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Operation of the Egyptian Power Grid with Maximum Penetration Level of Renewable Energies Using Corona Virus Optimization Algorithm

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Abstract: Countries around the world are looking forward to fully sustainable energy by the middle of the century to meet Paris climate agreement goals. This paper presents a novel algorithm to optimally operate the Egyptian grid with maximum renewable power generation, minimum voltage deviation and minimum power losses. The optimal operation is performed using Corona Virus Optimization Algorithm (CVO). The proposed CVO is compared to the Teaching and Learning-Based Optimization (TLBO) algorithm in terms of voltage deviation, power losses and share of renewable energies. The real demand, solar irradiance and wind speed in typical winter and summer days are considered. The 2020 Egyptian grid model is developed, simulated, and optimized using DiGSILENT software application. The results have proved the effectiveness of the proposed CVO, compared to the TLBO, to operate the grid with the highest share possible of renewables. The paper is a step forward to achieve Egyptian government targets to reach 20% and 42% penetration level of renewable energies by 2022 and 2035, respectively.

Keywords: penetration level; corona virus optimization; egyptian grid; benban photovoltaic park; wind farms; hydro power plants



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1. Introduction

The world is moving towards achieving the sustainable development goals (SDGs) [1]. One of the most famous SDGs is SDG 7 which is targeting access to clean energy. The whole world is looking forward to fully sustainable energy to meet 2016 Paris agreement goals for climate change [2]. From this point, many countries put a plan to reach 100% sustainable energy; there are promising and significant situations. Iceland has 100% renewable power generation, Norway achieved more than 98%, Costa Rica has now more than 95% of its electricity from renewable resources [3]. In Africa, there are two promising situations; Kenya achieved 70% penetration level of renewable energy as primary source of electricity production. Egypt has a region with installed renewable energy generators, mainly hydro and photovoltaics [4]. Egypt is also aiming to achieve 42% renewable power generation by 2035 [5].

Many researchers have tracked the idea of 100% renewable energy power grids. In [6], the researchers presented techniques for secondary voltage control of power grid with 100% renewable energies. In [7], the authors presented a study to convert the Japanese power grid to 100% sustainable power system. In [8], the authors studied the setting of standard parameters of a power system with high share of photovoltaics. In [9], the authors presented how to convert a conventional power system to work with 100% sustainable energy from the policies, technical and institutional perspectives. In [10], the paper illustrates how to convert Macedonia to 100% sustainable energy country by 2050. In [11], the paper presents techniques to optimally operate a power system with high share of renewables

while reducing the running cost of the grid generators. Sweden has set a plan to reach 100% clean electricity by 2040 [12]. In [13], the research presented a techno-economically optimized energy system for Portugal to achieve 100% renewable energy in 2050 through hydropower stations. In [14,15], the authors studied the repowering of wind turbines and how this could improve the penetration level of renewable energies in Spain.

In [16], the authors studied the role of communication and IT in achieving sustainable development goals including SDG 7. Many power system optimization techniques have been applied to perform many tasks. In [17], an optimization process is applied to operate a power system including conventional and renewable generators with minimum cost which was achieved through maximum operation of wind systems. In [4], the authors applied optimal power flow to maximize the renewable power generation in Egypt while minimizing the total power losses.

Several optimization techniques have been used to improve the performance of various systems. Genetic Algorithm (GA) is presented in [18], Particle Swarm optimization algorithm (PSO) is employed in [19]. Rao in [20] presented Teaching Learning-Based Optimization (TLBO) for the first time in 2011. In [4], TLBO is used to operate the Egyptian power system with maximum sharing of renewable energies and minimize the total power losses. Since 2020, the world has been living in the biggest pandemic which is Corona Virus (COVID-19). Turning the behavior of Corona virus to an optimization algorithm may be useful to be applied in various systems. In [21], Martinez-Alvarez et al. presented the Corona Virus Optimization (CVO) for the first time in November 2020.

The main contributions of this paper are:

- i. Maximization of renewable power generation in the Egyptian power system considering also achieving the lowest total power losses possible and minimum voltage deviation.
- ii. The paper presents the application of the new CVO optimization technique to the Egyptian power system. The Egyptian power system performance is compared in the following three cases: (i) with CVO optimal power flow, (ii) with TLBO optimal power flow and (iii) without optimization.
- iii. The research is also focusing on operating the Upper-Egypt region with 100% renewable energy for most of the daytime hours as it currently includes three renewable energy power stations in terms of a large photovoltaic park and two hydro power stations.

The rest of the paper is partitioned into sections. Section 2 illustrates the developed model of the power system in Egypt. Section 3 illustrates the renewable energy technologies integrated to the Egyptian power system. Section 4 illustrates system optimization using CVO technique. Section 5 is the results of optimization applied to the simulated grid. Section 6 is the discussion on the results and the applicability of the research while Section 7 concludes the highlights of this research.

2. Egyptian Power System

The 2016 Egyptian grid is modelled in [22] using DIgSILENT power factory software application. The 2016 model includes all the power stations, transmission lines, transformers, reactors and loads at that time. In [4], the model was updated to simulate 2020 power system including new power stations which are now in service: Benban one of the world's largest photovoltaic parks (1.8 GW as planned) and expanded Gabalzeet wind farm (0.54 GW) in addition to the three 4.8 GW combined cycle power stations which are located at Burullus, Beni Suef and New Capital as shown in Figure 1. The mentioned large power plants in the updated model and their associated expanded transmission have led the system to be partitioned geographically into six regions. The six regions are:

1. Cairo
2. Alexandria
3. Canal
4. Delta

5. Middle-Egypt
6. Upper-Egypt

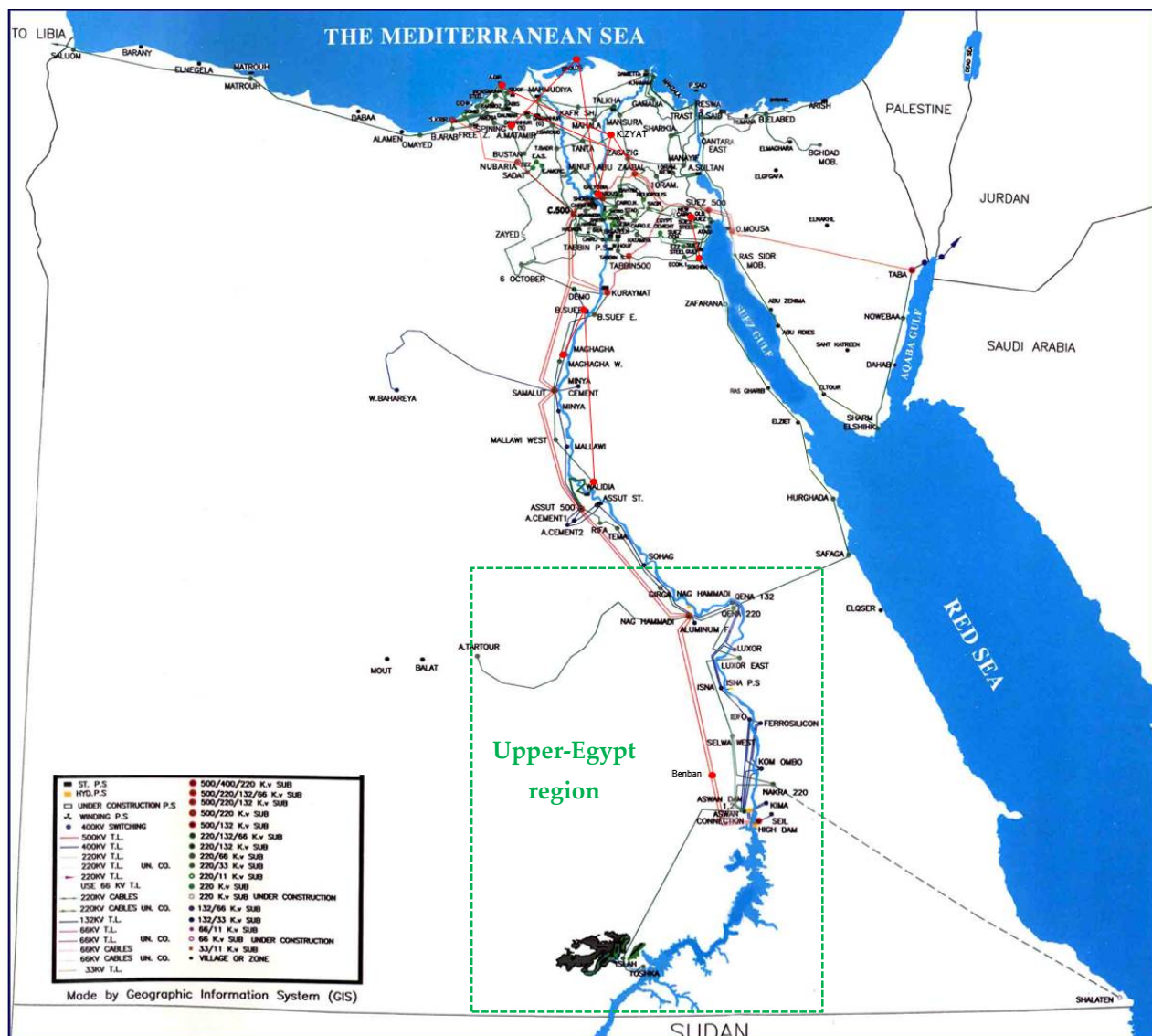


Figure 1. The Egyptian grid.

The Upper-Egypt region has three power plants, all from sustainable resources, namely High Dam power plant (2.1 GW), Aswan reservoir power plant (0.55 GW) and Benban photovoltaic park (1.8 GW as planned). The Upper-Egypt region is connected to the Middle-Egypt and Canal regions. The Canal region includes wind farms and fossil fuels power stations.

In this work, optimal operation is applied to accomplish maximum penetration level of renewable energies, minimum total power loss and minimum voltage deviation in the Egyptian power system. The paper also studies how many hours the Upper-Egypt region can operate with 100% sustainable energy without importing electricity generated by fossil fuel energies through the Middle-Egypt region.

The work is performed in DigSILENT power factory software application due to its ability to perform different studies and apply optimization and control to large power grids. The following functions can be applied by DigSILENT [22]:

1. Power flow calculations

2. Optimal power flow calculations
3. Short circuit analysis
4. Contingency analysis
5. Transient analysis

3. Renewable Energies in Egypt

In Egypt, there are three renewable energy technologies now applied, which are photovoltaics, hydro power stations and wind farms.

3.1. Photovoltaics

Egypt is famous for high solar radiation over the whole year. The average daily radiation varies between 5 and 8 kWh/m² [23]. Aswan has average solar intensity 0.367 kW/m² [24]. It was decided in September 2014 to start the installation of a large photovoltaic park in Aswan as part of the Egyptian sustainable development strategy 2035 [25].

Benban photovoltaic power station is planned to have installed capacity 1800 MW as one of the world's largest photovoltaic parks without storage. The power station is sited 40 km in the western desert northwest Aswan. The park is connected to the grid through four substations. Three substations are linked to the 220 kV grid while the fourth is connected to the 500 kV grid through a 220/500 kV step up transformer [20].

The main apparatuses of a PV system are PV modules, two converters DC/DC and DC/AC with transformer as shown in Figure 2.

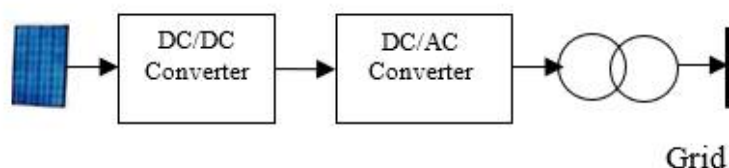


Figure 2. PV system configuration.

Benban is simulated in DIgSILENT power factory in the form of a PV static generator [23,24]. The static generator has three types of action which are:

1. PQ manner
2. Voltage control manner
3. Droop control manner

In this work, Benban is selected to work in voltage control mode. According to the Egyptian grid code for hosting large solar power stations, the reactive power range of Benban park varies between -0.33 p.u. and $+0.33$ p.u. at rated active power as shown in Figure 3.

3.2. Hydro Power Stations

In Egypt, two old famous dams which are Aswan dam and High Dam are present. Aswan dam was initiated in 1899, now it has total installed capacity 0.55 GW. High Dam was initiated in 1960 with 12 units; each unit has installed capacity 175 MW with total installed capacity 2.1 GW.

3.3. Wind Farms

Egypt has a high wind energy potential along the Red sea region. The first wind farm is Zaafarana power station was established in 2001. The capacity of Zafarana farm is 0.745 GW. Zaafarana is sited 120 km south of Suez.

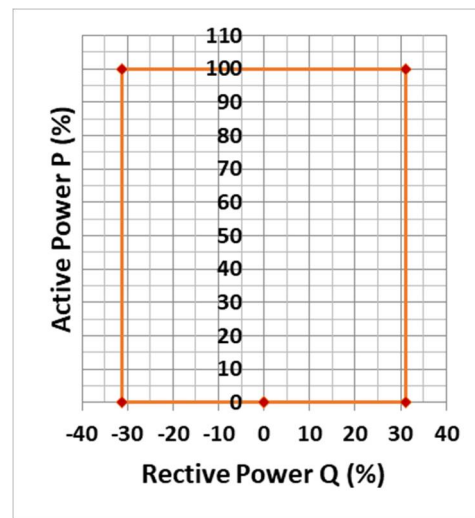


Figure 3. P-Q capability chart for large scale renewable power plants [4,26,27]. (Reprinted with permission from ref. [4]. Copyright 2021 IEEE).

Along the Suez Gulf, Gabalzeet region, there is a big potential of wind energy. Gabalzeet wind power station project is implemented in three stages [28]. Stage one is the implementation of 240 MW wind farm, stage two is the implantation of 220 MW wind farm and stage three is the implementation of an additional 120 MW farm. In 2016, the Egyptian power system was simulated including Gabalzeet with capacity 240 MW and now has been elevated to be 580 MW.

In this research, the wind farms are represented to be of type 3 with Doubly Fed Induction Generator system (DFIG). Figure 4 shows a simplified form of type 3 wind system and defined as generator bus [29].

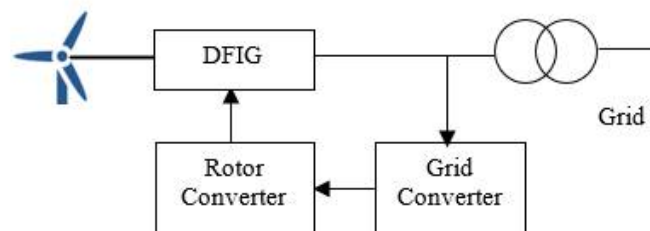


Figure 4. Type 3 wind turbine and farm.

