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Article

Optimal power load flow considering stochastic wind and solar power

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ABSTRACT

Optimal power flow (OPF) is a popular model in the study of power systems that aims to achieve optimization and operational stability while minimizing costs. Multiple research documents depict the various methods and algorithms to further explore system configurations that would achieve OPF or multi-objective OPF. In relation to power systems, many power plants rely on non-renewable sources such as fossil fuels to generate power to be supplied to cities, towns, and rural areas, but these sources are steadily decreasing in their availability and are no longer suitable for sustainability. Renewable sources (solar, wind, and hydro) have been around for decades and have been found to be suitable alternatives for power plants, but due to their stochastic nature, the power needed via this method of generation is inconsistent. The relationship between the types of sources and OPF can be seen via costs, emissions, and power since the costs required for generation and distribution are dependent on their source, be they renewable or non-renewable, including the possibility of a decrease in emissions from these power plants. This research is expected to show that OPF can be achieved using renewable sources within power systems, even with their stochastic behaviors.

1. Introduction

Due to their steady decline and continuous use over the years, non-renewable sources are forecasted to be depleted soon [1, 2]. Non-renewable energy sources such as fossil fuel are widely used for power plants, generators, and motorized vehicular transport, but the declining availability of non-renewable sources has resulted in a spike in prices and costs due to their high demand, and this has proven to be non-sustainable [3, 4]. Optimal power flow (OPF) was introduced by Carpentier in 1962 and is defined as a representation model that achieves optimal and stable operational levels with the minimization of costs and losses [5]. The goal of optimal power flow is to set up a network to run in a steady and optimal condition by modifying control variables, including shunt capacitor outputs, bus voltages, magnitudes, real power outputs, and generating costs. Accordingly, ideal power flow should minimize losses across the system and maintain voltage deviation quality while being able to meet the generation needs of a network and minimize overall generation costs. Multiple research and studies have been conducted over the years with the implementation of algorithms, optimization tools, and hybrid designs that produced varying results and would often be optimized to further explore and achieve transient stability in all aspects related to OPF. Past research findings implemented specific algorithms and functions, such as the Three-Component Mixture Distribution (TCMD) function and the Mayfly Algorithm. This method utilized the three-mixture distribution method to optimize wind and solar data by analyzing the effects of power generation scheduling with cost coefficients for total operational costs. Their results were successful as the function resolved the scheduling issues of renewable sources for generation and forecasting [6, 7]. In contrast, the algorithm resolved the multiple OPF issues regarding losses, costs, and emissions after multiple cases of simulation [8]. This study aims to contribute to OPF analysis and further investigate the dynamic aspects of OPF by utilizing the renewable sources of solar and wind within the WSCC 9-bus test system. The data obtained would be implemented into MATLAB's Multi-Objective Genetic Algorithm (MOGA) [9, 10] to analyze and plot the relationship between costs and emissions while acknowledging the system's stochastic nature of solar and wind power.

2. Methodology

2.1 Stochastic wind and solar power

Renewable power has been used as a viable energy source over the years as it is abundant and provides clean and sustainable power for countries worldwide. Countries such as the United States of America and Denmark have utilized green and clean power generation for their cities as an alternative to non-renewable sources. However, these clean and abundant sources have the drawback of being stochastic in nature; this means that the power generated from these sources is inconsistent and often fluctuates with respect to the weather conditions and seasons. According to past research papers, solar power has been noted to have a higher volatility rate than wind power, albeit at different time scales [11]. Figure 1 and Figure 2 show the hourly generation rates of renewable sources such as solar and wind power. It is apparent that both renewables reach their peak at different times of the day, with solar being active in the daytime while wind power being active with a gradual increase earlier in the day, then fluctuating before a gradual rise at the end of the day. According to sources, a solar utility farm has the capability to generate power of 1 to 2000MW that would supply a higher load. However, a wind farm generates up to an approximate value of 8 to 12MW offshore, while onshore wind farms generate 3 to 4MW with respect to the size and design of the turbines.

