Under Voltage Load Shedding on a Modified IEEE 14-Bus System using Hybrid ABC-PSO Algorithm for Voltage Stability Enhancement

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Abstract

Voltage collapse tends to occur due to the voltage instability created during large faults. As a last resort, under-voltage load shedding (UVLS) is performed after all the available power operation and control mechanisms have been exhausted, in order to save a system from voltage collapse. Load shedding techniques have advanced from the conventional and adaptive techniques that were less optimal compared to computational intelligence techniques (CITs). Recent works have identified hybrid algorithms to give more optimal solutions for UVLS problems with multi-objective functions. In this paper, a novel hybrid ABC-PSO algorithm, adapted from a software estimation project, was used to perform UVLS on a modified IEEE 14-bus system. The modified system was made to reflect a real-life system with considerations on different load models. From the FVSI ranking used, 8 overload conditions were imposed on the system ranging from 105% to 140% loading. The load shedding was performed in accordance to decentralized relay settings of 3.5 seconds, 5 seconds and 8 seconds, which resulted in an overall 99.32% recovery of voltage profiles. The proposed hybrid ABC-PSO algorithm was able to shed optimal amounts of load, giving an 85.50% post-contingency load, compared to GA's 77.04%, ABC-ANN at 84.03% and PSO-ANN at 80.96%. This study was simulated on MATLAB software, using the Power System Analysis Toolbox (PSAT) graphical user and command line interfaces.

Keywords: Under-Voltage Load Shedding, Voltage Stability, Fast Voltage Stability Indexing, Hybrid Metaheuristic Algorithms, Artificial Bee Colony, Particle Swarm Optimization.

I. Introduction

The ability of power systems to remain stable during large faults remains to be a key area of study amongst researchers. With the high concentration of loads in urban centers, which are often located far from the generation sources, protection and control techniques have been continuously improving to factor in the complex nature of power systems [1]. Power blackouts have been a long persisting challenge to all power systems in the world affecting overall productivity in industries and other socio-economic environs [2], [3]. Significant efforts have been made by researchers and utility companies to prevent voltage collapse caused by both natural and technical faults [4].

In order for a power blackout to occur, the transmission network gradually degrades due to imbalances in demand and supply, especially for reactive power. As a result, a stressed power system is most susceptible to power outages, and is characterized by long transmission distances, strict economic limitations for grid expansion and an ever-increasing load demand [5]. Over the last decade, blackout reports cite voltage instability, instead of frequency fluctuations, to be the root-cause of cascading grid failure [6]. As a result, Under voltage load shedding (UVLS) schemes have been adopted over time as a last-resort to regain voltage stability at a relatively affordable cost in power control and operation [7].

In this study, several factors were considered in the implementation of the UVLS with reference to previously done studies. In [8], [9], the authors show how Artificial Intelligence (AI) has been integrated in to modern day power system operations, especially in UVLS schemes. The use of metaheuristic algorithms has been practically tested on an Iranian system using Particle Swarm Optimization (PSO) algorithm and modal analysis [10]. Similarly, a 66kV, 45-bus Egyptian grid has used the Comprehensive Learning PSO (CLPSO) algorithm in their UVLS scheme [11].

Computational Intelligence Techniques (CITs) come into focus in the advent of grid automation. Conventionally, under-voltage load shedding was performed in fixed time steps, presenting a time-consuming and sub-optimally performing system. The adaptive techniques that followed are slowly changing to Optimal Power Flow (OPF)-based techniques [4], [6], [12], [13], which can now be integrated with faster computing techniques such as the swarm algorithms (e.g. Particle Swarm Optimization and Artificial Bee Colony algorithms), mutation algorithms (e.g. Genetic Algorithm), amongst other Computational Intelligence Techniques (CITs) [8], [9]. These algorithms are considered to be robust, scalable, and more accurate in solving modern-day scientific problems.

In this paper, the approach followed was based on three steps: First, to model the test system considering the voltage-dependent load models (VDLM), automatic voltage regulators (AVRs) and turbine governors (TGs) in order to replicate real-life system dynamics[14]. Second was to subject this system to multiple overload conditions and evaluate their impact on voltage stability of the system. Lastly was to formulate the hybrid algorithm, evaluating the parameters extracted from the models for optimal load shedding.