4. Egyptian Power Grid Optimization

4.1. Optimization Problem Definition

One of the six regions is the region of Upper-Egypt which has three power stations, based on sustainable energy technologies. So, the region has the chance to get electric energy generated from sustainable energy most of the hours of the day. The Upper-Egypt region has interconnection with the Canal and Middle-Egypt regions. Carbon dioxide emission reduction can be achieved in this region by importing power from the wind farms in the Canal region and reducing consumption from the Middle-Egypt region. The optimization of the Egyptian power system operation problem can be defined as follows:

Objective Function (F): Maximization of penetration level of renewable energies (F_1), maximum reduction in total power losses (F_2) and minimization of voltage deviation (F_3). The multi-objective function is created in a way where the weights F_1 , F_2 and F_3 are simply selected to be equal.

Objective functions:

4.1.1. Maximization of the Share of Sustainable energy

The objective is to maximize the share of sustainable energy by reducing the curtailed power of each sustainable energy power plant/park/farm.

$$F_1 = \min F = \sum_{t=1}^{N_T} \sum_{i=1}^{N_R} P_{Curt_R} \Delta t \quad (1)$$

4.1.2. Minimization of Total Power Losses

$$F_2 = \min F = \sum_{i \in N_L} P_{Loss} = \sum_{i \in N_L} G_{ij} (V_i^2 + V_j^2 - 2V_i V_j \cos \theta_{ij}) \quad (2)$$

where the number of transmission lines/cables in the power system is N_L , conductance of the line connecting i and j buses is G_{ij} , the voltage at i th bus is V_i , V_j is the voltage at j th bus, P_{Loss} is the total active power loss and θ_{ij} is the phase angle of the voltage value between i and j buses.

4.1.3. Minimization of Voltage Deviation

$$F_3 = \min F = \sum_{i=1}^{N_B} (1 - V_i) \quad (3)$$

Variables: voltage of each bus bar, tap settings of the transformers and active and reactive powers produced by each generator.

Constraints:

- Equality constraints (load flow equations)

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)) = 0 \quad (4)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \sin(\delta_i - \delta_j) + B_{ij} \cos(\delta_i - \delta_j)) = 0 \quad (5)$$

- Inequality constraints (limits)
- Generation limits of each power station

$$P_{Gi_{min}} \leq P_{Gi} \leq P_{Gi_{max}} \quad (6)$$

$$Q_{Gi_{min}} \leq Q_{Gi} \leq Q_{Gi_{max}} \quad (7)$$

- Bus voltage magnitude level limits

$$V_{i_{min}} \leq V_i \leq V_{i_{max}} \quad (8)$$

- Cables and transmission lines maximum loading.

$$P_{line} \leq P_{line_{max}} \quad (9)$$

- Tap changing limits of each transformer

$$T_{k_{min}} \leq T_k \leq T_{k_{max}} \quad (10)$$

- Capacitors limits

$$Q_{ci_{min}} \leq Q_{ci} \leq Q_{ci_{max}} \quad (11)$$

where N_B is the number of bus bars in the power system, δ_i is the angle of voltage value of the i th bus, B_{ij} is the susceptance value between i and j buses, T_k is the transformer tap changer range, Q_{ci} is the reactive power of capacitor, P_{Gi} and Q_{Gi} are the active and reactive powers of the generator, respectively, P_{Di} and Q_{Di} are the demanded active and reactive powers, respectively.

4.2. CVO Design

Since December 2019, the world has been suffering from Corona Virus 2 which is widely known as (COVID-19) respiratory virus. The total infected humans with the virus worldwide are more than 83,000,000 in 2020 including 1,800,000 deaths and 60,000,000 recoveries [30]. From the fact that Bio-inspired optimization techniques are widely used and proved good performance in the machine learning optimization at different applications, the quick propagation of COVID-19 worldwide has inspired researchers to use CVO as a novel metaheuristic optimization algorithm. The CVO has the following advantages among state-of-the-art metaheuristic techniques

- i. CVO parameters are set with actual values for rates and probabilities, preventing the user from applying an additional study on the appropriate setup configuration.
- ii. In CVO, the solution exploration can stop after several iterations, without an obligation to be configured.
- iii. The high rate of COVID-19 spreading is useful for searching in promising regions more carefully, whereas the use of parallel draining confirms that all regions of the search space are consistently explored.

The CVO algorithm flow chart is shown in Figure 5 following the next steps.

Step 1: Initial population generation (patient zero); the first patient ever to catch COVID-19. If no previously reached optimal solution, it will be set randomly.

Step 2: The propagation of disease is applied based on the following cases.

- (1) Case 1: each patient has a probability of dying (P_{DIE}) according to the death rate of COVID-19. In this case, patients cannot infect other individuals.
- (2) Case 2: patient who is still alive has a probability to infect new individuals according to a probability PSUPERSPREADER. The PSUPERSPREADER is set according to two possibilities:
 - (a) Ordinary: patient will infect new individuals according to a normal spread rate ($R_{Spreading}$).
 - (b) Super spreaders: patient will infect new individuals according to super spreading rate ($R_{Superspreading}$).
- (3) Case 3: patients either considered ordinary or super spreaders may travel. The patient will explore different solutions in the search space. The probability of the patient to travel (P_{Travel}) and the rate to infect new individuals based on travelling scenario is R_{Travel} .

Step 3: populations updating, the following three populations are updated according to:

- (1) Death, any individual who has died is recorded in the current population and will not be used furthermore.
- (2) Recovered, after each iteration, the recovered individuals are recorded in the recovered population. Any recovered individual has a probability of being re-infected again ($P_{Reinfected}$) at any coming iteration. The isolated individuals, if they are properly isolated will be added to the recovered population too with a probability ($P_{Isolated}$)
- (3) New infected population which includes all the infected individuals of each iteration. It is possible that the new infected individuals are repeated in more than one iteration; the recommendation in this case is to remove the repeated new infection from the population before jumping to the next iteration.

