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# Congestion and Workflow Management in Energy Systems Using Adaptive Generation Rescheduling Techniques

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**ABSTRACT**

Congestion management (CM) in power system, is another difficulty, especially for industries that have been privatized to enhance market competition since the flow capacity may result in resonance of operation and generation costs, and instabilities in transmission lines. To achieve this, there is a need of a new approach, which this paper presents as Modified Teaching-Learning-Based Optimization (MTLBO). The proposed method has been devised toward reduction on rescheduling costs, system losses and improvement on grid stability through efficient management of the power generation. The parameter-free, evolutionary algorithm enhances the Teaching-Learning-Based Optimization (TLBO) known as MTLBO, based on a two-phase structure of teaching and learning to achieve a better balance of exploration and exploitation in the search process. MTLBO is tested and assessed utilizing IEEE-30 and IEEE-57 bus test systems in terms of congestion, both in the sense of line outages and loading variations. As is seen from the results, MTLBO performs better than PSO and TLBO and is up to 15% less costly in rescheduling, up to 4.2% less in system loss and 50% faster to converge. Furthermore, MTLBO obtains a higher accuracy, precision, recall and F1 score, leading to a better performance in addressing congestion problems without affecting the optimal functionality of the system. Based on the results obtained above, it becomes obvious that MTLBO is capable of functioning as efficient real-time congestion management tool in modern power grids while also meeting grid operators' needs for network scalability in a highly dynamic market environment.

## 1. INTRODUCTION

Currently, energy demand is growing at an alarming rate worldwide hence creating pressure to the power systems to find ways of enhancing its efficiency and effectiveness in delivering electricity to consumers cheaply. More often power systems involve extensive coupling, and integration of numerous energy types, while imposing severe operational limitations [1]. Such dynamics pose certain difficulties, especially related to congestion and work flow which are central for system stability, costs containment and efficiency.

Nowadays, OPF is one of the main approaches to deal with these challenges. OPF has since its initial use in the 1960s, grown into an essential tool for system operators [2, 3]. It is mainly used to define the secure and efficient operation of a power system in steady-state by providing the lowest value of cost, for example, cost of fuel or loss cost under the juris of set of constraints so as to maintain the system secure with feasible operational conditions. Nevertheless, the fact that OPF is inherently a non-linear, non-convex and large-scale optimisation predicament renders its solution both computationally intensive and complex [4, 5].

Congestion, with regard to energy systems, is the situation in which the flow of power through some of the channels of its transmission gets to a point where actual physical and thermal limitations or forces have to be coordinated. This condition is usually experienced due to unpredicted load fluctuations, generation malfunctions or problems with transmission network [6, 7]. Congestion contributes to system unreliability and hikes operational costs and threatens to skew the supply of energy for fair use.

To select the appropriate management strategies, their aims are to regulate demand and generation by awaiting their proven overload and making sure that the existing transmission capacity is used in the most effective way possible [8, 9]. There has been the development of adaptive generation rescheduling techniques; the approach provides the operators with the ability to reschedule the flows of generations depending on the congestion levels in the system. Regarding the challenges of OPF, numerous techniques has been proposed throughout the years, starting with fundamental mathematical programming, and including heuristic and metaheuristic methods. These methodologies positively affect system reliability and efficiency, not only in integrating renewable energy sources but also in Flexible AC Transmission Systems (FACTS) devices as shown in Figure 1.

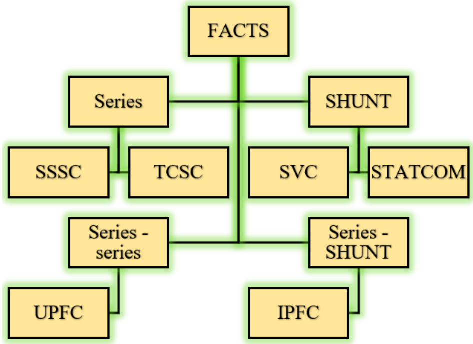


**Figure 1.** Classification of FACTS devices

In power systems workflow management can be defined the process of integration and management of all the various components and the procedures which control the capability of generating, transmitting and distributing electricity. Its objectives include process rationalisation, minimisation of wastage, and improvement of structures and systems [10-12]. With the incorporation of renewable energy capitals and sophisticated modern grid infrastructure, the overall working patterns have enhanced the more challenging aspects of workflows, making use of sophisticated optimization tools and methods are inevitable.

OPF offers power system's supply and demand a mathematical model where it seeks to find the most efficient way of operating the system from economic dispatch to voltage control [13]. In adaptive generation rescheduling, the OPF is used to determine how the rescheduling of generator outputs can alleviate the congestion problem without violating the constraints of the systems [14]. It is especially valuable in real-time application environments because context changes occur continually and synchronous responses are expected.