The rest of the paper covers the problem statement in section II, relevant literature review in section III and the methodology used to study various load models on an IEEE 14-bus test system (in section IV). The results and discussion of the findings are captured in section V, with a conclusion drawn in section VI.

II. Problem Formulation

The existing UVLS techniques are faced with a common challenge of sub-optimal performance with the increasing complexity of the power systems. These performance challenges include suboptimal amounts during load shedding, long convergence time, and the failure to achieve voltage stability [12], [15]. PSO-based schemes are susceptible to fall into local minima in high-dimensional search spaces, failing to achieve optimal load shedding; while ABC-based techniques have a triple-search mechanism, which is advantageous but has a relatively slower convergence time as compared to PSO. GA, on the other hand, has slow convergence time due to the mutation in its algorithm. When combined together, researchers show an improvement in solutions obtained as the strengths of two algorithms increases their effectiveness, such as hybrid GA-PSO [16].

Therefore, this study was carried out to seek to a more viable solution for the UVLS problem by hybridizing ABC and PSO algorithms [17]. The main objective of the study was to develop a hybrid metaheuristic algorithm for UVLS analysis to enhance voltage stability. The specific objectives for the study revolved around: (i) the modification of the IEEE 14-bus test system and simulation of simultaneous loss of transmission lines; (ii) the formulation of a multi-objective optimization problem, solved using the hybrid ABC-PSO algorithm; and (iii), the validation of the algorithm's performance by comparing it to other algorithms obtained from existing literature.

The mathematical formulae were derived as:

A: Multi-Objective Function

$$\min f = \sum_{k=1}^{m} \left(w_k * OF_k \right) \#(1)$$

where k is the number of Objective Functions (OF), and m is the maximum number, in this case 3 objective functions as shown in equations (2) to (4). These equations represent the minimization of the amount of load to be shed, the costs incurred (interruption costs), and the voltage deviation respectively [7].

$$OF_1 = \min \left(\frac{\sum_{i=1}^{j} P_{loss}(i,i+1)}{\rho_l} \right) \#(2)$$

For values of P_{loss} obtained from simplified calculations on the line data for each bus, and ρ_l representing the total active power demand in the system. The data was obtained from the power flow analysis of the test system, with *i* representing the sending-end bus and *j* the receiving-end bus.

$$OF_2 = \min\left[\sum_{p=1}^{n} C_i\left(\frac{\Delta P_{Di}}{\frac{\delta\lambda}{\delta \mathrm{P}_i}}\right)\right] \#(3)$$

The sensitivity value (δλ/δP) represents the penalty/ interruption cost, while ΔP_{Di} represents a small change in power demand, which is a control variable for real power. The bus numbers are represented by *b*, with *n* being the maximum number of buses. C_i represents the cost for each of the buses, such that the priority of each load is considered before UVLS as highlighted in Section II-D.

$$OF_3 = \min|1 - V_i| \#(4)$$

The last objective function was used in finding the absolute voltage deviation from the range of voltages (0.95 – 1.06p.u) for each bus (*i*) as part of the optimal solution of the algorithm [18].

B: Equality Constraints

The real and reactive power flows equations given in (5) and (6) were used to identify the power mismatches between the sending end (*s*) and the receiving end (*r*) as shown in Figure 1 [7].

$$P_{si} - P_{ri} + \Delta P_{ri} = \sum_{j=1}^{N}|V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_i - \delta_j) \#(5)$$

$$Q_{si} - Q_{ri} + \Delta Q_{ri} = -\sum_{j=1}^{N}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} + \delta_i - \delta_j) \#(6)$$

Δ represents a small change in active power (*P*) and reactive power (*Q*) resulting from the overload conditions subjected to the system. The voltage magnitudes (V) and phase angles (δ and θ) are obtained from the power flow analyses.