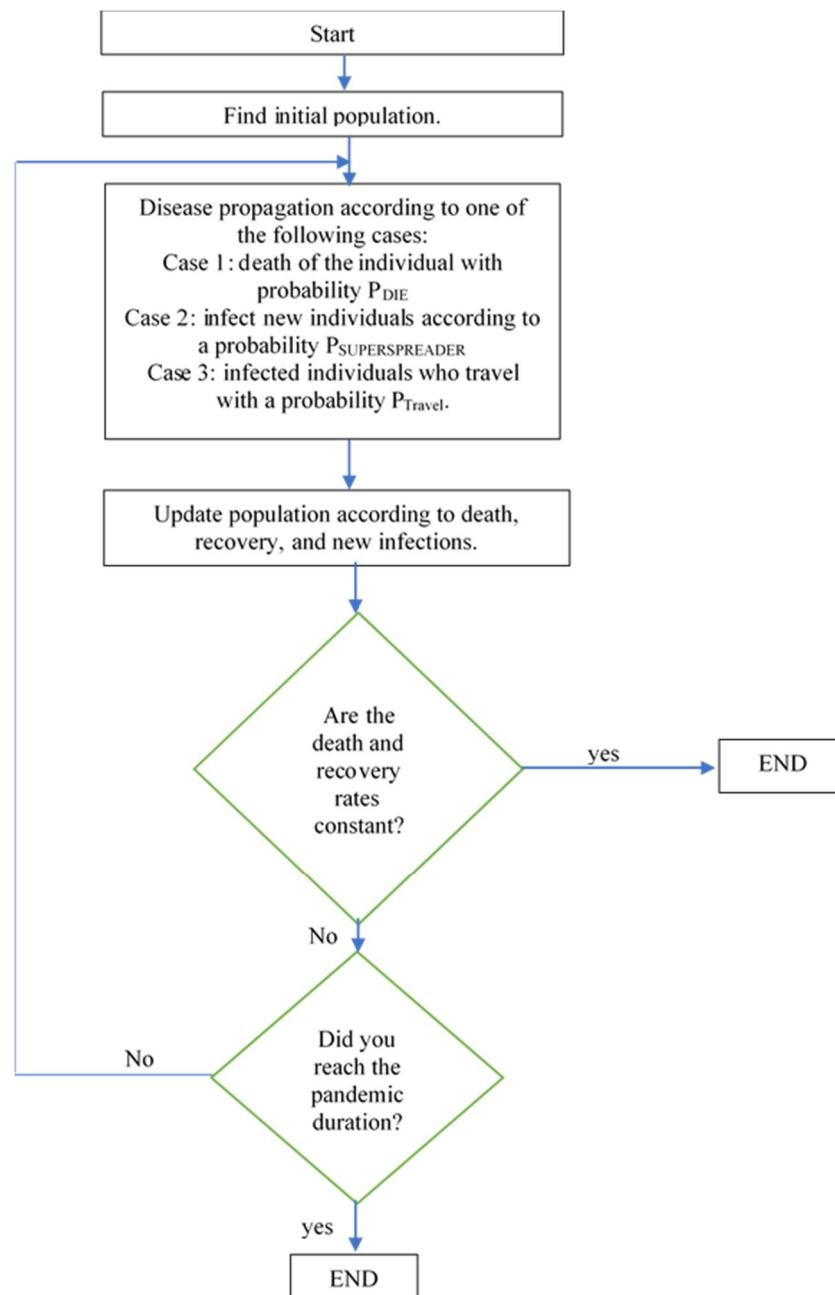


Figure 5. CVO flowchart.

Step 4: stop criteria, the process can be ended at any time without need to control any parameter because the numbers of death- and recovery-based population rates become constant as time passes and the new infected population cannot infect new individuals. It is also possible that at certain iterations, the number of infected individuals increases, however at other particular iterations the number of infected individuals could be small because of the large size of death and recovered populations. A preset stop based on number of iterations is also available in the form of pandemic duration. The social distance can also stop the optimization process.

Parameter's settings: $P_{DIE} = 0.05$, $P_{SUPERSPREADER} = 0.1$, $P_{Travel} = 0.1$, $P_{Reinfected} = 0.02$, $P_{Isolated} = 0.8$, Pandemic duration = 30 and social distance = 8 [21,31].

To avoid premature convergence to local optima, the best set of parameters for the optimization problem is selected by adapting the number of population members, social

distance and pandemic duration of the proposed CVO in DIgSILENT. To reduce the possibility of falling local minima, the optimization process is repeated many times.

CVO is applied since appearing for the first time in some applications such as transportation network [32] and training of neural networks [31].

CVO is created in DIgSILENT software application using DPL language (the software programming language) as function then employed to perform the optimal power flow calculations.

5. Simulation Results

The objective of the presented simulation studies is to investigate the possibility of maximizing the share of renewable energies while minimizing both: total power losses and voltage deviation. The studies are focusing on two typical days representing a daily summer demand and a daily winter demand. Tables 1 and 2 show the daily demand, solar isolation and wind speed at a summer day and a winter day, respectively. The penetration levels of sustainable energy in the Upper-Egypt region are presented.

Table 1. Summer daily load, solar radiation and wind speed in Egypt.

Time (h)	Total Load (MW)	Solar Radiation (W/m ²)	Wind Speed (m/s)
0	29,184	0	5.5
1	28,799	0	5.1
2	27,904	0	4.6
3	27,396	0	4.0
4	26,728	0	4.2
5	25,949	0	4.3
6	25,208	14	4.8
7	25,329	63	4.4
8	26,086	172	4.3
9	28,170	395	4.1
10	29,147	653	4.3
11	29,512	849	4.5
12	30,250	979	4.8
13	30,476	1020	4.9
14	30,830	978	5.3
15	30,546	856	6.2
16	30,654	663	7.1
17	30,613	417	7.9
18	30,190	184	8.2
19	30,746	49	8.6
20	31,751	2	7.5
21	31,348	0	6.8
22	30,829	0	5.9
23	30,558	0	5.6

Table 2. Winter daily load, solar radiation and wind speed in Egypt.

Time (h)	Total Load (MW)	Solar Radiation (W/m ²)	Wind Speed(m/s)
0	18,313	0	3.8
1	17,210	0	3.9
2	16,376	0	3.8
3	15,672	0	3.9
4	15,268	0	4.0
5	15,184	0	3.9
6	16,057	24	3.9
7	17,261	72	4.0
8	18,035	271	4.5
9	19,130	608	5.0

Table 2. Cont.

Time (h)	Total Load (MW)	Solar Radiation (W/m ²)	Wind Speed(m/s)
10	19,975	718	5.2
11	20,494	623	5.4
12	20,920	491	6.0
13	21,113	554	6.3
14	21,375	112	6.4
15	21,763	45	6.6
16	21,984	8	6.5
17	22,297	1	6.4
18	24,588	0	6.2
19	24,154	0	5.8
20	23,456	0	5.2
21	22,688	0	4.7
22	21,733	0	4.4
23	20,592	0	4.1

Case Study 1: Operation of the Egyptian grid at a summer day: Figure 6 shows the share of sustainable energy in the Upper-Egypt region and in the whole grid as defined in (12) and (13), respectively. Figure 7 shows the total power losses and voltage deviation index [6]. Figure 8 shows the penetration levels of PV, wind and hydro, as defined in (14), (15) and (16), respectively. Comparisons are shown in the following three cases: (i) with CVO, (ii) with TLBO and (iii) without optimization.

$$\text{Penetration level of renewables in Upper Egypt} = \frac{P_{PV} + P_{Hydro} + P_{Wind\ imported}}{\text{Total power feeding the region}} \quad (12)$$

$$\text{Penetration level of renewables in whole grid} = \frac{P_{PV} + P_{Hydro} + P_{Wind}}{\text{Total power generated in the grid}} \quad (13)$$

$$\text{Penetration level of photovoltaics in whole grid} = \frac{P_{PV}}{\text{Total power generated in the grid}} \quad (14)$$

$$\text{Penetration level of wind in whole grid} = \frac{P_{Wind}}{\text{Total power generated in the grid}} \quad (15)$$

$$\text{Penetration level of hydro in whole grid} = \frac{P_{Hydro}}{\text{Total power generated in the grid}} \quad (16)$$

where the power injected from Benban PV power station is P_{PV} , the power injected from High Dam and Aswan Reservoir power stations is P_{Hydro} , the wind power injected in the eCanal region is P_{Wind} and the wind power exported to the Upper-Egypt region from the Canal region is $P_{Wind\ imported}$ assuming the 220 kV connection exists.