Opposed to this, the OPF problem can be defined as an optimisation problem with an independent function and restrictions. Normally, the aim function comprises terms such as generation cost, transmission losses or both which must both be minimized [15-17]. Constraints in OPF are classified into:

- *Equality constraints*: Coarse-grained stochastic activities meant to represent the relationships between substations in terms of power physics laws for example; real power = reactive power.
- *Inequality constraints*: Comprises generator output constraints, voltage restraints, and transmission line thermal constraints.

Adaptive rescheduling techniques makes use of enhanced resource allocation models to solve the OPF problem in varying power system conditions [18]. These methods use actual real-time data to balance generation schedules with hour-by-hour constraints and in this regard, costs are minimized while meeting system constraints.

However, mixed results show that solving OPF problems has several difficulties. Due to the nature of the OPF formulation which is non-convex and non-linear nature, the solution space has many local minimums hence making the determination of the global solution difficult. However, the incorporation of distributed renewable resources like wind and solar energy sources has WSM ACC, and variability and uncertainty complications that amplify the difficulties of OPF problems [19].

First-generation optimization procedures such as the LP, QP, and Newton type methods have been harnessed to solve OPF problems. However, these methods encounter difficulties in the convergence of solutions and the computational load increases rapidly for extensive systems [20]. To overcome these limitations, optimization heuristics and metaheuristic algorithms are advanced techniques that have been proposed by the researchers.

- *Metaheuristic algorithms*: Methodology like GA, PSO, SA has showed a promising result in handling with complex OPF issues [21]. These algorithms can easily solve multimodal and non-convex OPF problem with high degree of accuracy and provide solutions from whole universe.
- *Hybrid optimization techniques*: That is why the combination of methods based on the algorithms' iterative application with heuristic optimization has been shown to enhance both the speed of convergence to the solution as well as the quality of the solution. For instance, the optimization of OPF solutions in congested systems has in the past been accomplished by combining TLBO with PSO.
- *FACTS*: FACTS devices, including TCSC and SVC, utilize power flow and voltage profile for controlling congestion. Further, the incorporation of these devices into OPF formulations increases flexibility and stability in the power system.
- *AI-based techniques*: OPF has recently been shown to be tractable using AI and ML. These procedures are very useful in real-time systems where decision making has to be done in real-time mode.

Adaptive generation rescheduling offers several benefits for congestion and workflow management in energy systems:

- *Enhanced system reliability*: Where generation produces a quantity of energy that varies over time, adaptive rescheduling balances the energy so produced in a way that the flow through transmission lines does not overload them as well as stabilizing the voltage.
- *Cost efficiency*: Reducing the fuel utilisation in generator schedules bring down the fuel cost and transmission losses thus a great saving.
- *Integration of renewable energy*: variable renewable energy sources are easily incorporated into the approach, which improves the grid related resilience and sustainability.
- *Scalability and flexibility*: These techniques make it possible to analyse different layouts of systems and as such they are applicable for both small and big power systems.

Technological advancement in renewable power and smart grid, among other factors, make it important to adopt new more elaborate congestion, and the flow of work. Generation rescheduling technologies which adapt with human beings are in the list of potential contenders to guide future energy systems powered by new optimization and artificial intelligence concepts [22]. Algorithms are still being developed for these methods as the scope of the techniques is anticipated to grow with future uses including microgrid control, demand response, and energy storage.

## 2. RELATED WORK

Optimal power flow is an essential component of power systems management; it aims at solving different objectives incorporating cost functions, loss functions, and stability function within the power system constraints [23]. Regarding the challenges of OPF, numerous techniques has been proposed throughout the years, starting with fundamental mathematical programming, and including heuristic and metaheuristic methods. These methodologies positively affect system reliability and efficiency, not only in integrating renewable energy sources but also in FACTS devices.

Existing methods as listed in Table 1 for congestion management, such as GA, PSO, and hybrid techniques, face challenges like slow convergence, parameter sensitivity, and high computational costs. GA ensures stability but is computationally expensive, while PSO improves speed but struggles with local optima. Hybrid approaches enhance optimization but increase complexity. MTLBO overcomes these limitations by eliminating parameter dependency, achieving a better balance between exploration and exploitation, and significantly improving convergence speed. Unlike PSO, it avoids premature convergence, and compared to GA, it reduces computational overhead. MTLBO effectively optimizes rescheduling, minimizes losses, and enhances grid stability, making it a superior congestion management tool.

