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Enhancing power system security using soft computing and machine learning

Purpose. *To guarantee proper operation of the system, the suggested method infers the loss of a single transmission line in order to calculate a contingency rating.* ***Methods****. The proposed mathematical model with the machine learning with particle swarm optimization algorithm has been used to observe the stability analysis with and without the unified power flow controller and interline power flow controller, as well as the associated costs. This allows for rapid prediction of the most affected transmission line and the location for compensation.* ***Results****. Many contingency conditions, such as the failure of a single transmission line and change in the load, are built into the power system. The single transmission line outage and load fluctuation used to determine the contingency ranking are the primary emphasis of this work.* ***Practical value****. In order to set up a safe transmission power system, the suggested stability analysis has been quite helpful.* References 16, figures 9.

Key words: **machine learning, particle swarm optimization, power system security, interline power flow controller, unified power flow controller.**

Мета*. Щоб гарантувати правильну роботу системи, запропонований метод передбачає втрату однієї лінії передачі розрахунку рейтингу непередбачених обставин.* ***Методи****. Запропонована математична модель з алгоритмом машинного навчання з оптимізацією рою частинок використовувалася для спостереження за аналізом стійкості з уніфікованим регулятором потоку потужності та міжлінійним регулятором потоку потужності та без нього, а також з відповідними витратами. Це дозволяє швидко передбачити найбільш постраждалу лінію передачі та місце для компенсації.* ***Результати****. Багато позаштатних ситуацій, таких як відмова однієї лінії електропередачі та зміна навантаження, вбудовані в енергосистему. Основна увага у цій роботі приділяється відключенню однієї лінії електропередачі та коливанням навантаження, які використовуються для визначення рейтингу непередбачених обставин.* ***Практична цінність****. Пропонований аналіз стійкості виявився дуже корисним до створення безпечної системи передачі електроенергії.* Бібл. 16, рис. 9.

Ключові слова: **машинне навчання, оптимізація рою частинок, безпека енергосистеми, вбудований контролер потоку потужності, уніфікований контролер потоку потужності.**

Introduction. Multiple renewable and non-renewable power sources have been added to the grid in recent years in an effort to keep up with rising demand. Generators, transmission lines, and distribution networks already have it rough, and transient load changes make matters worse. Investigating the most appropriate load modeling is necessary for predicting the system's features. When paired with contingency criteria and constant-impedance, constant-current, and constant-power loads, the ZIP load model creates accurate and durable representations of loads over extended time periods (ZIP is a common acronym for the polynomial load model – constant impedance Z, constant current I, constant active power P).

Even the most basic contemporary lives require complex electrical systems. Therefore, it is crucial to keep the electrical system reliable. A power system's users, infrastructure, and bottom line must all be safeguarded if the system is to be considered secure. The failure of a transmission line or generator, an unexpected increase in load demand, the destruction of a transformer, etc. are just a few examples of the kinds of occurrences that might make such a power system useless. Maintaining the safety of the power system is an intriguing problem. Power outages have increased as a consequence of system instability. Many companies go bankrupt, and the lives of regular people are disrupted. Because this is the source of the blackout, taking decisive action to stop it from spreading to other lines is crucial. The reliability of a system after an outage or other disruption may be swiftly evaluated with the use of a contingency analysis. The device's normal operation may be affected once a faulty part is removed; thus, the backup strategy must account for this possibility. Any significant disruption to line traffic has the potential to overload neighboring lines and set off a chain reaction. There needs to be swift action from the regulator when a line failure leads to a spike in demand. The electricity grid's operators and planners should always have the system's future in mind. The process of contingency screening utilizes a wide variety of static and time-dependent techniques [1, 2].

Load models allow for the prediction of how loads will react to a change in voltage or frequency. Finding a load model that is user-friendly and accurate across a variety of load response scenarios is crucial. Implementing strategies is essential. The impacts of the polynomial load model and the steady-state load model are compared in this study. The model's imprecision stems from its over-reliance on a single load to characterize three distinct types of attributes. In terms of constant impedance, constant current, and constant power, polynomial load models can characterize resistive loads, induction motor loads, and variable-frequency loads. As a result, the accuracy of the polynomial load model is maximized. Devices in the flexible AC transmission system (FACTS) may reduce the impact of many disturbances in the power grid. The line overload index and the voltage stability index must be used together to estimate system stress in an emergency. Faulty bus hotspots may be found more quickly and precisely using the line stability index because it takes less time and effort to calculate [3-7].