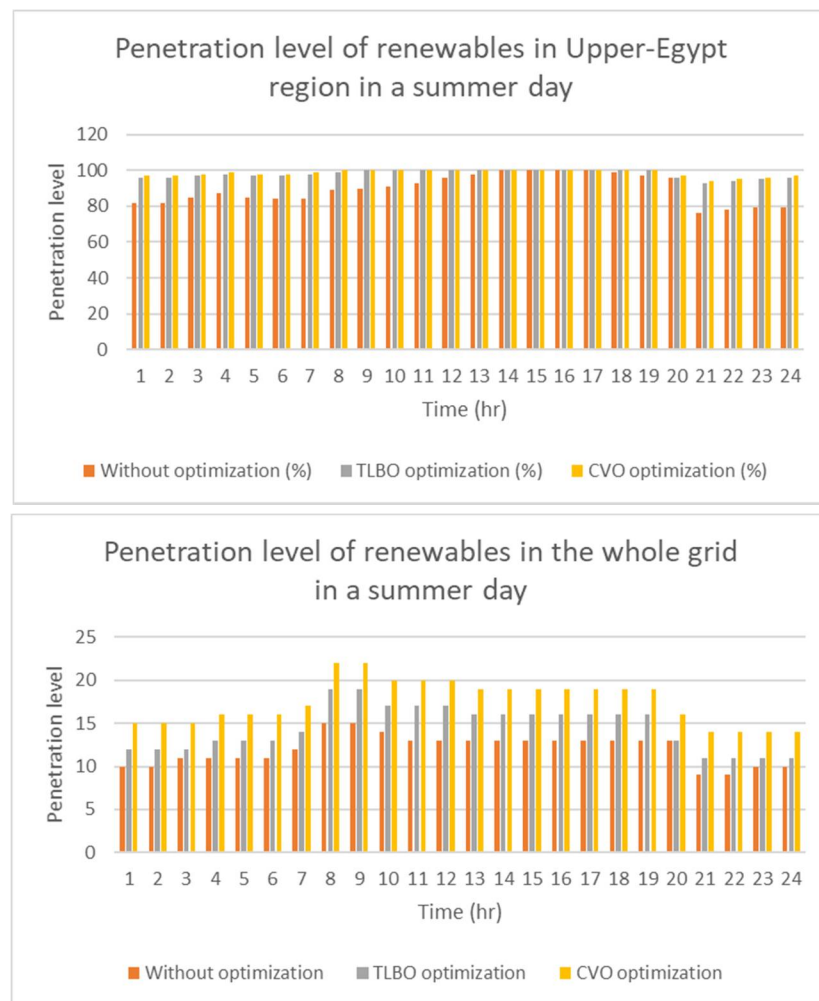


Figure 6. Penetration level of renewable energies in the Upper-Egypt region and the whole Egyptian grid in a summer day.

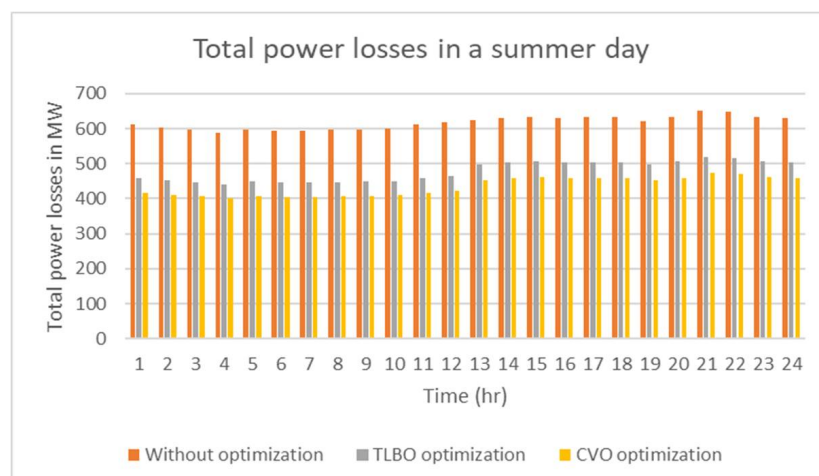


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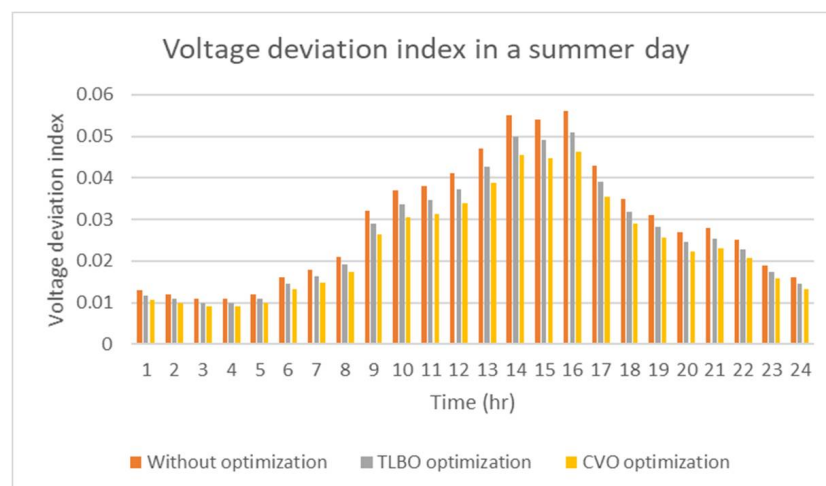


Figure 7. Total power losses and voltage deviation index in a summer day.

