Maximization of Renewable Power Generation for Optimal Operation of the Egyptian Grid

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***Abstract*—This paper presents optimal operation of the Egyptian grid to achieve maximum penetration level of renewable energies in the Egyptian grid operation and minimum power losses. The Upper-Egypt region includes only three power stations, all are based renewable energies: Benban photovoltaic park (world largest photovoltaic park), High Dam and Aswan Dam hydro power stations. The daily load, radiation and wind speed are considered in this study. The optimization is applied using Teaching and Learning Based Optimization (TLBO). The results show that the proposed TLBO based optimal power flow effectively maximizes the penetration level of the available renewable energy and minimizes the total power losses. The applied optimization in this paper is a step towards minimum generating cost operation of the grid. The Egyptian power system at the 500 / 220 kV level is simulated and, the conventional and optimal power flow calculations are performed.**

***Index Terms*—100% Renewable Power Generation, Egyptian Grid, Upper-Egypt Region, Penetration Level of Renewables, Teaching and Learning Based Optimization (TLBO).**

I. Introduction

The world is targeting 100% renewable energies by 2050 [1]. The penetration level of renewables in many countries hits significant levels which cultivated the land for a green energy world in near future. In Iceland, for example, the electricity is generated based fully renewable energy resources. Countries like Costa Rica and Norway have more than 95% penetration level of renewables. In Brazil, the presence of renewable energies in producing electricity is more than 70%. The percentage of renewable energy as a primary form of electric energy worldwide reached 23% in 2019 [2], [3].

In Egypt, the continuous increase of population and investments requires more energy generation. Egypt is rich with solar energy; the amount of solar energy incidence per square meter varies between 5 and 8 kWh per day with duration of 3000-4000 hours per year [4]. Egypt also has a good potential of wind energy on the shore of the Red Sea and other places. The Egyptian government is recently focusing on establishing solar and wind energy power plants.

Researchers in the recent years started to study the operation of grids with 100% renewable power generation. In [5], the authors presented a 1 MW microgrid based 100% renewables in terms of solar and wind energies; the study was focusing on how energy storage can balance between renewable energy generation variation and variable load requirement. In [6], the study presented in 2019 illustrated how to integrate large amount of renewable energies into the Japanese power system targeting 100 % renewable power generation by 2030 while keeping the stability of the grid.

Many researchers tracked the idea of optimal operation of the power system in terms of achieving minimum generating cost or minimum total power losses. In [7], the authors presented optimal operation of a power system, by solving the generation scheduling optimization problem of a complex system consisted of conventional and renewable energies, the method applied proved that using wind energy achieved less generation cost.

In 2011, Rao proposed TLBO bio-inspired optimization algorithm [8]. TLBO algorithm is used recently in many applications and proved better system operation as shown in [9], better maximum PV power point tracking achieved and in [10], less inter-area oscillation achieved.

This research presents TLBO algorithm based optimal operation of the Egyptian grid to achieve maximum penetration level of renewables in the Egyptian grid in addition to minimum total power losses as a step towards minimum generating cost of the grid. The paper is organized as follows: Section II describes the simulated Egyptian grid. Section III explores the renewable energies in Egypt. Section IV discusses power system TLBO algorithm. Section V presents the simulation and optimization results. Finally, Section VI summarizes the main conclusions.

II. Egyptian Power System Description

In [11], the 2016 Egyptian 500 / 220 kV power grid was fully described and simulated using DIgSILENT software. Fig. 1 shows a geo-schematic diagram of the updated simulated Egyptian grid [4]. The update includes the added transmission lines and power stations till 2020.