The most flexible FACTS device is the unified power flow controller (UPFC), which uses a combination of series and parallel inverters connected over a DC bus. In practice, devices are positioned along the weakest line to mitigate its effects. A proposed severity index is a grading system for outcomes. It is hypothesized that the UPFC will be in the most perilous position. Paycheck distribution is a top priority in UPFC's layout. The suggested technique is tested in a pilot program using the IEEE 30 bus system. In this post, we will describe the techniques used to analyze the reliability of electrical grids. The criteria for determining vital lines and the procedures to follow in the event of an interruption are detailed. There is no hiding from the book's significance and effectiveness. We compare the outcomes from before and after compensation were provided.

Examination of contingency method. Unpredictability and instability characterize the occurrence of a contingency phenomenon within a control framework. In the field of control systems, numerous substantial investigations of

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probable outcomes have been done. The particle swarm optimization (PSO) technique is used to determine the best possible FACTS installation site and configuration settings.

Load modeling is the most common causes of contingencies are unexpected shifts in load. When analyzing various loads, load modeling is crucial. Modeling the relationship between power and voltage on a load bus mathematically is known as load modeling. It has far-reaching implications for research into electrical grids [8, 9]. In this research, we consider two distinct load models to conduct our risk assessment. Models of constant and variable loads as below.

Steady state load model. The continuous load paradigm is also known as steady state load. The model's active and reactive power equations are:

$$P_i = \sum_{j=1}^{n} V_i Y_{ij} V_j \cos\left(\theta_{ij} + \delta_j - \delta_i\right); \qquad (1)$$

$$Q_i = -\sum_{j=1}^{n} V_i Y_{ij} V_j \sin\left(\theta_{ij} + \delta_j - \delta_i\right). \qquad (2)$$

Elements of active power and reactive power, both on and off the diagonal, are derived using P_i and Q_i as the active and reactive powers, respectively.

Polynomial load model. A common acronym for the polynomial load model is ZIP (constant impedance *Z*, constant current *I*, constant active power *P*). Power equations for the model are :

- at bus *i*:

$$P_i = \left[\sum_{j=1}^{n} V_i Y_{ij} V_j \cos\left(\delta_{ij} + \theta_j - \theta_i\right)\right]\left[P_1 V_i^2 + P_2 V_i + P_3\right]; \ (3)$$

$$Q_i = \left[-\sum_{j=1}^{n} V_i Y_{ij} V_j \sin\left(\delta_{ij} + \theta_j - \theta_i\right)\right]\left[P_1 V_i^2 + P_2 V_i + P_3\right]; \ (4)$$

- at bus *j*:

$$P_j = \left[\sum_{i=1}^{n} V_j Y_{ji} V_i \cos\left(\delta_{ji} + \theta_i - \theta_j\right)\right]\left[P_1 V_j^2 + P_2 V_j + P_3\right]; \ (5)$$

$$Q_j = \left[-\sum_{i=1}^{n} V_j Y_{ji} V_i \sin\left(\delta_{ji} + \theta_i - \theta_j\right)\right]\left[P_1 V_j^2 + P_2 V_j + P_3\right], \ (6)$$

where bus *i* has an active power of P_i, whereas bus *j* has a reactive power of Q_i and so on. Values of nodal voltage at buses *i* and *j* are denoted by V_i and V_j; δ_{ij} is the angular voltage of the i^{th} and j^{th} units; the line's admissions denoted by Y_{ji}; the parameters for the ZIP load are denoted by P_1, P_2, and P_3.