**Table 1.** The Existing work done on the same field

| Technique | Objective | Outcomes |
|---|---|---|
| Genetic Algorithm (GA) | Multi-objective OPF problem solving [24] | Illustrated best numbers for generation settings that were concurrently low in cost yet high in stability. |
| Particle Swarm Optimization (PSO) | Cost and loss optimization using TCSC [25] | Lower generation cost and better voltage profiles and stability IEEE 30-bus systems were attained. |
| PSO vs GA | Comparative study on voltage stability and power loss | It can be concluded that PSO yields better than GA in both accuracy and computation time in the case of power loss and voltage enhancement [26]. |
| PSO with FACTS devices (TCSC, SVC) | Optimization of power loss and] location of FACTS devices [27] | Defined the locations of devices that allowed minimizing energy losses and enhancing system efficiency. |
| Hybrid Genetic Algorithm (HGA) | Optimizing UPFC location and system cost | Improvement in voltages stability and, reduction of the investment and operating costs. |
| Multi-objective PSO | Line flow limitation with stability constraints | manufacturing costs were kept to a bare minimum all while still implementing sensible constraints to the systems in place. |
| Krill-Herd Algorithm (KHA) | Hybrid Wind-PV energy system optimization [28] | Possibility to integrate renewables, renewables forecasting and prevent from over-sizing/under-sizing. |
| GA with MATLAB simulation | FACTS device placement and parameter [29] optimization | Shown that the proposed schemes help to minimize power losses and increase the load-carrying capacity of transmission lines. |
| Dynamic Bacterial Foraging Algorithm | OPF problem in dynamic environments with varying loads | The abilities of equipment to automatically cope with load fluctuations with less fuel consumption and better operational flexibility of OPF [30]. |

Thus, this literature survey develops the flow of OPF optimization methods from traditional methods to advanced AI-based and metaheuristic approaches. Genetic Algorithms, PSO and recent trends such as Krill-Herd Algorithm have proved to improve system integrity and computation time enormously. While power systems develop, the optimization tools integration and consideration of sustainability objectives will stay essential. Future research may concern with real-time use and method study to fit for the reality of renewable integrated power system.

Congestion management in power systems is crucial, particularly for privatized industries facing flow limitations, rising costs, and grid instabilities. Existing methods like PSO and TLBO struggle with efficiency, cost-effectiveness, and convergence speed. This research introduces MTLBO, enhancing TLBO with an improved exploration-exploitation balance. MTLBO optimizes rescheduling, reduces losses, and stabilizes grids [31]. A key novelty is its workflow management integration, dynamically adjusting power generation and transmission to prevent congestion. Tested on IEEE-30/57 bus systems, MTLBO outperforms existing methods, ensuring scalability and real-time grid adaptability.

### 2.1 Objective

The main research topic is in the area of overcrowding administration in transmission line systems in electrical power systems. It introduces a new MTLBO for efficient congestion control with cheap costs and losses and high reliability of the system.

*Research objectives*: Minimize Congestion Costs: Propose the cost-effective way to reduce the rescheduling cost during congestion management in power systems.

*Enhance system efficiency*: Overcoming overall system weaknesses by improving the timing of generators and load distribution.

*Maximize social welfare*: This kind of economic cost structure should be balanced to assign proper power across the market players for the benefit of all.

*Mitigate Overload Conditions*: It may involve using sound algorithms that may enable it 'shed off' lines that may much as well prove to be congested in a bid to keep the grid secure under different circumstances.

### 2.2 Motivation

The growth in power systems' complexity, deregulation, and escalating energy needs have aggravated congestion issues affecting transmission networks. Such congestion causes ineffectiveness, costs, and system unreliability. Present techniques used to control traffic congestion fail to show flexibility and efficiency when deployed under various system performance profiles. The development of this research is informed by an urgency to find a solution that can reduce congestion costs and losses while at the same time shaping grid stability. To overcome these challenges, this research identifies an innovative Modified Teaching-Learning-Based Optimization algorithm that enhances the feasibility of power system operations in dynamic contexts in terms of effectiveness, reliability, and cost.

## 3. PROPOSED WORK

Congested transmission line is a major constraint in electrical power system, more especially, in deregulated system. Congestion management (CM) ensures maximum utilization and economic dispatch of power by controlling the flow of power within the network constraint limit. In case of conventional methods involving OPF and PSO, additional complexity and restrictions-specifically in terms of computational algorithms-are observed. The MTLBO algorithm is a new parameter less and efficient approach to solve the CM problems for minimizing rescheduling costs, system losses and line overloads in this research. The subsequent sections in Figure 2 describe the definition, realization and verification of MTLBO algorithm, and the mathematical models and numerical simulations applied in the present work.