The Egyptian grid is partitioned geographically into six regions:

1. Cairo region
2. Alexandria region
3. Delta region
4. Canal region
5. Middle-Egypt region
6. Upper-Egypt region

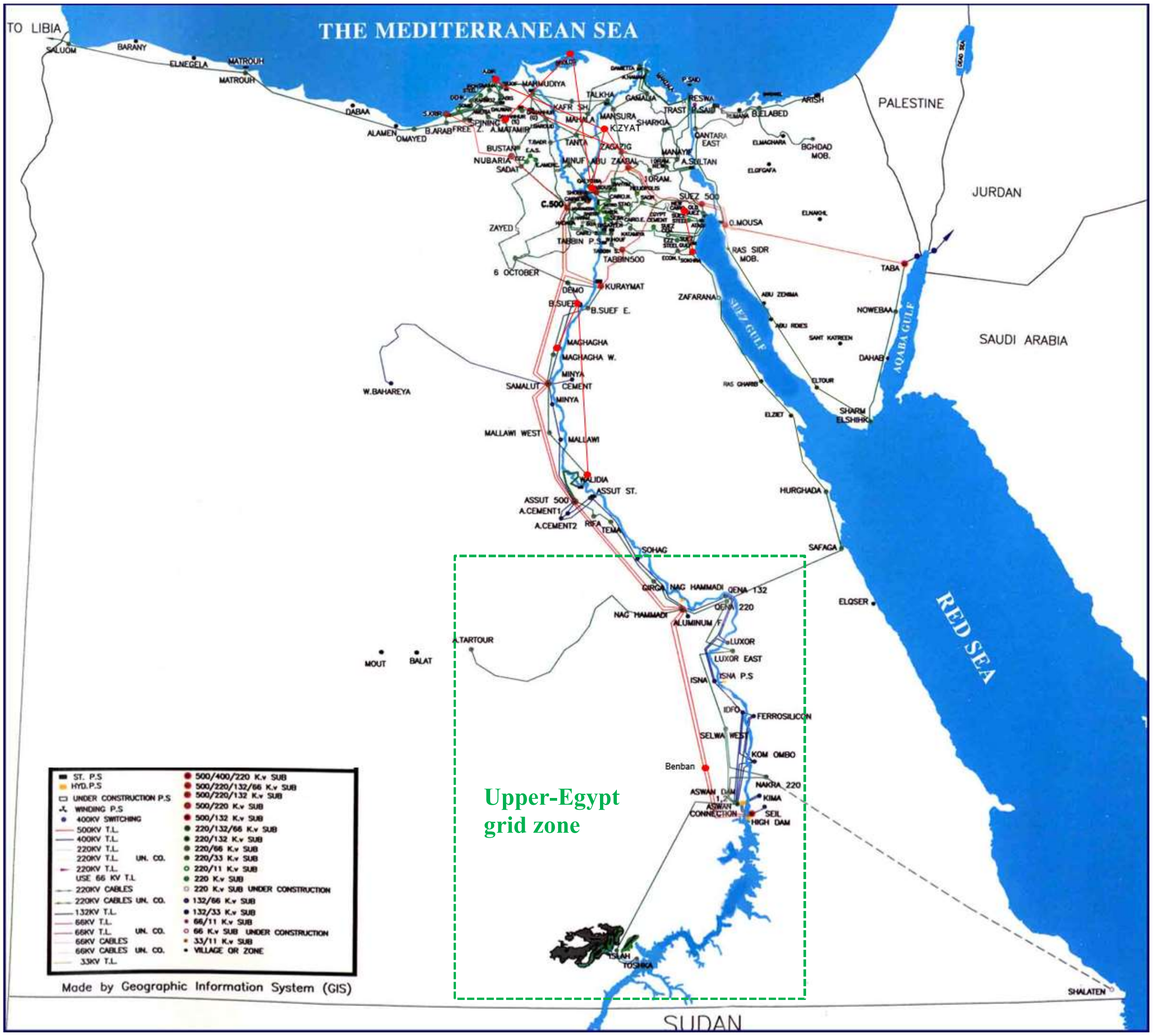

Fig. 1. The simulated Egyptian grid [4]

The generation of the Upper-Egypt region is only from three power stations based renewable resources which are: 2.1 GW High Dam hydro power station, 550 MW Aswan Dam hydro power station and 1.8 GW Benban photovoltaic park (the world largest solar PV park). The Upper-Egypt region is interconnected with two regions: Canal region (East) which includes wind generation and Middle-Egypt region (North). The Canal region includes both conventional power stations and wind farms at Zaafarana, Suez gulf and Gabalzeet unlike Middle-Egypt region which generates electricity only from fossil fuels.

