| 23.7588       |
| $P_{G_11}$ (MW)  | 18.0473           | 23.8900| 29.5100| 16.7590       |
| $P_{G_{13}}$ (MW)| 19.8514           | 34.2300| 33.2700| 23.6716       |
| Total Generation (MW) | 288.585 | 289.330| 289.320| 255.492       |
| $P_{\text{wind}}$ (MW) | 0.00000 | 0.00000| 0.00000| 32.3655       |
| Fuel Cost ($/h) | 897.430           | 907.170| 922.360| 784.653       |
| Emission (ton/h) | 0.23990           | 0.24302| 0.23640| 0.22423       |
| Power Losses (MW) | 5.18590           | 5.92000| 5.93000| 4.45820       |
| CEEC          | 1232.80           | 1234.44| 1238.09| 1095.72       |
| Computation Time (s) | 189.140 | 515.100| 521.300| 189.180       |

Figures 4–7 show the convergence curves of the defined objective functions for the Test System 1 after 500 iterations.

Figure 4. The convergence curves for the fuel cost minimization considering and neglecting the valve-point effect for the Test System 1.

Figure 5. The convergence curves for the minimization of power losses across the transmission lines for the Test System 1.
Figure 5. The convergence curves for the minimization of power losses across the transmission lines for the Test System 1.

Figure 6. The convergence curves for emission minimization for the Test System 1.

Figure 7. The convergence curves for CEEC minimization for the Test System 1.

3.2. Case 2: IEEE 57-Bus Test System

The IEEE 57-bus test system, which consists of 7 generators located at the buses 1, 2, 3, 6, 8, 9, and 12 with 15 transformers under load tap settings, is chosen as test system 2. Three reactive power sources are taken at buses 18, 25, and 53. In this paper, TCSCs are located in transmission lines 18–19, 31–32, 34–32, 40–56, and 39–57. TCPSs are also installed in transmission lines 4–5, 5–6, 26–27, 41–43, and 53–54. The wind farm is placed at bus 52 [27]. The same as the previous section, two case studies, considering the wind farm in power systems and neglecting it, are carried out. Tables 8–11 show the best control variable settings for different objective functions of the IEEE 57-bus test system using KHA.

According to the obtained results from Tables 8–11, considering wind farm in power system cause a significant reduction on power losses across the transmission lines, emission, and CEEC.
Table 8. Results for fuel cost minimization without considering the valve-point effect for the Test System 2.

| Control Variable Without Wind Farm | With Wind Farm |
|-----------------------------------|----------------|
|                                   | KHA    | ALC-PSO | DEA    | RCGA   | KHA    |
| \( P_{G1} \) (MW)               | 584.6750 | 514.2600 | 520.0900 | 517.4500 | 422.6630 |
| \( P_{G2} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 105.4910 |
| \( P_{G3} \) (MW)               | 75.16610 | 123.5300 | 103.7400 | 94.81000 | 161.5274 |
| \( P_{G4} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 182.3932 |
| \( P_{G5} \) (MW)               | 166.0264 | 159.6700 | 175.6300 | 181.7500 | 0.00000 |
| \( P_{G6} \) (MW)               | 253.7019 | 0.000000 | 0.000000 | 0.000000 | 125.9095 |
| \( P_{G7} \) (MW)               | 211.8802 | 486.8900 | 485.2300 | 489.7700 | 256.8480 |
| Total Generation (MW)           | 1291.449 | 1284.350 | 1284.690 | 1283.780 | 1254.832 |
| Fuel Cost ($/h)                 | 7768.000 | 8103.180 | 8309.270 | 8413.430 | 6748.000 |
| Emission (ton/h)                | 2.379500 | 2.397820 | 2.433300 | 2.433100 | 2.018000 |
| Power Losses (MW)               | 40.64980 | 33.55000 | 33.89000 | 32.98000 | 40.41060 |
| Computation Time (s)            | 678.9000 | 680.1200 | 689.9000 | 847.9000 | 714.7000 |

Table 9. Results for minimizing the active power losses across the transmission lines for the Test System 2.