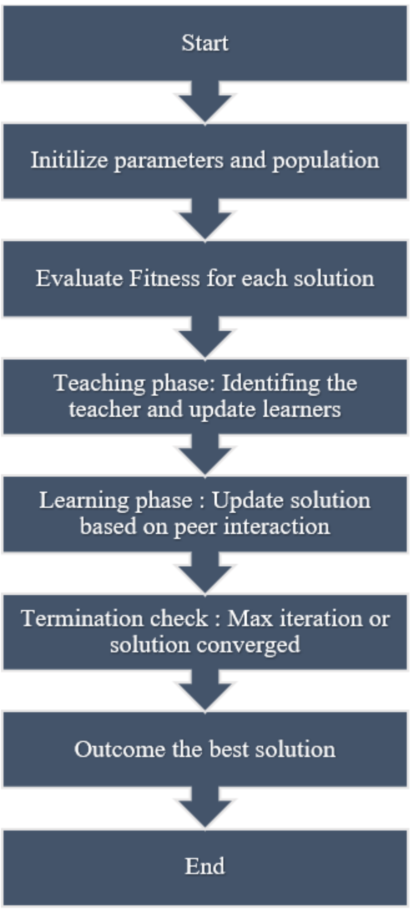


**Figure 2.** Flow illustration of the MLTBO

The CM problem is a big problem, containing several objectives, but for easier calculation it is reduced to one. The key objectives are:

•Minimizing congestion cost.

•Minimizing system losses.

•Maintaining power flow within safe limits.

This objective function reduces congestion management costs as the schedules of the generators are optimized as written in Eq. (1). It accounts for active power adjustments and associated costs:

$$F = \sum_{i=1}^{M} (C_i^{+} \Delta P_i^{+} + C_i^{-} \Delta P_i^{-}) \quad (1)$$

This leads to economic dispatch while achieving system stability without incurring congestion costs.

Here $M$ = total generators, $F$ = total congestion management cost, $\Delta P_i^{+}$ = active power outcome increment, $\Delta P_i^{-}$ = active power outcome decrement, $C_i^{+}$ = cost coefficient for increasing power generation, $C_i^{-}$ = cost coefficient for decreasing power generation.

It is because of this that the total power produced corresponds to the load demand plus the system losses as shown in Eq. (2):

$$\sum_{k=1}^{m} P_{G_k} = \sum_{l=1}^{N} P_{D_l} + P_{loss} \quad (2)$$

It balances between supply and demand and this is very important in grid operations during different situation.

Where $P_{G_k}$ = active power outcome of generator $k$, $P_{D_l}$ = active power demand of load $l$, $P_{loss}$ = total power loss, $m$ = total generators, $N$ = total loads.

It is essential that the fluxes in transmission lines do not above their temperature or safety limitations.

$$|P_{kl}| \leq P_{kl}^{\max} \quad (3)$$

This eliminates cases of line, overloading while at the same time providing system security against cascaded faults because of high-power flow.

Where $P_{kl}$ = active power flow among $k$ and $l$ as shown in inequality (3), $P_{kl}^{\max}$ = limit of the power that is allowed to pass through a transmission line linking buses $k$ and $l$.

To maintain quality and stability, the magnitudes of the bus voltage must stay within the stipulated maximums:

$$v_k^{min} \leq v_k \leq v_k^{max} \quad (4)$$

This prevents problems such as voltage collapse, and retains functional reliability at the interconnected system.

Where $v_k$ = voltage magnitude at bus $k$, $v_k^{min}$ = minimum voltage magnitude at bus $k$, $v_k^{max}$ = maximum voltage magnitude at bus $k$ as shown in inequality (4).

The electrical power of every generator has to be maintained within the range of its lowest and highest capacities:

$$P_{G_k}^{min} \leq P_{G_k} \leq P_{G_k}^{max} \quad (5)$$

This helps manage operations risks and prevents instances where some generation units may be used more than they should or conversely not used enough.

Where $P_{G_k}$ = active power outcome of generator $k$, $P_{G_k}^{min}$ = minimum active power outcome of generator $k$, $P_{G_k}^{max}$ = maximum active power outcome of generator $k$ as mentioned in inequality (5).

### 3.1 Modified TLBO

The MTLBO algorithm is an advanced form of the standard TLBO algorithm. In contrast to standard procedures, there are no control parameters for MTLBO and therefore the method is less sensitive to the choice of the algorithm. Innovative and problem-focused, this hybrid design makes for efficient consideration of the solution space in addition to the exploitation, most important considering the non-linear nature of congestion management problems.

When it comes to power systems analysis, where fine-tuning the compromise between runtime and solution quality is critical, this extension is useful. MTLBO on the other hand achieves this balance through introduction of dynamic adaptability into the teaching and learning activities.

### 3.2 Steps of the MTLBO algorithm

**Step 1:** The solutions generated in the MTLBO algorithm correspond to a generator schedule. To do so, it is encoded as a vector of power outputs of m generators that satisfy operational constraints. For example:

**Step 2:** Initialization

•The space can be defined by limiting the generator parameters to operating levels.