In this research, the focus will be on the optimal operation of the Egyptian grid in terms of minimum power losses and maximum penetration level of renewables in the whole grid generally and Upper-Egypt region especially at different operating conditions. The daily load, radiation and wind speed in summer and winter will be considered to perform hourly conventional and optimal power flow calculations.

III. Renewable Energy in the Egyptian Grid

A. Upper-Egypt Region

1) *Photovoltaic power generation*

Benban Photovoltaic Park with its installed capacity of 1.8 GW is considered the largest PV park worldwide without storage. The park is located approximately 40 km northwest of Aswan city in the western desert. The park is connected to the 220 kV transmission system through four 22/220 kV substations, one of these substations is also connected to the 500 kV system through 220/500 kV transformers for further evacuation of the power from Benban site. There is a corridor with 2 x 500 kV at approximately 0.5 km from the eastern site border, between the site and Aswan-Luxor Highway [12].

Fig. 2 shows the main components of a typical PV power plant, it consists of a large number of solar arrays, DC/DC converters, DC/AC inverters, filters, and step up transformers [13].

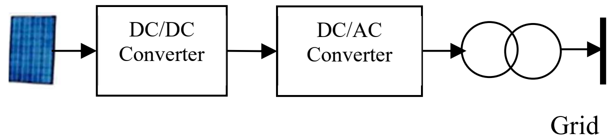

Fig. 2. Photovoltaic system [14].

Benban photovoltaic park is simulated as a static generator [14]. The static generator has 3 modes of operation which are PQ mode, voltage control mode and droop mode [14]. In this work, the voltage control mode is selected. The reactive power limits of the solar park are set to achieve 0.95 p.f. lead and 0.95 p.f. lag (at rated output) based on the Egyptian grid code for integrating large scale solar systems to the grid as illustrated in Fig. 3 [15].

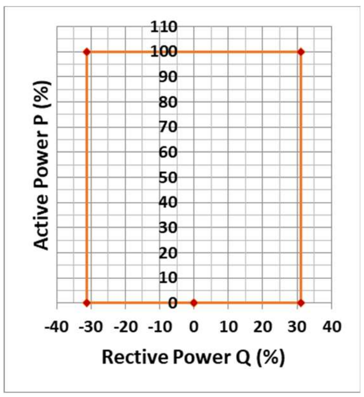

Fig. 3. P-Q capability chart for large scale renewable parks [15].

2) *Hydro power stations*

In Aswan, there are two dams which are High Dam and Aswan Dam. High Dam was built between 1960 and 1970 across the Nile in Aswan. The installed capacity of the High Dam is 2.1 GW. Aswan Dam was built between 1899 and 1906, it consists of two power stations with installed capacities of 280 MW and 270 MW.

B. Canal Region

Canal region includes wind power generation in addition to conventional power plants. Along the Red Sea shore in Egypt, there is big wind energy potential. Zaafarana wind farm was established in 2001 with total installed capacity reached 745 MW in 2016. Zaafarana location is 120 km south of Suez.

In Gabalzeet along the Suez Gulf, there is a large amount of wind energy potential. Gabalzeet wind farm project is established in three phases [16]. Phase one is designed with installed capacity of 240 MW, phase two capacity is 220 MW and phase three capacity is 120 MW. In 2016 power grid model, Gabalzeet was simulated with capacity 240 MW and upgraded in 2020 model to be 580 MW.

In this work, the wind farms are simulated as a Doubly Fed Induction Generator system (DFIG) which is widely known as type-3 system. Fig. 4 shows simplified form of a DFIG wind system. DIgSILENT includes two built-in DFIG models [2]. Model 1, the rotor side's power factor is controlled to be one, the controller is however not instantaneous and small amounts of reactive power are either produced or consumed [17]. Model 2, the DC-link is hidden, specifically concerning the load flow calculations, the user can define the generator bus as a voltage control or PQ bus [17]. In this research wind generation is simulated as model 2 and defined as voltage control bus.

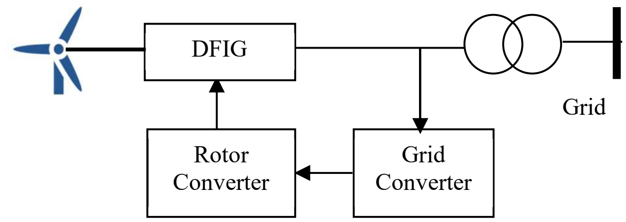

Fig. 4. DFIG wind energy system [2].