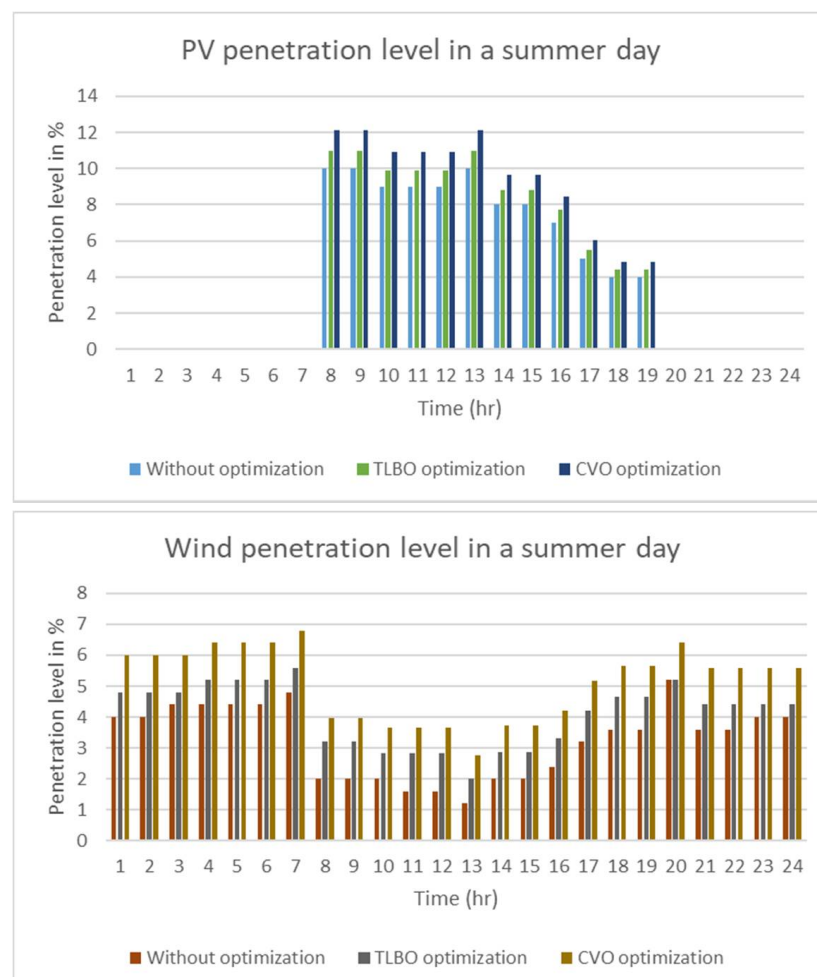


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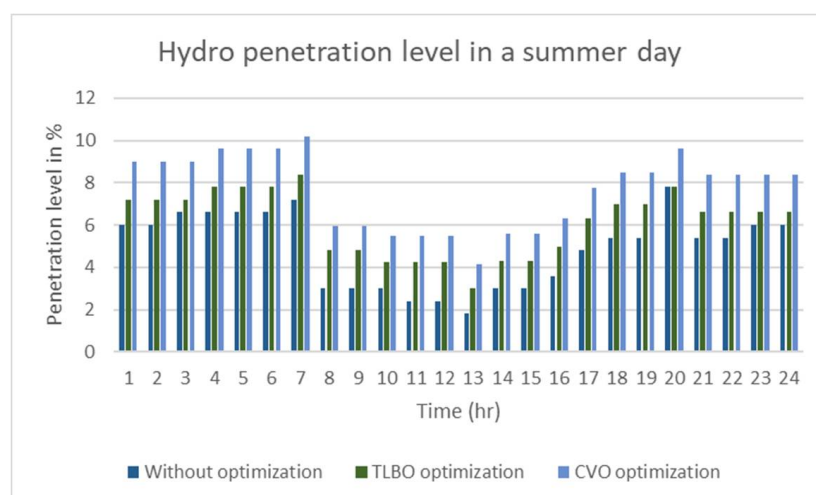


Figure 8. PV, wind and hydro penetration level in the Egyptian grid in a summer day.

The results show that through applying the CVO to optimally operate the power system, we can achieve 100% renewables in the Upper-Egypt region for more than half a day during the summer day while the time reduces to 11 h with the TLBO optimization. In the case of the system without power system optimization, 100% sustainable energy generation is achieved only 4 h in the region. The share of sustainable energy in Egypt using the CVO optimization reached 15%, or more, twenty hours during the summer day while TLBO achieved the same target only 12 h a day. The power system without optimization reached 15% share of renewable energies only two hours during the day. The total power losses of the system using the CVO are reduced by more than 10% compared to the case with TLBO optimization. In the case of no optimization the system has 30% losses more than that with the CVO and 20% more than with the TLBO technique. The use of the CVO also has resulted in minimum voltage deviation index compared to the TLBO and the case without optimization. The results show that the penetration level of PV can reach up to 12% during the peak sun hours using CVO while it reached 11% only using TLBO. The wind has penetration levels up to 7% using CVO and 5% using TLBO. The hydro has penetration levels up to 10% and 8% using CVO and TLBO, respectively. All the results are based on the existing energy mix.

Case Study 2: Operation of the power system at a winter day:

Figure 9 shows the share of the sustainable energies in the Upper-Egypt region and in the entire power system. Figure 10 shows the total power losses and the voltage deviation index. Figure 11 shows the penetration levels of the photovoltaics, wind and hydro without and with applying the CVO and the TLBO power system optimization techniques.

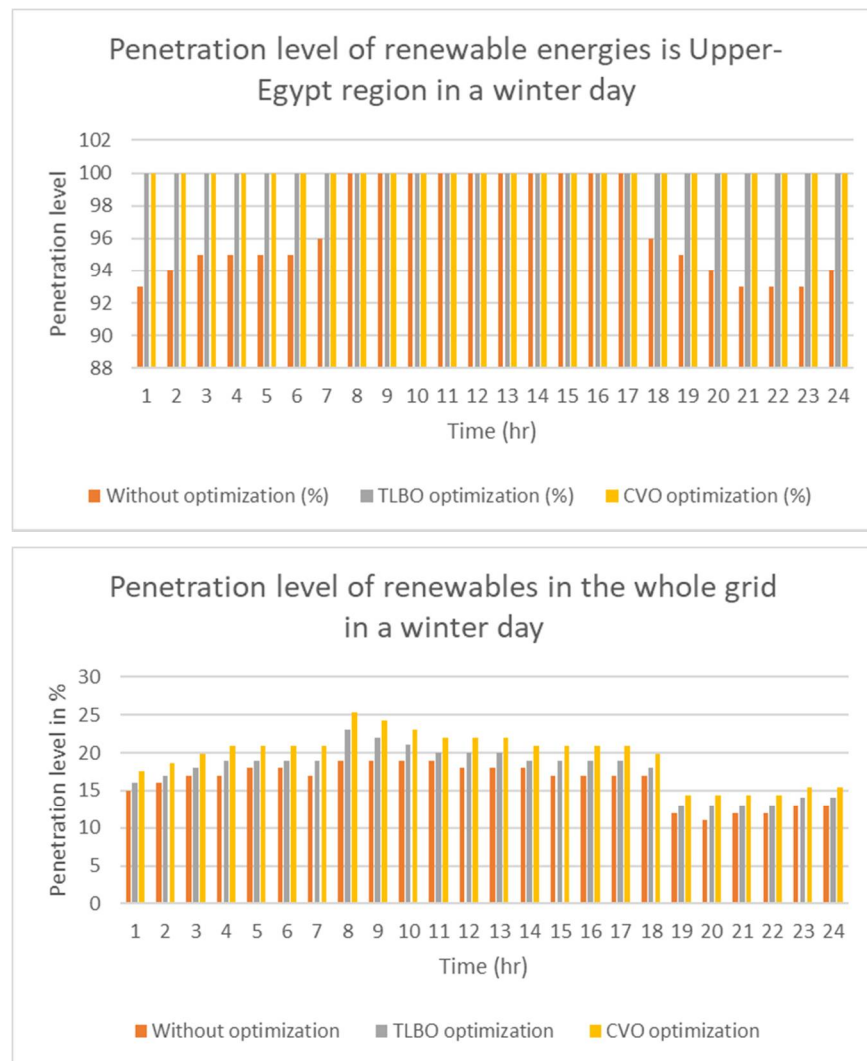


Figure 9. Penetration level of renewable energies in the Upper-Egypt region and the whole grid in a winter day.