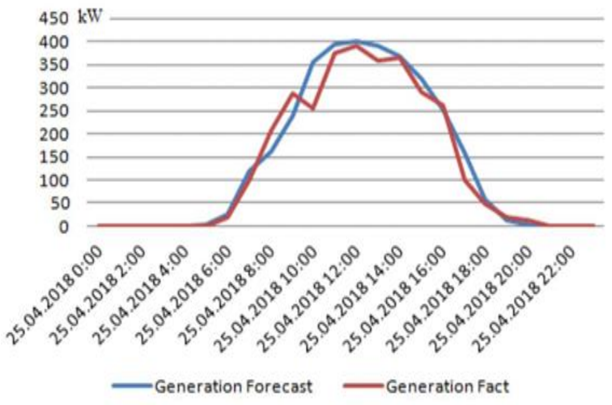

Figure 1. Hourly recorded solar power generation [12]

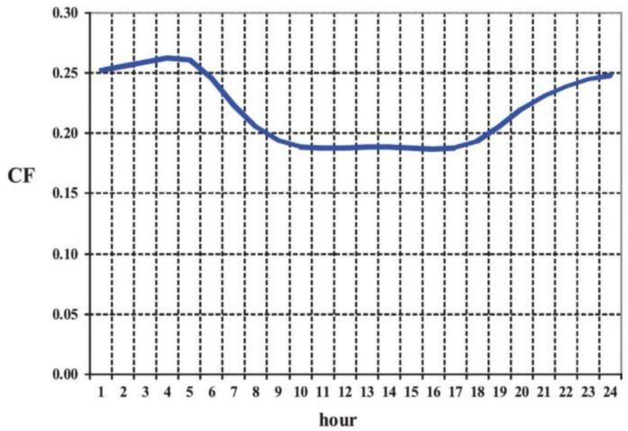

Figure 2. Hourly recorded wind power generation [13]

2.2 Review of multi-objective genetic algorithm (MOGA)

Genetic Algorithm (GA) is an optimization algorithm within MATLAB that forms appropriate solutions for optimization and research problems. However, the MOGA that will be utilized in this study focuses on achieving multiple objectives as it resolves conflicting objectives simultaneously through MATLAB programming and the use of its various toolbox functions. Initialization: The program would commence by coming up with an initial population set of solutions where each of these solutions would be represented as a set of decision variables which are treated as individual unknowns. Objective functions that would represent costs and emissions would be associated with these decision variables as they would influence the parameters set within costs and emissions.

Evaluation: All the solutions would then be evaluated accordingly based on the objective functions of costs and emissions, as the functions represent the objectives that need to be optimized as the program runs.

Pareto Dominance: This process is comprised of two parts: ranking and non-dominated sorting. Ranking begins by sorting and ranking the solutions based on Pareto dominance based on the solutions for costs and emissions. If a solution is better than or equal to the previous solution, it would be deemed the dominant solution and ranked above the others in that order. Non-dominated sorting would then compile these solutions into non-dominated fronts where the highest order would be the solution with the one that is not dominated and greater than the rest of the solutions, deeming it the best solution.

Selection: The solutions would undergo a selection process via the parent selection process, where the selected solutions would be used as a reference or “parent” for the next generated outcomes. After the Pareto dominance, the best solution would be the one selected to go through this process.

Crossover and mutation: The crossover creates new solutions by combining the decision variables of the “parent” solution to produce another “offspring” for the next generation. Then, mutation is applied, where the decision variables of the selected solutions are randomly changed.

Population update: This process begins by updating the solutions of the next generation through a combination of the “offspring” and the set of solutions. The multiple “offspring” with the best solution would often survive to go into the next generation.

Termination criteria: This criterion is determined when the condition to terminate is achieved, such as a particular set of convergence levels or reaching the maximum number of generations. It is essentially the limit that has been set to stop the algorithm from displaying the range set for the program to run.

Pareto front: The Pareto front is known as the set of all efficient solutions available. This shows that the set of solutions that have undergone the prior process should be approximate to the set of solutions of the Pareto front. The final result will represent the trade-off between cost and emissions.