| Control Variable Without Wind Farm | With Wind Farm |
|-----------------------------------|----------------|
|                                   | KHA    | ALC-PSO | DEA    | RCGA   | KHA    |
| \( P_{G1} \) (MW)               | 192.3159 | 303.2400 | 318.5800 | 311.3400 | 176.1450 |
| \( P_{G2} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 16.85120 |
| \( P_{G3} \) (MW)               | 34.34410 | 63.19000 | 45.90000 | 60.61300 | 156.9747 |
| \( P_{G4} \) (MW)               | 134.0298 | 0.000000 | 0.000000 | 0.000000 | 58.62480 |
| \( P_{G5} \) (MW)               | 469.7929 | 400.7500 | 407.6500 | 400.0600 | 158.5790 |
| \( P_{G6} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 290.1441 |
| \( P_{G7} \) (MW)               | 436.1565 | 500.0000 | 495.0300 | 495.1400 | 371.8631 |
| Total Generation (MW)           | 1266.639 | 1267.180 | 1267.160 | 1267.153 | 1229.181 |
| Fuel Cost ($/h)                 | 15,354.40 | 15,423.88 | 15,691.30 | 15,348.11 | 13,078.79 |
| Emission (ton/h)                | 1.916836 | 1.906545 | 1.966905 | 1.917299 | 1.507600 |
| Power Losses (MW)               | 21.93910 | 22.48000 | 22.46000 | 22.46300 | 21.10600 |
| Computation Time (s)            | 670.2000 | 881.3000 | 701.7000 | 691.0450 | 715.0000 |

Table 10. Results for minimizing the active power losses across the transmission lines for the Test System 2.

| Control Variable Without Wind Farm | With Wind Farm |
|-----------------------------------|----------------|
|                                   | KHA    | ALC-PSO | DEA    | RCGA   | KHA    |
| \( P_{G1} \) (MW)               | 333.585 | 341.910 | 298.12 | 300.23 | 143.311 |
| \( P_{G2} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 149.200 |
| \( P_{G3} \) (MW)               | 170.617 | 91.9000 | 83.24 | 91.43 | 158.020 |
| \( P_{G4} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 161.346 |
| \( P_{G5} \) (MW)               | 311.707 | 419.250 | 413.63 | 406.26 | 220.977 |
| \( P_{G6} \) (MW)               | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 173.139 |
| \( P_{G7} \) (MW)               | 453.292 | 418.450 | 474.14 | 472.08 | 228.994 |
| Total Generation (MW)           | 1269.20 | 1271.51 | 1269.13 | 1270 | 1234.99 |
| Fuel Cost ($/h)                 | 15,667.9 | 15,856.1 | 15,914.3 | 15,577.3 | 15,202.6 |
| Emission (ton/h)                | 1.82129 | 1.88918 | 1.85870 | 1.83871 | 1.72090 |
| Power Losses (MW)               | 18.4038 | 20.7100 | 18.3300 | 19.2000 | 18.4442 |
| Computation Time (s)            | 690.1000 | 878.7000 | 694.2000 | 690.1400 | 705.510 |
Table 11. Results for CEEC minimization for the Test System 2.

| Control Variable | Without Wind Farm | With Wind Farm |
|------------------|-------------------|---------------|
|                  | KHA   | ALC-PSO | DEA   | KHA   |
| $P_{G1}$ (MW)    | 346.8868 | 480.9300 | 475.6800 | 92.82350 |
| $P_{G2}$ (MW)    | 0.000000 | 0.000000 | 0.000000 | 286.8995 |
| $P_{G5}$ (MW)    | 173.0854 | 80.14000 | 80.64000 | 13.55130 |
| $P_{G6}$ (MW)    | 0.000000 | 0.000000 | 0.000000 | 193.2463 |
| $P_{G8}$ (MW)    | 157.0796 | 270.4200 | 276.0300 | 13.55130 |
| $P_{G9}$ (MW)    | 0.000000 | 0.000000 | 0.000000 | 89.01440 |
| $P_{G12}$ (MW)   | 583.2398 | 446.0400 | 447.2000 | 459.5085 |
| Total Generation (MW) | 1260.291 | 1279.530 | 1279.550 | 1224.918 |
| $P_{\text{wind}}$ (MW) | 0.000000 | 0.000000 | 0.000000 | 36.18200 |
| Fuel Cost ($/h) | 9917.870 | 10,237.79 | 10,408.49 | 8481.851 |
| Emission (ton/h) | 2.200089 | 2.227447 | 2.211635 | 1.620300 |
| Power Losses (MW) | 9.491500 | 28.73000 | 28.75000 | 10.30090 |
| CEEC     | 11,410.00 | 13,032.56 | 13,183.42 | 10,060.00 |
| Computation Time (s) | 690.1000 | 700.1400 | 702.2000 | 717.5100 |

In addition, Figures 8–11 show the convergence curves of the defined objective functions for the Test System 2 after 500 iterations.

Figure 8. The convergence curves for the fuel cost minimization considering and neglecting the valve-point effect for the Test System 2.