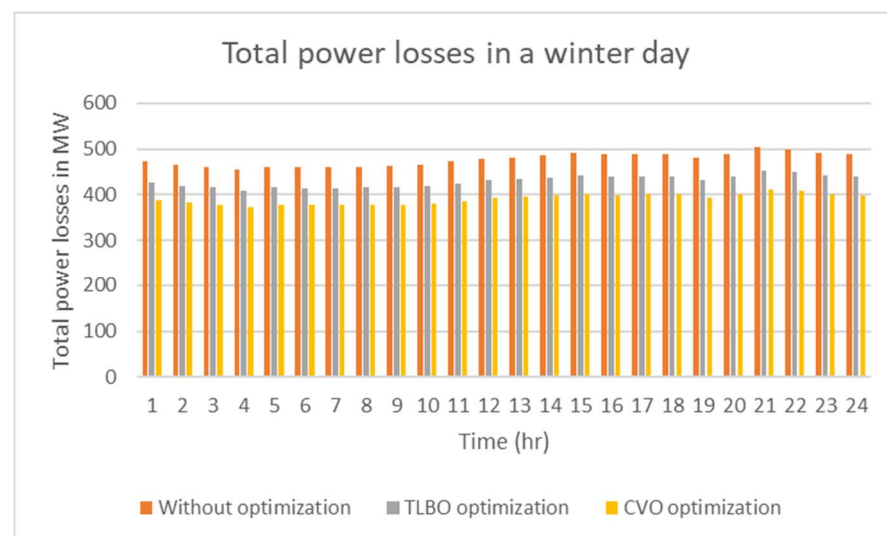


Figure 10. Cont.

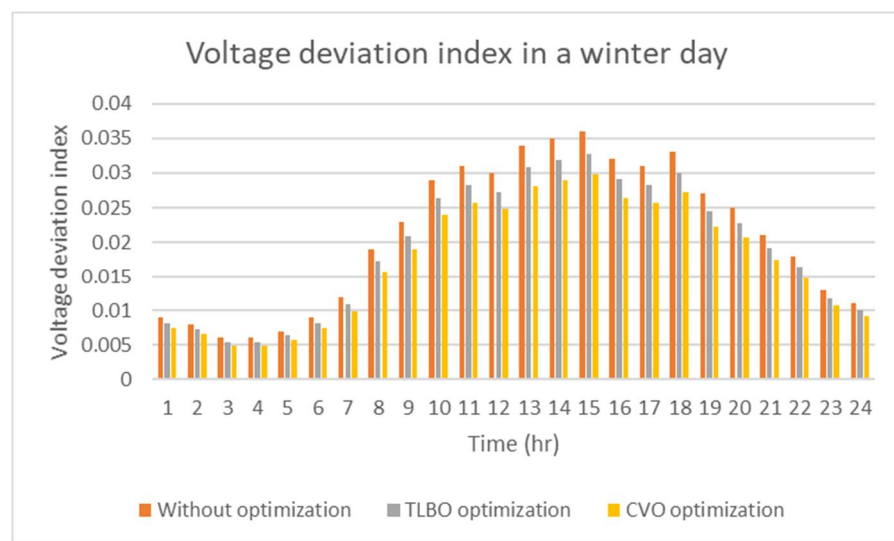


Figure 10. Total power losses and voltage deviation index in a winter day.

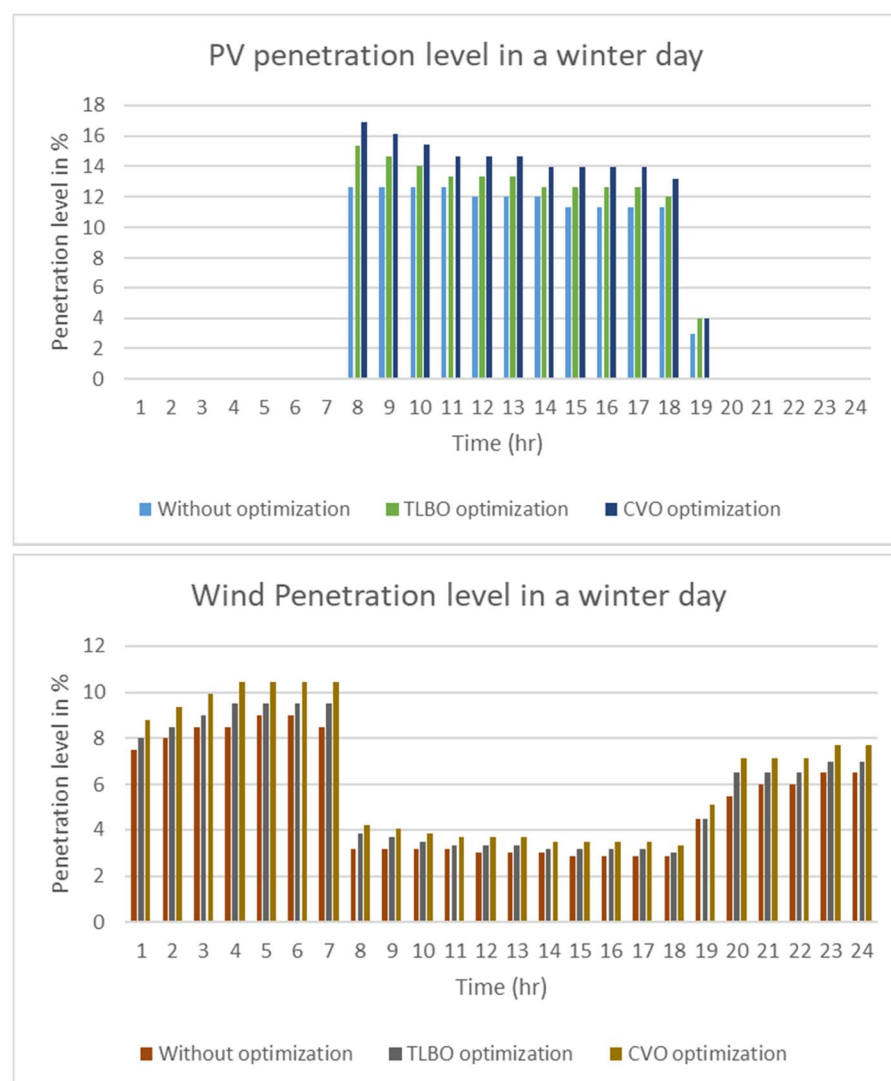


Figure 11. Cont.

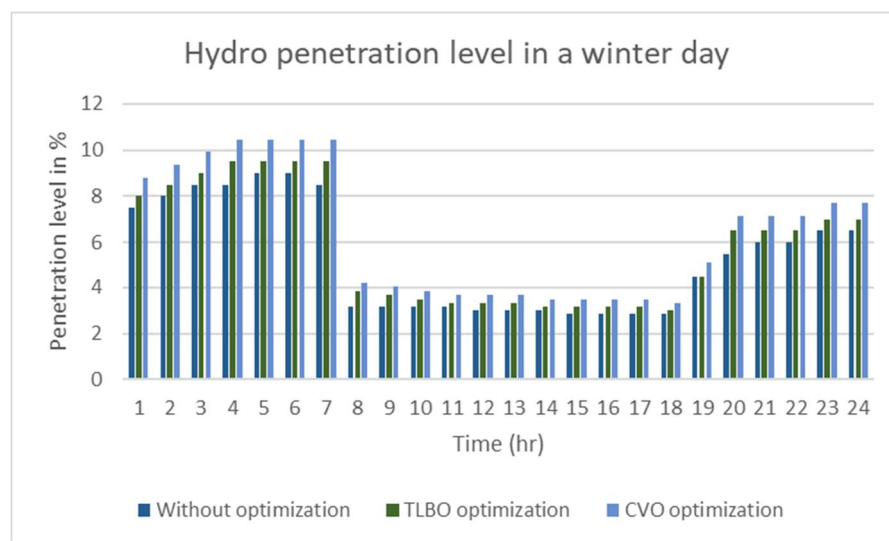


Figure 11. PV, wind and hydro penetration level in the whole grid in a winter day.