Machine learning (ML). Waikato University in New Zealand is responsible for developing WEKA (short for Waikato Environment for Knowledge Analysis). The program includes data-processing tools, machine-learning algorithm implementation, and visualization resources. It's open-source and free, so you may use it to analyze as much data as you like. Prediction techniques in ML are known as supervised learning. The case distribution in a dataset may be seen with unsupervised learning. Input-outcome associations are uncovered using supervised learning techniques. The relationships between them are a model. Common supervised approaches include classification and regression models. Different kinds of data analysis are available in ML. In this study, the J48 algorithm is employed to group information based on the suggested indices. The j48 tree represents C4.5. It's used to make data sets. Decision trees are useful for sorting data into groups. A tree is structured using this way. Assuming the tree already exists, we append the structure of data. Predicted missing values are disregarded by j48 during tree building.

Proposed index to find the severity of the line is named as hybrid lines stability ranking index (HLSRI) is employed to forecast and categorize, in descending order, a set of important lines' numerical values. After that, compensation is employed to guarantee the system's continued security:

$$HLSRI = \frac{4XQ_n}{\left[V_m\right]^2}\left[\frac{|Z|^2}{X_{Line}}\beta - \frac{XQ_n}{\left[\sin(\theta-\delta)\right]^2}(\beta-1)\right] \le 1; \qquad (7)$$

$$\text{where } \beta = \begin{Bmatrix} 1 & \delta < \delta_C \\ 0 & \delta \ge \delta_C \end{Bmatrix},$$

where δ is used as a modifier and β is utilized as a toggle. In a stable system, HLSRI is less than 1, whereas in an unstable system, HLSRI is close to 1 [10]. The generated values of HLSRI is upload to train the ML tool (Fig. 1). The j48 category also is shown in Fig. 1.

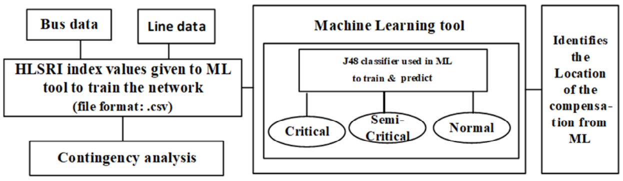

Fig. 1. Transmission line data analysis, categorization, and prediction

The configuration described is seen in Fig. 2. The 5-foot tree has 3 leaves and 1 branch. It demonstrates that the range of the HLSRI fluctuates [11, 12], while the size and number of leaves in the decision tree remain constant. Here, we classify rankings according to 3 criteria for the testing system [13]:

Classifier model, J48 tree Structure, IEEE 30
1) most stress/critical (7.0): HLSRI > 0.0461;
2) moderate stress/semi-critical (10.0): 0.0296 > HLSRI ≤ 0.0461;
3) healthy line/non-critical (24.0): HLSRI < 0.0296.

Weka Classifier Tree Visualizer

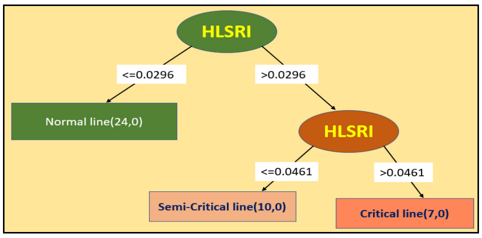

Fig. 2. HLSRI using ML-J48 algorithm tree structure for IEEE 30 bus

Modeling of custom power devices is also included are works from the UPFC and interline power flow controller (IPFC). An injection model may be used to estimate the ranking index for actual and reactive power flow, which is relevant for FACTS appliance control restrictions. Here is a basic summary of the mathematical modelling process used by FACTS.

Shunt and series controller (UPFC). There are really 2 controllers at work in a unified power flow system which is linked to the transmission line through DC link capacitors shared by the shunt and series voltage source converters. The arrangement converter's yield voltage is added to the nodal voltage at bus *i* to get the final nodal voltage at bus *j*. How the power's intensity is controlled is shown by the δ_{CR} phase angle, and the voltage's direction is provided by the yield voltage V_{CR}. A three-stage UPFC is supported by 2 voltage sources and power restrictions.