The result would be plotted and displayed where the trade-off between costs and emissions would be balanced or imbalanced, translating as being successful or unsuccessful within the set range or parameters. The toolbox within MATLAB offers a wide array of computational and methodical approaches for utilizing MOGA and GA. This would allow the simulation of multiple objectives and cases to help further show the different outcomes, as the genetic algorithm shows a practical approach to simulating the costs and emissions with the set of data obtained from the bus system simulation.

2.3 WSCC 9-Bus Test System

The WSCC 9-Bus test system is a typical test system used in power system research and instruction. It is a component of the reliability test system, a set of power system test cases with varying levels of complexity and size [14]. The relative simplicity of the WSCC 9-bus test system made it commonly used to test and validate different power system optimization and analytic methods. It is shown in Figure 3. The simulation would be carried out via PowerWorld Simulator software. Generator 2 and Generator 3 would be replaced by solar power and wind power with a set range of values, whereas Generator 1 would be a slack generator. The system would follow the standard design of the WSCC 9-bus test system, with the tables below displaying the values that would be utilized throughout the simulation. Initial voltage and power limitation are listed in Table 1 and Table 2, respectively.

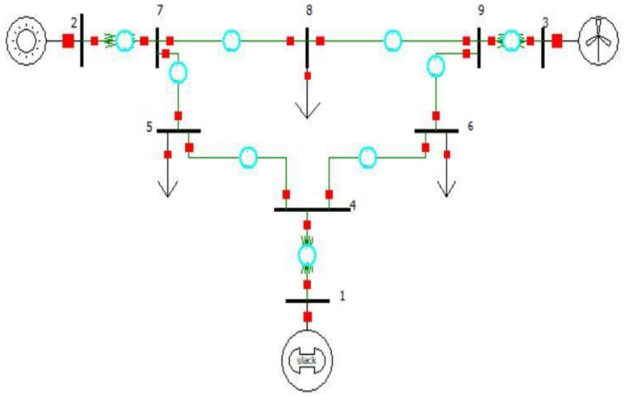

Figure 3. Model of 9-bus test system with solar and wind power

Table 1. Bus characteristics of 9-bus test system

Bus no.	Nominal Voltage (kV)	Voltage (pu)
1	16.5	1.04
2	18	1.025
3	13.8	1.025
4	230	1
5	230	1
6	230	1
7	230	1
8	230	1
9	230	1
Bus no.	P (pu)	Q (pu)
5	125 MW	50 MVAR
6	90 MW	30 MVAR
8	100 MW	35 MVAR

Table 2. Generator data for 9-bus test system [15]

Generator	Pmax	Pmin	Qmax	Qmin	Vmax	Vmin
Gen 1	250	10	300	-300	1.1	0.9
Gen 2	300	10	300	-300	1.087	0.9
Gen 3	270	10	300	-300	1.087	0.9

Table 3. Generation cost characteristics [16]

a	b	c
0.11	5	150
0.085	1.2	600
0.1225	1	335

3. Results and discussion

This study will simulate the varying effects of the stochastic nature of solar and wind within the system. Hence, three different scenarios will be carried out within the system to observe resulting economic load dispatch based on losses, generation. The generation cost are listed in Table 3. Hourly costs, with MOGA represented as plots showing the results of costs against emissions.

3.1 Scenario A

In scenario A, the simulation will consist of all generators operating simultaneously and supplying to all three loads. This scenario is considered the ideal scenario where all generators are operational with sufficient solar and wind. This is to simulate the condition where solar irradiance and wind speed are adequate and allow the wind and solar farms to generate power. The results of the simulation are shown in the Table 4 and Table 5. Also, Table 6 shows that the power generated was sufficient for the load of 315MW with losses at 5.67MW and an hourly cost of 9880.08 RM/hr. As mentioned, this scenario is treated as an ideal case because the power generated was sufficient for the loads with minimal losses within the system.