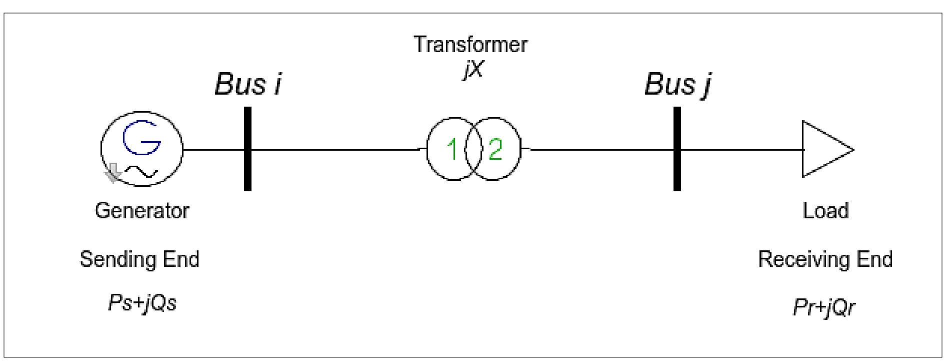

Figure 1: Two-Bus System

C: Inequality Constraints

By use of the Power System Analysis Toolbox (PSAT), some constraints were plugged into the components during modeling, such as the transmission line limits. For ease of recognizing the weakest lines, and consequently the buses to load shed, the Fast Voltage Stability Index (FVSI) was used to evaluate possibility of voltage collapse. A system is said to become unstable if the FVSI value is greater than or equal to unity, given by (7) [19].

$$FVSI_{ij} < \frac{4\,Z^2 Q_j}{{V_i}^2 X} \quad \#(7)$$

Other limits considered include minimum voltage limit (0.95 p.u.), maximum voltage limit (1.05 p.u.), with an exception of the slack bus at (1.06p p.u.). Additionally, the load shedding amount limits were set to a minimum of 5% for each bus selected in the FVSI selection, and a maximum of 20% [16].

D: Penalty Costs

Penalties considered in load shedding can be set either by the energy supplier or the consumer. They ensure that least priority loads are shed first before affecting higher priority loads. The buses were assigned penalties as shown in Table 1. Any load shed in the lower penalty ranges would incur minimum charges, and if the system remains unstable, then higher priority loads would be considered [20].

Table 1: Penalty Costs for UVLS

No.	Type of Load	Penalty Cost [$/MWh]
1	Residential	5
2	Commercial	8
3	Industrial	12
4	Municipal	15
5	Agricultural	8

III. System Modeling

The data for this study is obtained from a modified IEEE 14 test-bus system as presented in [21]. The load characteristics were considered so as to establish a comparison between the static analyses often used for UVLS. Static analysis is said to give accurate results for modeling and testing of protection and control instruments in long-term voltage stability studies. This study aimed at analyzing the effects of dynamic system characteristics in UVLS problem-solving, in order to depict real-life grid conditions. Therefore, the literature supporting the study revolved around:

A. Types of Loads

For the modification of the IEEE 14-bus test system, the PSAT model used was the '*d_014_dyn_l10.mdl*'shown in Figure 2. Bus 14 was then selected for variation of load, that is: Voltage Dependent Load Model (VDLM). Since by default, IEEE test systems use constant power loads, a polynomial (ZIP) model was used to account for the voltage-dependence of the loads. The voltage exponents of bus 14 represented (0,0) for constant power loads (P), (1,1) for constant current loads (I) and (2,2) for constant impedance loads. ZIP models are an example of *static load models*. On the other hand, a dynamic load modeled system has components such as the under-load tap changers (ULTC), over-excitation limiters (OEL), and automatic voltage regulators (AVR), amongst other components. This study involved the use of dynamic system components, which are commonly factored in voltage collapse analysis [22].