$$E_{VR} = V_{CR}(\cos\delta_{CR} + j\sin\delta_{CR})\,; \tag{8}$$

$$R_e = \{-E_{VR}I_{VR} + E_{VR}I_m\}. \tag{9}$$

Active and reactive power equations at bus *i* are:

$$\begin{gathered} P_i = \{V_i^2 G_{ii} + V_i V_j [G_{ij}\cos(\theta_i - \delta_j) + B_{ij}\sin(\theta_i - \delta_j)] + \\ + V_i V_{CR}[G_{ij}\cos(\theta_i - \delta_{CR}) + B_{ij}\sin(\theta_i - \delta_{CR})] + \\ + V_i V_{CR}[G_{VR}\cos(\theta_i - \delta_{CR}) + B_{ij}\sin(\theta_i - \delta_{CR})]\}[P_1 V_i^2 + P_2 V_i + P_3]; \end{gathered} \tag{10}$$

$$\begin{gathered} Q_i = \{-V_i^2 B_{ii} + V_i V_j [G_{ij}\sin(\theta_i - \delta_j) - B_{ij}\cos(\theta_i - \delta_j)] + \\ + V_i V_{CR}[G_{ij}\sin(\theta_i - \delta_{CR}) - B_{ij}\sin(\theta_i - \delta_{CR})] + \\ + V_i V_{CR}[G_{VR}\sin(\theta_i - \delta_{CR}) - B_{ij}\cos(\theta_i - \delta_{CR})]\}[P_1 V_i^2 + P_2 V_i + P_3], \end{gathered} \tag{11}$$

where G_{ij} and B_{ij} are the conductance and susceptance between bus *i* and bus *j*, respectively. Equations (10), (11) modified mathematical expressions of UPFC with ZIP load model [13].

Series and series controller (IPFC) typically makes use of many DC-to-AC converters, all of which provides series compensation for a different line. The IPFC really includes a number of the static synchronous series compensators. All of the converters have high reactive power transmission and storage capacities. In addition, the converters can produce or soak up reactive power at will. A series converter connected between bus *i* and bus *j* can provide complicated power, as described by below equations in that order:

$$\begin{gathered} P_{ij} = \{V_i^2 G_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{ij}(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}) + \\ + \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{seij}(G_{ij}\cos(\theta_{ij} - \theta_{seij}) - B_{ij}\sin(\theta_{ij} - \theta_{seij}))\}[P_1 V_i^2 + P_2 V_i + P_3]; \end{gathered} \tag{12}$$

$$\begin{gathered} Q_{ij} = \{V_i^2 B_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{ij}(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) - \\ - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{seij}(G_{ij}\sin(\theta_{ij} - \theta_{seij}) - B_{ij}\cos(\theta_{ij} - \theta_{seij}))\}[P_1 V_i^2 + P_2 V_i + P_3]; \end{gathered} \tag{13}$$

$$\begin{gathered} P_{ji} = \{V_i^2 G_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{ji}(G_{ij}\cos\theta_{ji} - B_{ij}\sin\theta_{ji}) - \\ - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{seij}(G_{ij}\cos(\theta_{ij} - \theta_{seij}) - B_{ij}\sin(\theta_{ij} - \theta_{seij}))\}[P_1 V_i^2 + P_2 V_i + P_3]; \end{gathered} \tag{14}$$

$$\begin{gathered} Q_{ji} = \{V_i^2 B_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{ji}(G_{ij}\cos\theta_{ji} - B_{ij}\sin\theta_{ji}) - \\ - \sum_{\substack{j=1 \\ j \neq i}}^{n} V_i V_{seij}(G_{ij}\sin(\theta_{ij} - \theta_{seij}) - B_{ij}\cos(\theta_{ij} - \theta_{seij}))\}[P_1 V_i^2 + P_2 V_i + P_3], \end{gathered} \tag{15}$$

where V_i and V_j are the maximum allowed bus *i* and *j* voltages, p.u.; V_{seij} and the conjugate of I_{ij} are the maximum allowed bus *i* and *j* series voltage and reference current. Mathematical expressions of IPFC incorporated in ZIP load model to assess its behavior and the above (12)–(15) modified IPFC mathematical expression with ZIP load model.