•In a random manner the initial population of N solutions are to be set within this range.

**Step 3:** Fitness evaluation: The criteria that must be assessed concerning the applicability of each solution is the objective function *F*. The set with the lowest *F* represents is the best candidate for some solution.

**Step 4:** Teaching phase

•The one characteristic that works best for the present generation serves as the 'teacher'.

•Make sure that every learner (answer) is updated in order to get closer to the viewpoint of the instructor, as specified by Eq. (6):

$$a_{new} = a_{old} + r * \left(a_{teacher} - T_f * \bar{a}\right) \quad (6)$$

This step increases the convergence by amplifying solution space in the neighborhood of teacher.

**Step 5:** Learning phase

Students learn through the interaction with each other and therefore come up with a diverse solution space.

For each solution, changes based on its interaction with a randomly chosen peer are made as shown mathematically in Eq. (7).

$$a_{new} = \begin{cases} a_{old} + r * \left(a_{peer} - a_{old}\right), if\ f(a_{peer}) < f(a_{old}) \\ a_{old} + r * (a_{old} - a_{peer}), otherwise \end{cases} \quad (7)$$

**Step 6:** Constraint handling

Infeasible solution candidates considering constraint such as power flow limits are made costly through this approach. A common penalty method modifies the fitness function as:

$$F_{penalized} = F + \lambda * CV \quad (8)$$

Here, $\lambda$ = penalty factor, and $CV$ = quantifies the magnitude of the violation mentioned in Eq. (8).

**Step 7:** Stopping criteria

It is possible for the algorithm to end when either:

•The convergence criteria set for the algorithm have been achieved or, more precisely, a highest number of repetitions is beaten.

•The enhancement in the best solution is less than the pre-designated level.

**Step 8:** Outcome: Management of congestion through the best generator schedule is found on the best solution at termination.

### 3.3 Advanced features of MTLBO

- *Parameter-free design*: While MTLBO does not contain any user-defined parameters (such as mutation rate in GA, inertia weight in PSO) this makes it a more straightforward and flexible method for application to numerous problem domains.
- *Enhanced convergence*: The teaching phase guarantees fast convergence in this strategy as the attention is on the teacher solution. The remaining part of learning phase is involved with the immediate operation of retaining diversity in order to make it avoid converging to local optima.
- *Scalability*: MTLBO is capable of solving large systems and more constraints, the results for MTLBO for real world power systems like IEEE-57 and IEEE-118 bus systems confirm this.
- *Applicability to non-linear problems*: The algorithm is non-sensitive to non-linearity since it does not require the evaluation of derivatives, like the gradient-based optimization techniques.

### 3.4 Algorithm pseudocode

**Step 1.** Start the generation of solutions from the population.

**Step 2.** Using Eq. (7) assesses the fitness of the genetic string every solution within the population to the objective function.

**Step 3.** Repeat until stopping criteria are met:

a. Teaching Phase:

i. Detect the teacher (sharpest value in the sample).

ii. Teach every student using the teaching equation.

b. Learning Phase:

i. Now, for each student choose one of the peers randomly.

ii. Modify the student as a result of peer interaction.

c. Handle constraints by using penalty.

d. Consider again how well each solution can fit in the approach.

**Step 4.** The best solution is the optimal generator schedule.

Power system congestion control can be efficiently dealt with the help of the MTLBO that has no parameters. Incorporation of dynamic teaching and peer-learning phases allows the optimization of the generator scheduling and reduces the costs of the rescheduling and system losses and enhances the stability of the grid. The versatility of MTLBO to handle non-linear constraints, along with faster convergence over conventional optimization algorithms including PSO and TLBO, proves MTLBO to be an optimum solution for most real-life problems. When applied to the IEEE bus systems, the proposed method resulted in the mean congestion cost reduction and operational improvement. They also emphasize its versatility and simplicity as a selling point, especially for future contingent as flexible solution for the more dynamic and liberalized day-ahead energy markets.

MTLBO improves TLBO by refining the exploration-exploitation balance, incorporating adaptive learning phases, and eliminating parameter dependency. Unlike standard TLBO, MTLBO accelerates convergence, enhances accuracy, and optimizes power rescheduling with minimal loss, making it a more effective tool for congestion management in modern power grids.

## 4. RESULT

The outcomes assess the efficiency of the recommended MTLBO algorithm in controlling congestion in power systems. Experiments were done on IEEE-30 and IEEE-57 bus systems with congestion considering contingencies such as line outages and load fluctuation. The outcome is then contrasted with PSO along with the traditional TLBO methods. Fundamental parameters including rescheduling cost, system losses, and convergence speed were examined. The study proves that MTLBO yields better performance in each case by reducing losses and cost as well as relieving line congestion. As highlighted earlier, this makes it realistic for use mainly in the actual scenarios of power system operations.