IV. Power System Optimization

A. Optimization Problem Definition

Since Upper-Egypt region includes only renewable technologies to generate electricity, it has a very big chance to operate with 100% renewable power generation at most operating conditions. Since the region is interconnected with Canal region and Middle-Egypt region, to ensure zero carbon dioxide emission in this region, it is required that if the region imported electricity at any operating condition, should maximize absorbing power from the wind generation in Canal region. The optimal power flow problem can be defined as follows:

- Objective Function (F): Minimization of total power losses (F_1) and maximization of penetration level of renewable energies (F_2). The multi-objective function is established such that weights of F_1 and F_2 are equal.

Objective functions:

a) Minimization of power losses

$$F_1 = minF = \sum_{i \in N_L} P_{Loss}$$

$$F_1 = \sum_{i \in N_L} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j \cos \Theta_{ij}) \qquad (1)$$

where N_L is the number of lines in the power system, G_{ij} is conductance of the line connecting i and j buses, V_i is the voltage at ith bus, V_j is the voltage at jth 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.

b) Maximization of penetration level of renewables

The objective is to maximize the penetration level of renewable energies in terms of minimizing the curtailed power of each renewable power plant / park / farm.

$$F_2 = minF = \sum_{t=1}^{N_T} \sum_{i=1}^{N_R} P_{Curt_R} \Delta t \qquad (2)$$

Where P_{Curt_R} is the curtailed power of renewable power station / park / farm in time t, N_R is the number of renewable power station / park / farm, N_T is the number of measurement period based on data, N_T = 24 and Δt is the time lag, $\Delta t = 15\, min$.

Variables: buses voltage, transformers tap settings and generating active and reactive powers.

Constraints:

- Equality constraints (load flow equations)

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)) = 0 \quad (3)$$

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

- Inequality constraints (limits)

  - Generating limits for each generator

$$P_{Gi_{min}} \leq P_{Gi} \leq P_{Gi_{max}} \quad (5)$$

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

  - Bus voltage magnitude level limits

$$V_{i_{min}} \leq V_i \leq V_{i_{max}} \quad (7)$$

  - Each Line loading thermal limit

$$Pline \leq Pline_{max} \quad (8)$$

  - Each tap changing transformer limits

$$T_{k_{min}} \leq T_k \leq T_{k_{max}} \quad (9)$$

  - Capacitors and FACTS limits

$$Q_{ci_{min}} \leq Q_{ci} \leq Q_{ci_{max}} \quad (10)$$

Where N_B is the total number of buses, δ_i is the angle of voltage value of the i[th] bus, B_{ij} is the suceptance value between i and j buses, $T_k$is the transformer tap changer range, Q_{ci} is the reactive power of capacitor or FACTS equipment, P_{Gi} is the active power of the generator Q_{Gi} is the reactive power of the generator, P_{Di} is the demanded active power and Q_{Di} is the demanded reactive power.

B. TLBO Design

Rao [8] established TLBO bioinspired algorithm to solve optimization problems. TLBO is considered a simple and effective metaheuristic method. Fig. 5 shows the flow chart to implement TLBO, which has two interdependent phases:

Teaching phase: Modifies the solution based on the best obtained one and the current mean fitness to avoid local minima and improve the mean fitness of all solutions.

Student phase: Solutions resulted from teaching phase are enhanced based on the relative fitness to move the solutions towards fitter ones.

V. Simulation Results

The aim of this study is achieving high penetration level of renewable energies in Egypt generally and 100% renewable power generation in Upper-Egypt region specifically in addition to minimum total power losses at different operating conditions. The studies presented here, are concentrated on two extreme lading days: summer peak demand and winter minimum demand as examples. Tables I and II show the daily load, radiation and wind speed at a summer day and a winter day.