Figure 9. The convergence curves for the minimization of power losses across the transmission lines for the Test System 2.
Figure 9. The convergence curves for the minimization of power losses across the transmission lines for the Test System 2.

Figure 10. The convergence curves for emission minimization for the Test System 2.

Figure 11. The convergence curves for CEEC minimization for the Test System 2.

4. Conclusions

A new meta-heuristic algorithm is proposed in this paper to cope with the Optimal Power Flow (OPF) problem of power systems incorporated with wind farm and FACTS devices. Four different objective functions, including minimization of fuel cost, minimization of power losses across the transmission line, emission reduction, and combined economic and environmental cost minimization are formulated separately in this paper. To show the effectiveness of the proposed approach, the IEEE 30-bus test system and the IEEE 57-bus test system with the installation of thyristor controlled phase shifter (TCPS) and thyristor-controlled series compensator (TCSC) and a wind farm are simulated. Based on numerical results, it is observed that the krill herd algorithm (KHA) has great capability to achieve an optimal solution in the target functions with less computation time. The proposed method indicates an improved convergence performance to optimal solutions than other heuristic techniques and can be applied to cope with complex optimization problems in modern power systems. It can efficiently deal with the uncertainties in wind power generation. In addition, it is shown that the presence of the wind farm in power systems minimizes the dependency of conventional power plants, thus, reducing power losses across the transmission lines and reducing emission as well as the combined economic and environmental costs (CEEC).
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References
1. Kahourzade, S.; Mahmoudi, A.; Mokhlis, H.B. A Comparative Study of Multi-Objective Optimal Power Flow Based on Particle Swarm, Evolutionary Programming, and Genetic Algorithm. *Electr. Eng.* 2015, 97, 1–12. [CrossRef]
2. Viafora, N.; Delikaraglou, S.; Pinson, P.; Holbøll, J. Chance-Constrained Optimal Power Flow with Non-Parametric Probability Distributions of Dynamic Line Ratings. *Int. J. Electr. Power Energy Syst.* 2020, 114, 105389. [CrossRef]
3. Dong, X.; Zhang, R.; Wang, M.; Wang, J.; Wang, C.; Wang, Y.; Wang, P. Capacity Assessment for Wind Power Integration Considering Transmission Line Electro-Thermal Inertia. *Int. J. Electr. Power Energy Syst.* 2020, 118, 105724. [CrossRef]
4. Miveh, M.R.; Rahmat, M.F.; Ghadimi, A.A.; Mustafa, M.W. Control Techniques for Three-Phase Four-Leg Voltage Source Inverters in Autonomous Microgrids: A Review. *Renew. Sustain. Energy Rev.* 2016, 54, 1592–1610. [CrossRef]
5. Heideier, R.; Bajay, S.V.; Jannuzzi, G.M.; Gomes, R.D.M.; Guanais, L.; Ribeiro, I.; Paccola, A. Impacts of Photovoltaic Distributed Generation and Energy Efficiency Measures on the Electricity Market of Three Representative Brazilian Distribution Utilities. *Energy Sustain. Dev.* 2020, 54, 60–71. [CrossRef]
6. Zhang, Y.; Yao, F.; Lu, H.H.-C.; Fernando, T.; Wong, K.P. Sequential Quadratic Programming Particle Swarm Optimization for Wind Power System Operations Considering Emissions. *J. Mod. Power Syst. Clean Energy* 2013, 1, 231–240. [CrossRef]
7. Baskaran, J.; Palanisamy, V. Optimal Location of FACTS Devices in a Power System Solved by a Hybrid Approach. *Nonlinear Anal. Theory Methods Appl.* 2006, 65, 2094–2102. [CrossRef]
8. Roy, R.; Jadhav, H.T. Optimal Power Flow Solution of Power System Incorporating Stochastic Wind Power Using Gbest Guided Artificial Bee Colony Algorithm. *Int. J. Electr. Power Energy Syst.* 2015, 64, 562–578. [CrossRef]
9. Gotham, D.J.; Heydt, G.T. Power Flow Control and Power Flow Studies for Systems with FACTS Devices. *IEEE Trans. Power Syst.* 1998, 13, 60–65. [CrossRef]
10. Bhattacharyya, B.; Gupta, V.K.; Kumar, S. UPFC with Series and Shunt FACTS Controllers for the Economic Operation of a Power System. * Ain Shams Eng. J.* 2014, 5, 775–787. [CrossRef]
11. Noroozian, M.; Angquist, L.; Ghandhari, M.; Andersson, G. Use of UPFC for Optimal Power Flow Control. *IEEE Trans. Power Deliv.* 1997, 12, 1629–1634. [CrossRef]
12. Behshad, M.; Lashkarara, A.; Rahmani, A.H. Optimal Location of UPFC Device Considering System Loadability, Total Fuel Cost, Power Losses and Cost of Installation. In *Proceedings of the 2nd International Conference on Power Electronics and Intelligent Transportation System*, Shenzhen, China, 19–20 December 2009.
13. Basu, M. Multi-Objective Optimal Power Flow with FACTS Devices. *Energy Convers. Manag.* 2011, 52, 903–910. [CrossRef]
14. Pattanaik, J.K.; Basu, M.; Dash, D.P. Optimal Power Flow with FACTS Devices Using Artificial Immune Systems. In *Proceedings of the International Conference on Technological Advancements in Power and Energy*, Kollam, India, 21–23 December 2017.
15. Vanitha, R.; Baskaran, J.; Sudhakaran, M. Multi Objective Optimal Power Flow with STATCOM Using DE in WAFGP. *Indian J. Sci. Technol.* 2015, 8, 191. [CrossRef]
16. Ongsakul, W.; Bhasaputra, P. Optimal Power Flow with FACTS Devices by Hybrid TS/SA Approach. *Int. J. Electr. Power Energy Syst.* 2002, 24, 851–857. [CrossRef]
17. Leung, H.C.; Chung, T.S. Optimal Power Flow with a Versatile FACTS Controller by Genetic Algorithm Approach. In *Proceedings of the 5th International Conference on Advances in Power System Control, Operation and Management*, Hong Kong, China, 30 October–1 November 2000.
18. Easwaramoorthy, N.K.; Dhanasekaran, R. Solution of Optimal Power Flow Problem Incorporating Various FACTS Devices. *Int. J. Comput. Appl. Technol.* 2012, 55, 38–44.