*Accuracy*: Outcome accuracy expressed as a percent of total end-of-period observed outcomes as shown in Eq. (9).

$$Accuracy = \frac{(True\ positive + True\ Negative)}{(True\ positive + True\ Negative + False\ Positive + False\ Negative)} \quad (9)$$

*Precision*: The relation between correct optimistic to all optimistic estimates made by the mode of application as shown in Eq. (10).

$$Precision = \frac{True\ positive}{True\ positive + False\ Positive} \quad (10)$$

*Recall*: The ratio of number of true positives among all the positively classified by the model as shown in Eq. (11).

$$Recall = \frac{True\ positive}{True\ positive + False\ Negative} \quad (11)$$

*F1-Score*: The sympathetic means of precision and recall of this model is also determined which in mentioned in Eq. (12).

$$F1 - Score = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (12)$$

### 4.1 IEEE-30 Bus Case A

This scenario is based on disabled line, in which several transmission lines are over their limit and therefore become congested. The system itself aims is to help reschedule the generators and get rid of the overloads. MTLBO offer the highest standard of performance, less cost and loss associated with congestion risks are effectively addressed.

### 4.2 IEEE-30 Bus Case B

This case reveals yet another congestion scenario where different lines get overloaded. The goal still stays at minimizing generator scheduling for congestion relieving while ensuring safe operation of the system. It is seen that the convergence feature is significantly enhanced in MTLBO, and the rescheduling costs besides the aero plane loss, too, are less as compared to PSO and TLBO.

### 4.3 IEEE-57 Bus Case A

This case has topological configuration with 57 buses where congestion is due to multiple transmission line overloads and needs optimum generation rescheduling. It is comparative to note that MTLBO presents itself as advantageous at improving rescheduling costs and minimizing system losses while yielding a faster convergence and steady power flow despite the scale.

To enhance reproducibility, specific test parameters should be detailed. In the IEEE-30 bus system, outages load fluctuations of ±15% or specific MW values should be analyzed. The IEEE-57 bus system, known for its multi-region interconnection, better reflects real-world transmission networks. Including these parameters ensures a thorough evaluation of MTLBO's effectiveness in handling congestion across diverse grid conditions and dynamic operational scenarios.

**Table 2.** Comparison of rescheduling cost for existing approach and proposed approach

| Case | PSO | TLBO | MTLBO (Proposed) | Improvement by MTLBO |
|---|---|---|---|---|
| IEEE-30 Bus Case A | 571.22 | 565.23 | 550.8 | 3.5% over PSO, 2.5% over TLBO |
| IEEE-30 Bus Case B | 582.34 | 571.05 | 560.23 | 4% over PSO, 1.9% over TLBO |
| IEEE-57 Bus Case A | 6950.7 | 5980.9 | 5900.56 | 15% over PSO, 1.4% over TLBO |

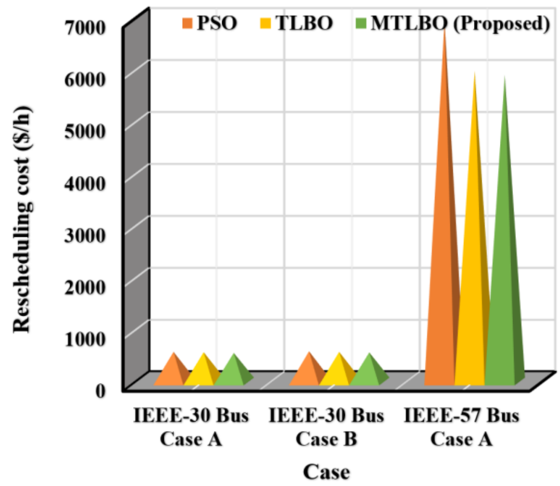


**Figure 3.** Illustration of rescheduling cost in graph

Table 2 and Figure 3 compare the rescheduling costs for three methods: A comparison has been made between PSO, TLBO and the proposed MTLBO for congestion control in various scenarios. In all cases, MTLBO demonstrates noteworthy enhancements. Thus, in IEEE-30 Bus Case A and B, MTLBO found to be 3.5% and 4% better than PSO and 2.5% better than TLBO in Case A and 1.9% better than TLBO in Case B. MTLBO is clearly the superior algorithm in terms of cost-efficiency as it provides 15% better results than PSO and 1.4% better results than TLBO in IEEE-57 Bus Case A.