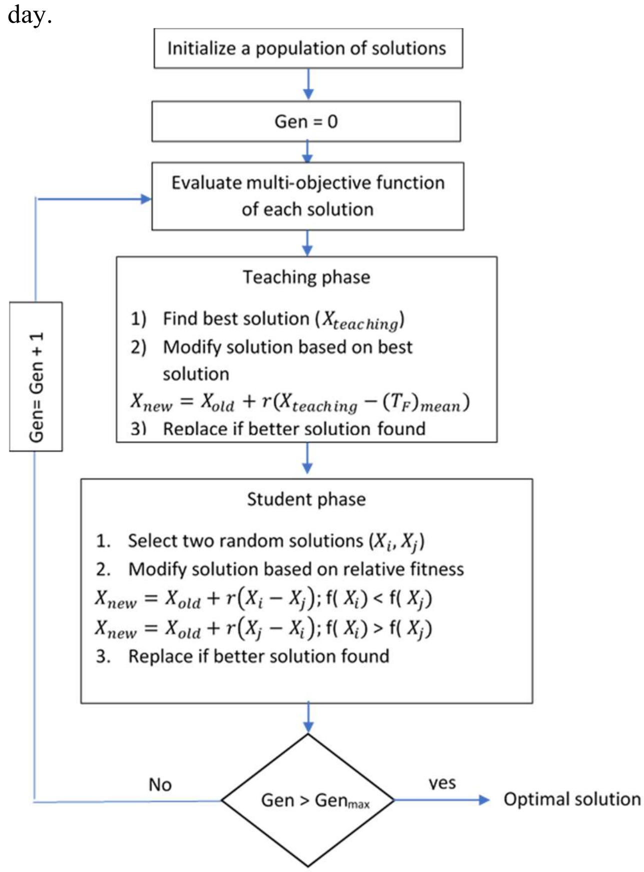

Fig. 5. TLBO algorithm [8].

TABLE I
SUMMER DAILY LOAD, RADIATION AND WIND SPEED

Time (hr)	Total load (MW)	Radiation (W/m^2)	Wind speed (m/s)
0	29184	0	5.5
1	28799	0	5.1
2	27904	0	4.6
3	27396	0	4
4	26728	0	4.2
5	25949	0	4.3
6	25208	14	4.8
7	25329	63	4.4
8	26086	172	4.3
9	28170	395	4.1
10	29147	653	4.3
11	29512	849	4.5
12	30250	979	4.8
13	30476	1020	4.9
14	30830	978	5.3
15	30546	856	6.2
16	30654	663	7.1
17	30613	417	7.9
18	30190	184	8.2
19	30746	49	8.6
20	31751	2	7.5
21	31348	0	6.8
22	30829	0	5.9
23	30558	0	5.6

Case 1: Operation of the power system at a summer day: Fig. 6, Fig. 7 and Fig. 8 show the penetration level of renewables in Upper-Egypt (11), in the whole grid (12) and the total power

losses respectively without and with applying the proposed power system optimization for each hour of the day (without means applying only conventional power flow).

$$Penetration\ level\ of\ renewables\ in\ Upper-Egypt = \frac{P_{PV}+P_{Hydro}+P_{Wind\ imported}}{Total\ power\ feeding\ the\ region} \quad (11)$$

$$Penetration\ level\ of\ renewables\ in\ whole\ grid = \frac{P_{PV}+P_{Hydro}+P_{Wind}}{Total\ power\ generated\ in\ the\ grid} \quad (12)$$

TABLE II

WINTER DAILY LOAD, RADIATION AND WIND SPEED

Time (hr)	Total load (MW)	Radiation (W/m^2)	Wind speed (m/s)
0	18313	0	3.8
1	17210	0	3.9
2	16376	0	3.8
3	15672	0	3.9
4	15268	0	4
5	15184	0	3.9
6	16057	24	3.9
7	17261	72	4
8	18035	271	4.5
9	19130	608	5
10	19975	718	5.2
11	20494	623	5.4
12	20920	491	6
13	21113	554	6.3
14	21375	112	6.4
15	21763	45	6.6
16	21984	8	6.5
17	22297	1	6.4
18	24588	0	6.2
19	24154	0	5.8
20	23456	0	5.2
21	22688	0	4.7
22	21733	0	4.4
23	20592	0	4.1

where P_{PV} is the power generated from Benban Photovoltaic Park, P_{Hydro} is the power supplied from High Dam and Aswan Dam power stations, P_{Wind} is the wind power generated in Canal region and $P_{Wind\ imported}$ is the wind power transferred from Canal region to Upper-Egypt region assuming the 220 kV connection is operational.