Results and discussion with compensation devices. To analysis the contingency of IEEE test system to asses the status of the power security:

Case 1: IEEE 30 bus with ML algorithm.

Case 2: Soft computing techniques are applied for modified IEEE test system.

Case 1: IEEE 30 bus with ML algorithm. IEEE 30 bus is considered from the historical data for ML algorithm to predict severity and status of the system in power system security point of view. Figure 3 represents voltage profile vs bus no. in ZIP load model under various load conditions.

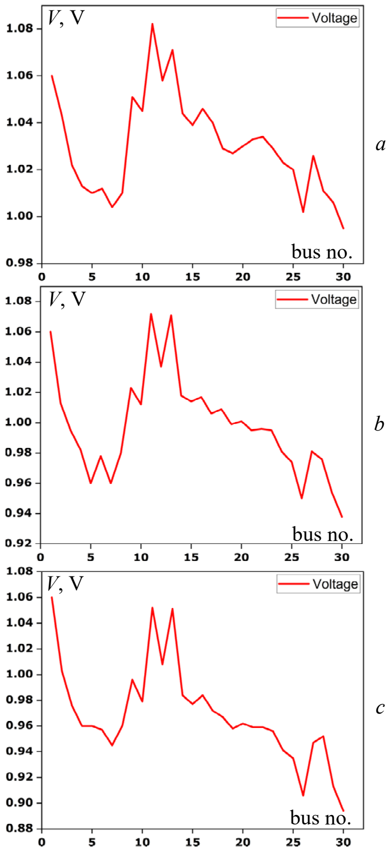

Fig. 3. Voltage profile vs bus no. with various loaded condition: *a* – base case; *b* – 130 % loading; *c* – 150 % loading

Figure 4 shows the demand, active generator capacity and corresponding fuel cost during various loading conditions.

Figure 5 shows the total active generator capacity and corresponding fuel cost before and after FACTS devices using ML. From Fig. 4, 5 it is clear that, IEEE 30 bus system consists of 6 generators, but only 2 generators are utilized (one slack bus another generator bus) due to this, generator is burden to meet the demand and fuel cost gets increases. Hence IEEE modified bus system is consider with 6 generators units.

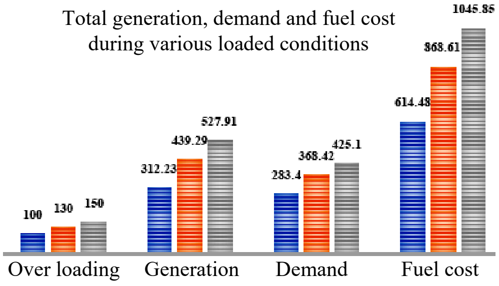

Fig. 4. Generation and fuel cost for various load conditions

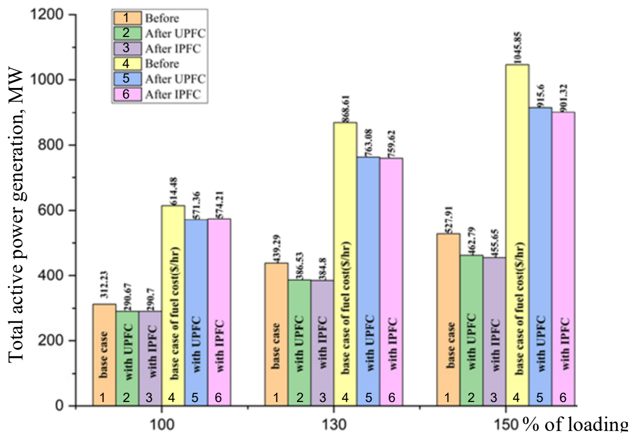

Fig. 5. Generation and fuel cost for various load conditions with compensation

Case 2: Soft computing techniques are applied for modified IEEE test system. In this case 1 IEEE 30 system having 6 generators, but only 2 are utilized due to this generator under stress and it leads to increase loss and fuel cost. So IEEE 30 bus system is modified and to reduce the stress on generators, generator reschedule is required and it is achieved by the objective function.