Table 4. Generator settings for scenario A

Generator Type	P (pu)
Slack (Bus 1)	0 MW
Solar (Bus 2)	50 MW
Wind (Bus 3)	15MW

Table 5. Results of scenario A

Parameters	Output
MW Load	315 MW
MW Generation	320.67 MW
MW Losses	5.67 MW
Hourly Costs	9880.08 RM/hr

Figure 4 shows the plot positioned slightly off the middle diagonally between cost and emissions. This indicates that the solutions within the Pareto front have achieved a balanced trade-off between the minimization of costs and emissions. This outcome is ideal within multi-objective optimization as it means the trade-off is efficient and the minimization of costs and emissions was successful.

3.2 Scenario B

In Scenario B, we will simulate the conditions when the renewables cannot provide sufficient power for the whole system. The slack bus will provide the power needed to supply the loads, but the aim is to observe the effects and resultant costs and losses for this set of parameters. This is to simulate real-world conditions where unpredictable weather patterns and seasons would often disrupt the charging of the solar cells and have little to no wind speed to rotate the wind turbines.

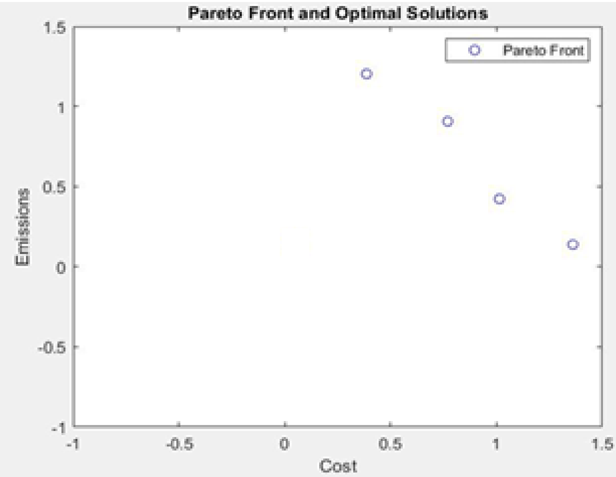

Figure 4. MOGA results for Scenario A

Table 6. Generator settings for Scenario B

Generator Type	P (pu)
Slack (Bus 1)	0 MW
Solar (Bus 2)	11 MW
Wind (Bus 3)	4 MW

Based on Table 7, it is apparent that there is a significant increase in hourly costs and losses. This is due to the slack generator having to provide more power to compensate for the lack of power from both renewables. This followed a slight increase in losses as the power had to be transmitted to the remaining buses and loads. The system may have become more unstable and costly, but it remains operational despite the lack of power generated by renewables. Compared to Scenario A, this scenario is most undesired as the system does not achieve stability or operate within desired parameters. This scenario also demonstrated the outcome of selecting inappropriate renewable sources for a power system, as some countries worldwide have abundant renewables. For example, a country with abundant solar irradiance should use solar power as an option for power generation. Solar farms should be the optimum choice if there are no suitable locations for constructing hydropower plants or wind farms.

As can be seen in Figure 5, there has been a significant change compared to Scenario A. There are currently two plots within the graph, meaning the optimization results contain several subpopulations or alternate trade-offs. The Pareto front's many plots indicate that various solutions represent a different compromise between the opposing goals. MOGA's optimization procedure distinguished between two unique sets of solutions with various cost-emissions compromise patterns. A bimodal distribution may arise when several trade-off possibilities are equally viable and non-dominated [13]. This indicates that the Pareto front has produced solutions having either high cost but low emissions or low cost but high emissions.

Table 7. Results of scenario B

Parameters	Output
MW Load	315 MW
MW Generation	324.35 MW
MW Losses	9.67 MW
Hourly Costs	13220.45 RM/hr