The results show that applying TLBO based power system optimization achieved 100% renewable power generation in Upper-Egypt region 11 hours during the summer day unlike the performance without TLBO application, 100% renewable power generation is achieved only 4 hours. The penetration level of renewables in Egypt using TLBO optimization is more than 15% twelve hours during the summer day unlike the case without applying TLBO optimization, the penetration level of renewables reached 15% only two hours during the day. The total power losses are reduced by more than 20% when TLBO optimization is applied.

Case 2: Operation of the power system at a winter day: Fig. 9, Fig. 10 and Fig. 11 show the penetration level of renewables in Upper-Egypt, in the whole grid and the total power losses respectively without and with applying the proposed power system optimization.

The results show that applying TLBO based power system optimization achieved 100% renewable power generation in Upper-Egypt region during the whole winter day, unlike the performance without TLBO application 100% renewable power generation is achieved only 10 hours. The penetration level of renewables in Egypt using TLBO optimization is more than 20% six hours during the winter day unlike without applying TLBO optimization, the penetration level of renewables did not reach 20% during the day. The total power losses are also reduced by more than 10% when TLBO optimization is applied.

VI. CONCLUSIONS

The proposed method of TLBO based power system optimization leads to efficiently utilizing the available renewable energy resources in the Egyptian grid. During the typical winter day, the TLBO based optimization achieved 100% renewable power generation in Upper-Egypt region 24 hours a day while normal power flow lead to 100% renewable power generation only 10 hours a day. During the typical summer day, the TLBO based optimization achieved 100% renewable power generation in Upper-Egypt region 11 hours a day while normal power flow lead to 100% renewable power generation only 4 hours a day. The penetration level of renewables in whole grid using the TLBO optimal power flow reached more than 20% six hours during the winter day and 15 % in twelve hours (half day) during the summer day. The proposed method also achieved reduction in the total power losses of the grid by more than 20% and 10% in the selected summer and winter days respectively. The proposed method is a step towards minimizing generating cost of the Egyptian grid which will be completed in a future work including also real fuel cost data of the thermal power stations.

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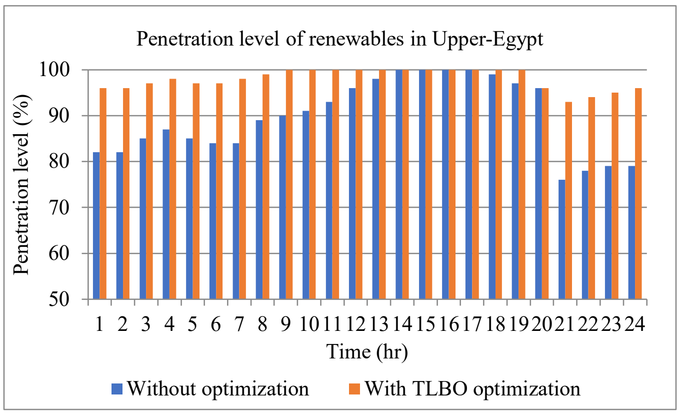

Fig. 6. Comparison of penetration level of renewable energy in Upper-Egypt at summer peak demand.

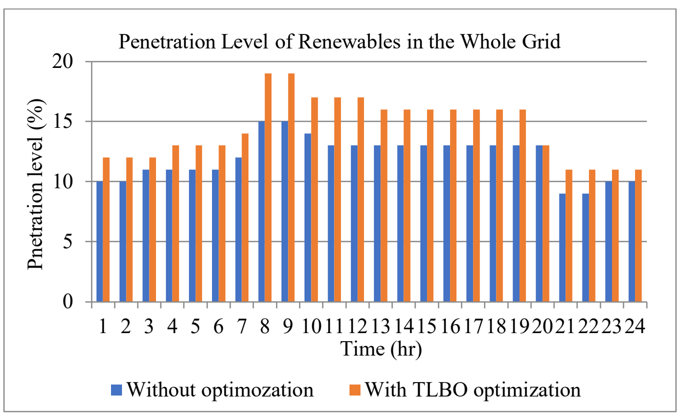

Fig. 7. Comparison of penetration level of renewable energy in the grid at summer peak demand.