In order to get the optimal generation values for the generators to meet the required demand. An objective function is developed. In the below analysis ML tool is used to find severity of line leads to the location of compensation and for optimal generator values PSO is utilized.

Particle swarm optimization (PSO). Many fields benefit from PSO's unique properties. PSO optimizes complex problems using collective intelligence. PSO finds optimal or near-optimal solutions using swarm particle communication and exploration. High-dimensional PSO outperforms traditional optimization methods. It solves complex problems efficiently. Also, PSO's iterative nature lets it adapt to changing environments. By adapting, PSO exploits search space. Finally, PSO is simple, its efficacy and simplicity make it popular across disciplines. So, PSO inspired efficient optimization algorithms and hybrid methods for complex problems [14, 15]. Figure 6 shows the block diagram shows the utilization of ML tool in combination with PSO to get minimum fuel cost with optimum generators values.

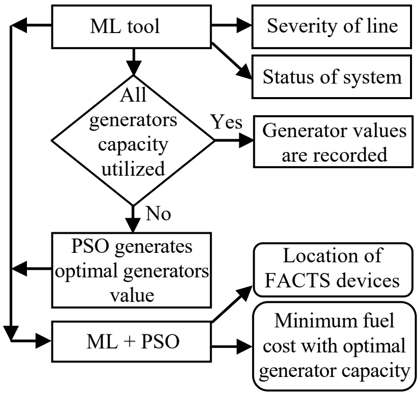

Fig. 6. Block diagram of ML+PSO

Objective function. The novel method mitigates the IEEE 30 bus severity index, power outages, capital costs, fuel use, and voltage changes. The PSO method is used to determine optimal generator values for the minimum fuel cost and dimensions of FACTS hardware. Here, we can see the objective function:

$$F = \min(F_1 + F_2 + F_3), \tag{16}$$

where F is the objective function; F_1, F_2, F_3 are the corresponding iterations. This objective function is implemented using PSO algorithm along with ML algorithms.

Optimization of real power loss. At this point, we've reached a point where our active power loss is as small as it can get. Effectively depicting the preliminary objective function, (17) shows how to significantly reduce the actual power loss in transmission lines:

$$F_1 = P_{Loss} = \sum_{k=1, j \neq i}^{n} G_{kj}[V_k^2 + V_j^2 - 2V_k V_j \cos(\delta_k - \delta_j), \tag{17}$$

where P_{Loss} is the actual power loss; n is the number of transmission lines; G_{kj} is bus k and j's conductance; V_k and V_j are their voltages; δ_k and δ_j are their angles.

Capital expenditures for FACTS devices. Here, the capital expenditure ($/h) for UPFC and IPFC are analyzed as:

$$F_3 = Cost_{UPFC} + Cost_{IPFC}, \tag{18}$$

where: $Cost_{UPFC} = 0.0003 \cdot s^2 - 0.26911 \cdot s + 188.22$;
$Cost_{IPFC} = Cost_{IPFCA} + Cost_{IPFCB}$;
$Cost_{IPFCA} = 0.00015 \cdot s_i^2 - 0.0134 \cdot s_i + 94.11$;
$Cost_{IPFCB} = 0.00015 \cdot s_j^2 - 0.0134 \cdot s_j + 94.11$;
$s = |Q_2| - |Q_1|$; $s_i = |Q_{i2}| - |Q_{i1}|$; $s_j = |Q_{i2}| - |Q_{i1}|$.

After the FACTS have been configured in MVAR, the reactive power flow in the line is represented by Q_2, whereas it was represented by Q_1 beforehand. The reactive power flow down the line is represented by Q_{i1} and Q_{i2}, and the cost function S_{ij} of the converters linked to buses i and j is shown in [10, 13, 16].

Cost reduction of fuel. Reduced fuel costs in the generator have finally been realized. The cost of fuel for the generator can be thought of as the quadratic of the sum of the costs involved in using fuel functions that are themselves convex. Equation (19) depicts the generators' quadratic fuel cost function:

$$F_4 = \min \mathrm{Cost} \sum_{i=1}^{N_g} [a_i p_{gi}^2 + b_i p_{gi} + c_i p_{gi}], \tag{19}$$

where N_g is the total number of generators; i is the index of the bus; a_i, b_i and c_i are the i^{th} generator's fuel cost coefficients; p_{gi} is its maximum active power output.