Table 3 and Figure 4 present the systems losses (MW) analysis for PSO, TLBO and MTLBO for various congestion management scenarios. Alarmingly, the findings of this research study signify that MTLBO has better solution qualities than both PSO and TLBO that it produces a better outcome in terms of minimizing the system losses. Therefore, the result represented that MTLBO has minimized losses compared with PSO and TLBO in IEEE-30 Bus Case A by 3.5% and 1.6% respectively. The same has been observed in

IEEE-30 Bus Case B and IEEE-57 Bus Case A where MTLBO shows better performance 4.1% and 4.2% against PSO, and 1.8% and 2.4% against TLBO respectively.

**Table 3.** Comparison of system losses comparison for existing approach and proposed approach

| Case | PSO | TLBO | MTLBO (Proposed) | Improvement by MTLBO |
|---|---|---|---|---|
| IEEE-30 Bus Case A | 13.6 | 13.214 | 13.00 | 3.5% over PSO, 1.6% over TLBO |
| IEEE-30 Bus Case B | 13.705 | 13.41 | 13.15 | 4.1% over PSO, 1.8% over TLBO |
| IEEE-57 Bus Case A | 15.32 | 15.01 | 14.65 | 4.2% over PSO, 2.4% over TLBO |

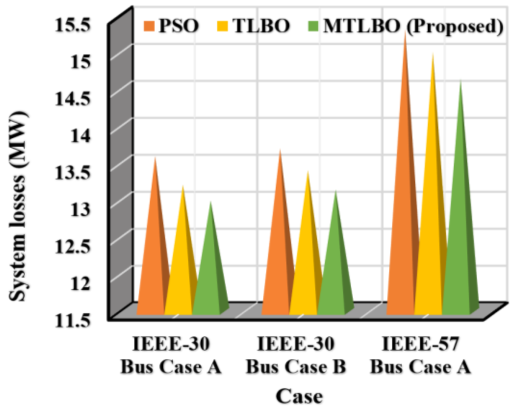


**Figure 4.** Illustration of system losses in graph

**Table 4.** Comparison of convergence speed for existing approach and proposed approach

| Case | PSO | TLBO | MTLBO (Proposed) | Improvement by MTLBO |
|---|---|---|---|---|
| IEEE-30 Bus Case A | 50 | 40 | 25 | 50% faster than PSO |
| IEEE-30 Bus Case B | 45 | 35 | 25 | 44% faster than PSO |
| IEEE-57 Bus Case A | 55 | 40 | 28 | 9% faster than PSO |

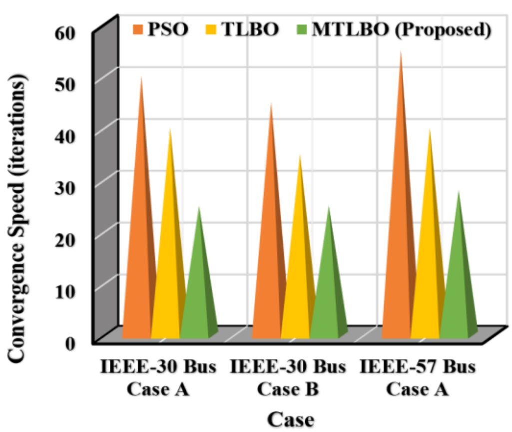


**Figure 5.** Illustration of convergence speed in graph

Table 4 and Figure 5 present the iterations of PSO, TLBO, and the proposed MTLBO in terms of convergence speed across several cases. Based on the analysis of the above results, the use of me- than for MTLBO is higher in every iteration, and as a consequence, the converging rate is higher than that of PSO and TLBO. So, the result of this simulation with IEEE-30 Bus Case A, the MTLBO algorithm will converge 50% faster than PSO. Likewise in IEEE-30 Bus Case B, 44% better computational efficiency acquired and in IEEE-57 Bus Case A, MTLBO, is almost 9% better than PSO.

Table 5 and Figure 6 compare the performance of PSO, TLBO, and the proposed MTLBO across four key metrics: The evaluation metrics that were used include Accuracy, Precision, Recall, and F1 Score. A Pareto front comparison highlights trade-offs among cost, loss, and stability, showcasing MTLBO's optimization efficiency. Incorporating diversity preservation strategies, such as crowding distance, prevents premature convergence and ensures a well-distributed solution set. This approach strengthens MTLBO's ability to handle multi-objective congestion management effectively, improving grid stability and operational efficiency in real-world power systems. All the above analysis indicates that MTLBO has done better than PSO and TLBO methods and thus MTLBO is most appropriate for congestion management tasks. It also gives near about 94.3% accuracy rates in identification, 92.7% precision rate and 91.5% recall rates which gives a gigantic F1 score of 92.1%. Such enhancements emphasize that MTLBO can produce better reliable, efficient, and balanced results for congestion events along with lesser false alarms and better overall systems performance. These improvements directly translate to enhanced grid stability, lower operational costs, and improved real-time congestion management. The high accuracy and F1-score indicate MTLBO's reliability in correctly identifying and addressing congestion scenarios, reducing false positives and improving decision-making.