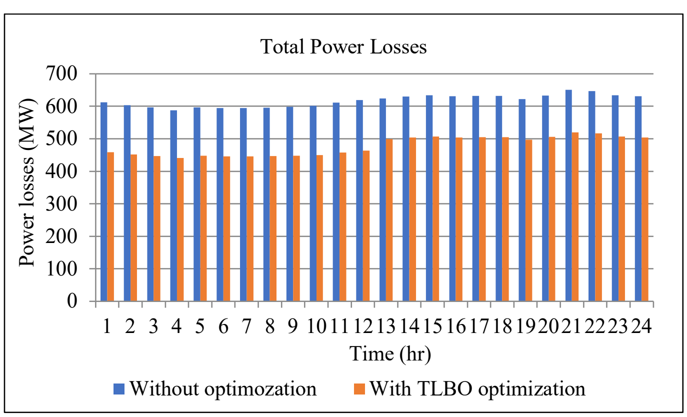

Fig. 8. Comparison total power losses in the grid at summer peak demand.

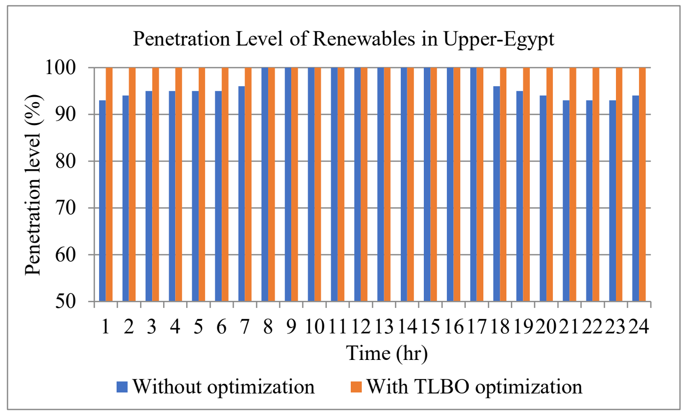

Fig. 9. Comparison of penetration level of renewable energy in Upper-Egypt at winter minimum demand.

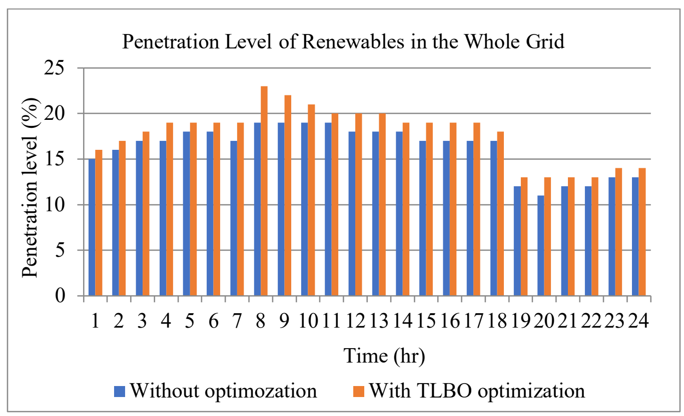

Fig. 10. Comparison of penetration level of renewable energy in the grid at winter minimum demand.

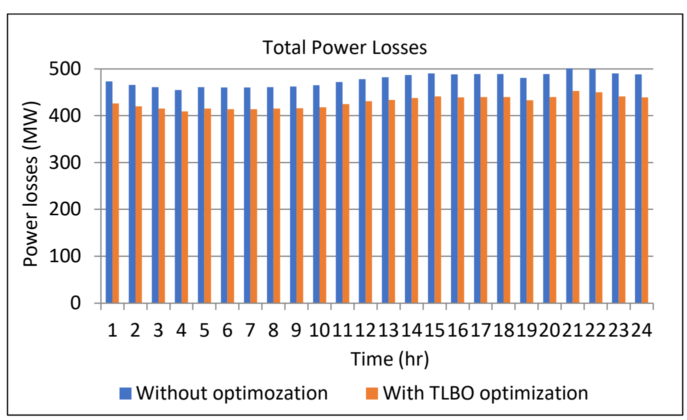

Fig. 11. Comparison total power losses in the grid at winter minimum demand.