Results and discussion. This study demonstrates the modified IEEE 30 bus system under varying loads and failure scenarios. Figure 7 shows the voltages profiles with soft computing techniques.

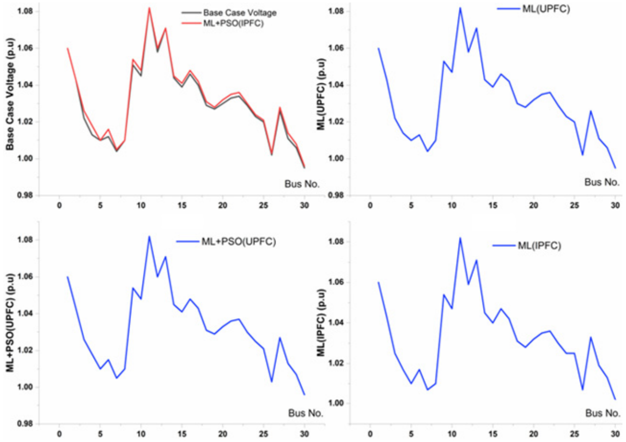

Fig. 7. Voltage profiles of modified IEEE 30 system

Figure 8 shows the active power transfer enhancement along with total system losses for ML and ML combined with PSO.

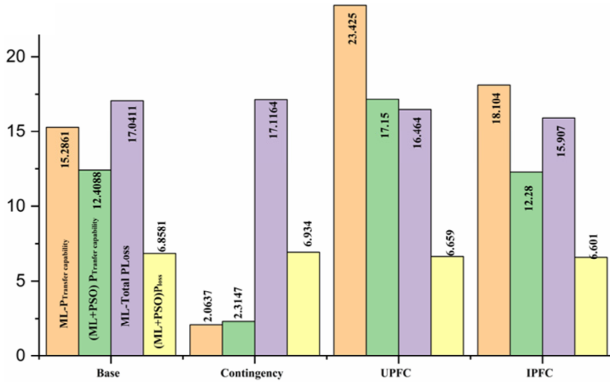

Fig. 8. Enhancement of active power and total system losses with soft computing techniques of modified IEEE 30 system

Figure 9 shows the total generator capacity based on demand along with fuel cost using ML and ML+PSO with 100% loading.

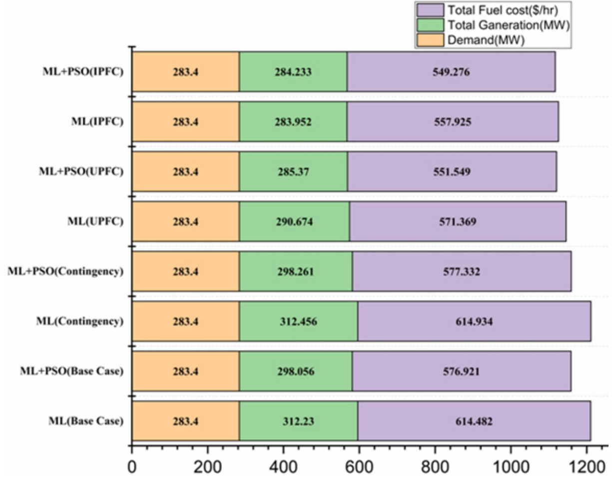

Fig. 9. Demand, generation and fuel cost with soft computing techniques

Conclusion. Hence mathematical analysis of ZIP load modeling and contingency analysis along with economic analysis is carried out for IEEE 30 and modified IEEE 30 test system in the view of the single line outage and overloading. The effective way of finding the critical lines during the faulted condition using hybrid lines stability ranking index. An objective function is developed to find the cost of devices with minimum fuel cost by optimal location of flexible AC transmission system devices (unified and interline power flow controllers) using particle swarm optimization algorithms. Here compensation devices (unified and interline power flow controllers) are used to maintain the stable and secure.

Conflict of interest. The authors declare that they have no conflicts of interest.

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