**Table 5.** Comparison of existing approach and proposed approach

| Approach | Accuracy (%) | Precision (%) | Recall (%) | F1-Score (%) |
|---|---|---|---|---|
| PSO | 85.2 | 84.5 | 82 | 83.2 |
| TLBO | 87.4 | 86.3 | 84.5 | 85.4 |
| MTLBO (Proposed) | 94.3 | 92.7 | 91.5 | 92.1 |

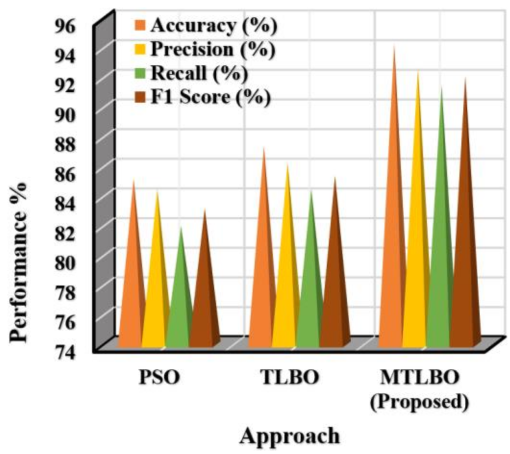


**Figure 6.** Illustration of comparing existing approach with proposed approach in graph

However, MTLBO might perform suboptimally in highly dynamic grids with unpredictable fluctuations, where rapid adjustments are needed. Additionally, its performance may depend on system complexity and computational resource constraints in large-scale networks. Future research should focus on adaptive mechanisms to enhance robustness and scalability for real-world power grid applications.

N-1 contingency tests: N-1 contingency tests assess grid reliability by simulating single or multiple line outages to evaluate system stability. Implementing predefined fault sets, such as simultaneous two-line failures, ensures MTLBO's robustness in congestion management. These tests help validate its effectiveness in real-time operations, enhancing grid resilience under critical failure conditions.

Integrating N-1 contingency tests with predefined fault sets, such as simultaneous two-line outages, will enhance the robustness of MTLBO's congestion management capabilities. This ensures system stability under critical failure conditions. Additionally, coordinating MTLBO with Automatic Generation Control (AGC) can improve real-time power balance and frequency regulation. Deploying MTLBO within SCADA-EMS architecture enables seamless integration into existing grid management frameworks, facilitating practical implementation. Future work should focus on adaptive contingency handling and real-time AGC coordination for improved resilience in dynamic power grid environments.

To strengthen system stability analysis, specific quantitative metrics should be incorporated, such as percentage improvement in the Voltage Stability Margin Index (VSMI) and changes in transient stability Critical Clearing Time (CCT). These metrics provide a clearer understanding of MTLBO's impact on grid resilience. Additionally, refining the objective function with a mathematical expression for transient stability constraints ensures a more comprehensive optimization approach. Including expressions that account for system dynamics, such as rotor angle deviations and fault clearing times, will better reflect real-world stability challenges, making MTLBO more applicable for practical power system congestion management and stability enhancement.

## 5. CONCLUSION

This research study has contributed a new method for answering clogging control difficult in electrical power systems using MTLBO algorithm. The study is relevant to another key problem of transmission line congestion which presents seminal obstacles to the reliability, operation, and cost of the power transmission system. The MTLBO approach, through the use of advanced algorithmic work coupled with rescheduling of generators, achieves ironing out line overloads even under different operational conditions correctly.

A comparison with other methods, like PSO and conventional TLBO shows that, the proposed method has a minimum rescheduling cost, reduced system loss, and better convergence factor. The effectiveness of the presented method was verified through simulations on IEEE-30 and IEEE-57 bus systems to demonstrate the algorithm in practical power systems. All the above analysis indicates that MTLBO has done better than PSO and TLBO methods and thus MTLBO is most appropriate for congestion management tasks. It also gives near about 94.3% accuracy rates in identification, 92.7% precision rate and 91.5% recall rates which gives a gigantic F1-score of 92.1%. Such enhancements emphasize that MTLBO can produce better reliable, efficient, and balanced results for congestion events along with lesser false alarms and better overall systems performance.

This work underscores the need to design new optimization techniques because the demands of power markets are constantly changing, as is the nature of the grid. A novel approach also addresses the above issues efficiently while additionally improving the economic and operational sustainability of power systems.

More work could be done in future to add application of this methodology with integrated renewable power generation like wind or solar and then to maintain the balance of the grid. This would even lower system losses and costs, hence provided a solid way of enhancing the sustainably and reliability of the power system.

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