19. Singh, B.; Kumar. A Comprehensive Survey on Enhancement of System Performances by Using Different Types of FACTS Controllers in Power Systems with Static and Realistic Load Models. *Energy Rep.* 2020, 6, 55–79. [CrossRef]

20. Singh, R.P.; Mukherjee, V.; Ghoshal, S.P. Particle Swarm Optimization with an Aging Leader and Challengers Algorithm for Optimal Power Flow Problem with FACTS Devices. *Int. J. Electr. Power Energy Syst.* 2015, 64, 1185–1196. [CrossRef]

21. Nguyen, T.T.; Mohammadi, F. Optimal Placement of TCSC for Congestion Management and Power Loss Reduction Using Multi-Objective Genetic Algorithm. *Sustainability* 2020, 12, 2813. [CrossRef]

22. Nguyen, T.T.; Pham, L.H.; Mohammadi, F.; Kien, L.C. Optimal Scheduling of Large-Scale Wind-Hydro-Thermal Systems with Fixed-Head Short-Term Model. *Appl. Sci.* 2020, 10, 2964. [CrossRef]

23. Saeed, M.A.; Ahmed, Z.; Yang, J.; Zhang, W. An Optimal Approach of Wind Power Assessment Using Chebyshev Metric for Determining the Weibull Distribution Parameters. *Sustain. Energy Technol. Assess.* 2020, 37, 100612. [CrossRef]

24. Shaw, B.; Mukherjee, V.; Ghoshal, S.P. A Novel Opposition-Based Gravitational Search Algorithm for Combined Economic and Emission Dispatch Problems of Power Systems. *Int. J. Electr. Power Energy Syst.* 2012, 35, 21–33. [CrossRef]

25. Gandomi, A.H.; Alavi, A.H. Krill Herd: A New Bio-Inspired Optimization Algorithm. *Commun. Nonlinear Sci. Numer. Simul.* 2012, 17, 4831–4845. [CrossRef]

26. Mishra, C.; Singh, S.P.; Rokadia, J. Optimal Power Flow in the Presence of Wind Power Using Modified Cuckoo Search. *IET Gener. Transm. Distrib.* 2015, 9, 615–626. [CrossRef]

27. Mohseni-Bonab, S.M.; Rabiee, A.; Mohammadi-Ivatloo, B. Voltage Stability Constrained Multi-Objective Optimal Reactive Power Dispatch Under Load and Wind Power Uncertainties: A Stochastic Approach. *Renew. Energy* 2016, 85, 598–609. [CrossRef]

28. Mukherjee, A.; Mukherjee, V. Solution of Optimal Power Flow with FACTS Devices Using a Novel Oppositional Krill Herd Algorithm. *Int. J. Electr. Power Energy Syst.* 2016, 78, 700–714. [CrossRef]