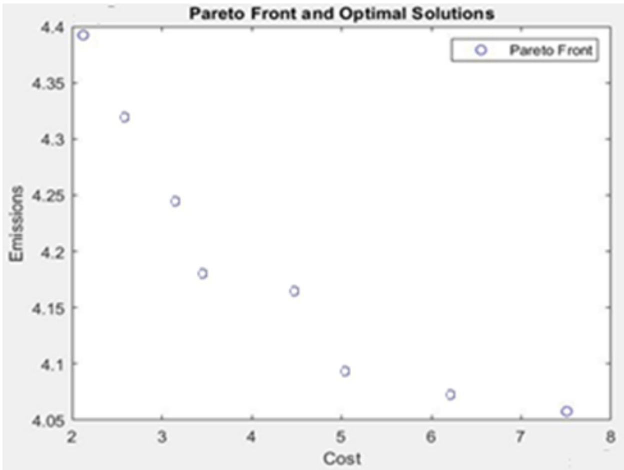

Figure 5. MOGA results for Scenario B

3.3 Scenario C

In Scenario C, we will simulate conditions where the power generated exceeds the load. The generation values are listed in Table 8. Solar power will increase its power generation to a value greater than the load of 315 MW. The resultant setting caused the system to no longer be able to operate as the software showed the "Blackout" message upon simulation commencement. This was done to simulate a scenario in California where there was an oversupply of power to the grid from their solar plant, and this resulted in the grid operators carrying out curtailment and disconnecting the active solar panels from the grid [16,17]. As there was no data to be provided into MOGA [18,19], there were no variables or solutions to be displayed on the Pareto front graph.

Table 8. Generator settings for Scenario C

Generator Type	P (pu)
Slack (Bus 1)	0 MW
Solar (Bus 2)	500 MW
Wind (Bus 3)	15MW

3.4 Discussion

It was important to simulate the different scenarios and set parameters to analyze and study the operational stability of each system to find which system was suitable for achieving OPF [20]. Hence, the parameters and system used in Scenario A were analyzed to determine if the system characteristics were suitable for achieving OPF conditions. Based on Table 9, the real power losses at each bus connection are minimal, with Bus 4 being high as it is connected to the transformer located at the Slack bus. The per unit voltages at each bus remained unchanged, as referred to in the initial set values of Table 1. The simulation was conducted on a smaller-scale power system design, and using the parameters set in Scenario A, we can see that it fulfills the conditions of minimized losses, whereas the MOGA results present a balanced trade-off between costs and emissions. Despite the results, it is mentioned that OPF may have one or more solutions, or it could have none at all, as it has been stated that OPF solution must meet both a necessary and sufficient condition while adhering to a strict yet calculable lower bound on the number of OPF solutions that were determined.

Table 9. Load flow analysis of buses

Buses		MW Losses	Voltage (pu)	Angle (Deg)
From	**To**			
1	4	0	16.5	0
2	7	0	18.45	1.41
3	9	0	13.8	-17.50
4	5	2.14	230	-8.65
4	6	2.39	230	-15.84
7	5	0.15	230	-15.14
6	9	0.4	230	17.42
7	8	0.35	230	-20.17
8	9	0.24	230	-18.01

4. Conclusion

To conclude, the study and analysis of optimal power load flow considering stochastic wind and solar using the 9-bus test system showed the complexity and challenges of achieving proper operational stability while attempting to minimize the losses, costs, and emissions for a power system. This project utilized a systematic approach by simulating a commonly used bus system to study the effects of incorporating renewable sources within set parameters and using a multi-objective genetic algorithm to help determine the appropriate solutions and trade-offs for optimal conditions between costs and emissions. The Power World Simulator was crucial in simulating the 9-bus test system as its multiple functions and tools helped further understand the system's characteristics and operations. The renewable sources may be inconsistent in power generation due to the stochastic nature, weather conditions, location, and seasons, but by selecting a set of parameters for the simulation, we could assess the effects within the power system as simulations where conditions were ideal or undesired. The use of MATLAB's multi-objective algorithm provided insights into the best solutions for achieving a balanced trade-off for the set conditions through crossover and mutation of the various iterations while incorporating the best solutions into the population. Overall, the project showed that OPF can be achieved using stochastic renewable sources with the help of appropriate tools, functions, and algorithms within the set parameters and clear problem statement. By conducting the study of this project, it is hoped that future researchers can further explore and determine the best approach or design that would truly achieve operational stability and optimal power flow for the future of power system studies.

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Ethical issue
The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement
The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest
The authors declare no potential conflict of interest.

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