The results investigate that by applying the CVO and the TLBO to optimally operate the power system, we achieved fully renewable energy generation in the Upper-Egypt region in the whole day in winter. In the operation without grid optimization, fully renewable power generation is achieved only for 10 h in the Upper-Egypt region. The share of sustainable energies in all regions of Egypt using the CVO optimization reached 20% or more for fifteen hours during the winter day while the TLBO achieved the same target only 6 h in that day. The power system without optimization did not reach 20% penetration level of renewables during the day. The total power losses of the system using the CVO are reduced by more than 10% compared to that of TLBO optimization. In the case without optimization, the losses are 20% more than the case with the CVO and 10% more than the case with the TLBO optimization technique. The CVO also has resulted in minimum voltage deviation index compared to the other two cases, in the winter day. The results also show that the penetration level of PV can reach up to 17% during peak sun hours using the CVO while it reached 15% only if we use the TLBO method. The wind has penetration levels up to 10 % using the CVO and TLBO. Additionally, the hydro has penetration levels up to 10% using the CVO or TLBO. Figure 12 shows the convergence characteristics of the TLBO and CVO confirming that the CVO reach optimal fitness function with a smaller number of iterations than TLBO. Figures 13 and 14 show the CPU time in the operation of the TLBO and CVO at each hour of a summer day and winter day, respectively. The results show that the CVO has less CPU time by an average of 10% than the TLBO in most of the hours of the day either in summer or in winter.

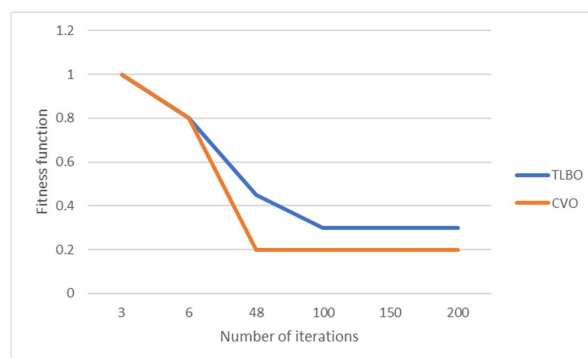


Figure 12. Convergence characteristics of TLBO and CVO.

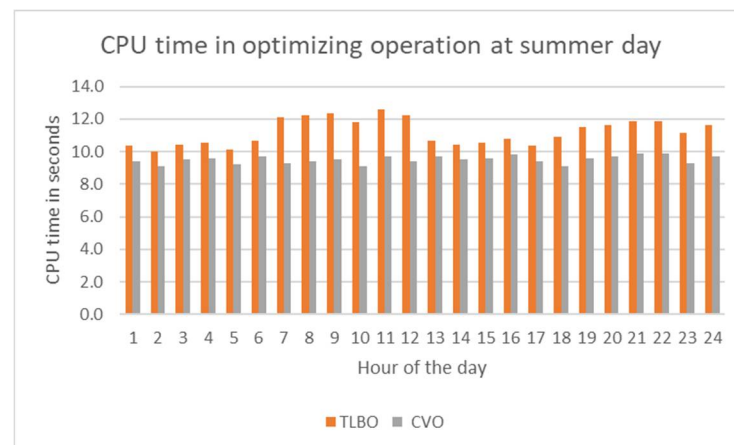


Figure 13. CPU time in the operation of TLBO and CVO at each hour of a summer day.

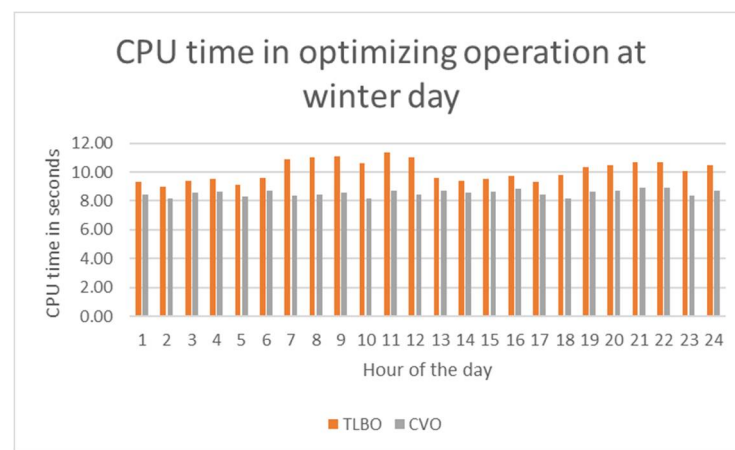


Figure 14. CPU time in the operation of TLBO and CVO at each hour of a winter day.

6. Discussions

The research has presented a study for optimal operation of the Egyptian power system to achieve maximum penetration level of renewable energies, minimum power losses and minimum voltage deviation. The optimization is performed using CVO and TLBO in DigSILENT software application as well as the simulated model of the grid. The results show that CVO has better performance than TLBO in achieving the three objectives as illustrated in the Table 3. The convergence characteristic of CVO is almost linear due to its faster response than that of TLBO.

Table 3. Error between CVO and TLBO in %.

Winter Day	
Renewable energy share	38%
Power losses	10%
Voltage deviation	14%
CPU time	11%
Summer Day	
Renewable energy share	40%
Power losses	20%
Voltage deviation	13%
CPU time	9%

The proposed CVO technique can be applied practically to the Egyptian power grid by calculating the optimal power that should be generated by each power plant. The application can be implemented in the national control center that instructs power plants to make necessary changes in its output power.

In future, the authors will study possible solutions to maximize the penetration level of renewable energies during the year to reach the targeted share of RE in the Egyptian grid as per the plan. In addition, a suggested extension of this research is to study the impact of renewable uncertainties [33,34] on the optimization results.

7. Conclusions

The paper has presented a novel technique to maximize the share of sustainable energies in the Egyptian power system considering achieving minimum total line losses and minimum voltage deviation. The applied method of the CVO-based grid optimization drives the system to resourcefully use the available sustainable energy technologies compared to the TLBO algorithm and the case without optimization. During the simulated summer day, the CVO optimization technique achieved fully sustainable power generation in the Upper-Egypt region 13 h a day compared to 11 h if the TLBO is applied or 4 h if no optimization. During the representative winter day, the use of the CVO and TLBO, can lead to achieving 100% renewable energy in the Upper-Egypt region 24 h a day while in the case without optimization 100% renewable energy is possible only for 10 h a day. The penetration level of sustainable energy in whole grid using the CVO optimal power flow stretched to more than 20% for 15 h during the winter day compared to 6 h if the TLBO is applied. During the summer day, the share of sustainable energies in the grid reached 15 % or more for twenty hours a day compared to twelve hours using the TLBO method. With the CVO optimization, we can achieve decrease in the total power losses of the grid by more than 10% compared to the TLBO method and 20–30% in the representative summer and winter days. The results prove that the CVO-based multi-objective power flow resulted in minimum voltage deviation compared to that of the TLBO and the case without optimization. The results also show that the penetration level of PV can reach up to 17% in winter at peak sun hours and 12% in summer if the CVO is applied. The results also investigate that the CVO has less CPU time and number of iterations to reach optimal solution than TLBO.

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