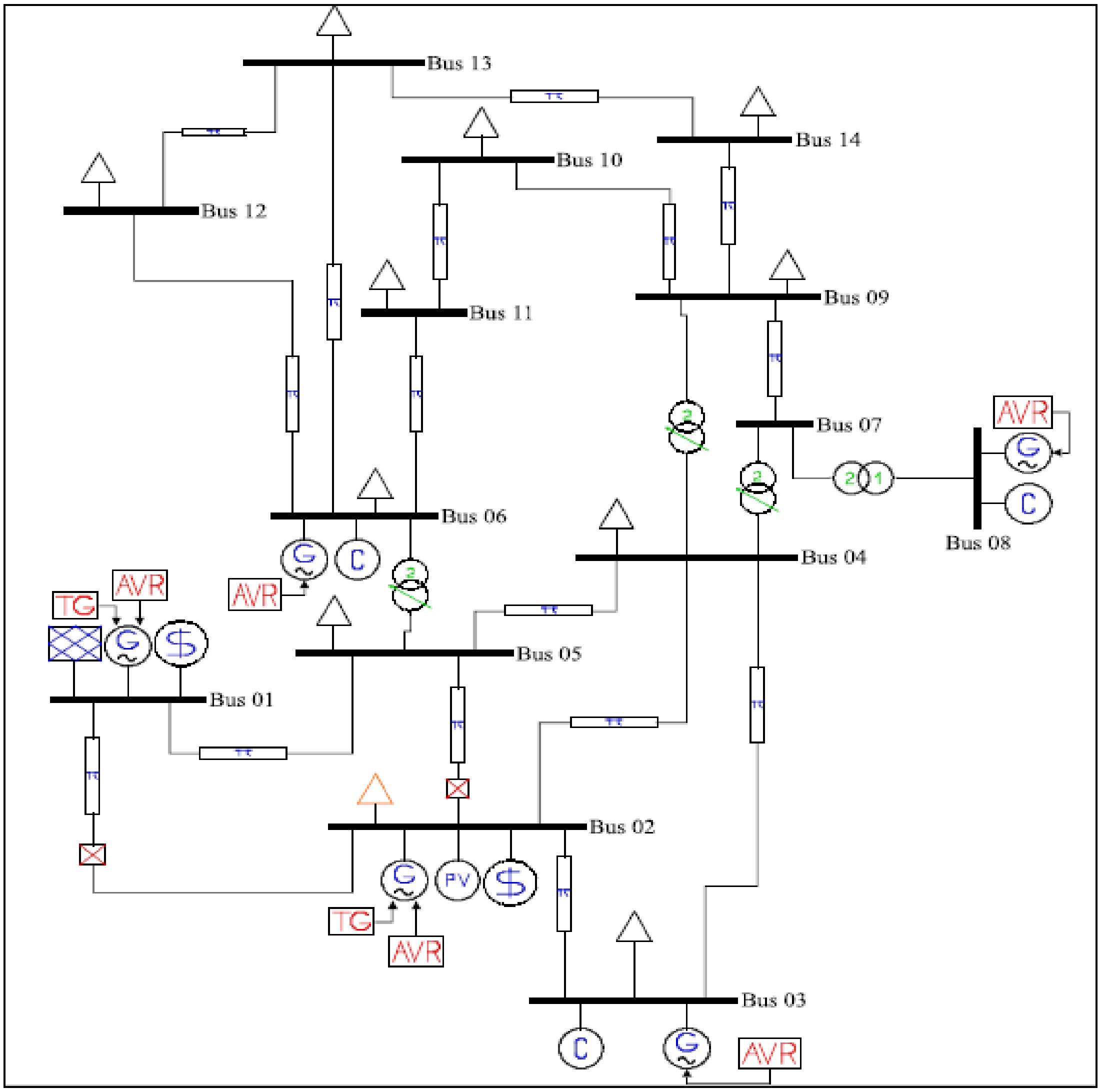

Figure 2: Modified IEEE 14-bus Test System

B: Impact on Voltage Stability

Voltage instability occurs when bus voltages decline gradually and uncontrollably, whereby the acceptable tolerance for transmission systems is ±5%, and ±6% for distribution systems. The parameters affecting voltage stability considered include:

- Generator Characteristics e.g., presence of AVRs.
- Transmission Line Characteristics, e.g., Surge Impedance Loading (SIL).
- Load Characteristics as discussed in part III.A.

The expected graphical illustrations resulting from loading a system to its tipping point (Saddle Node Bifurcation Point – SNB) is given in Figure 3.

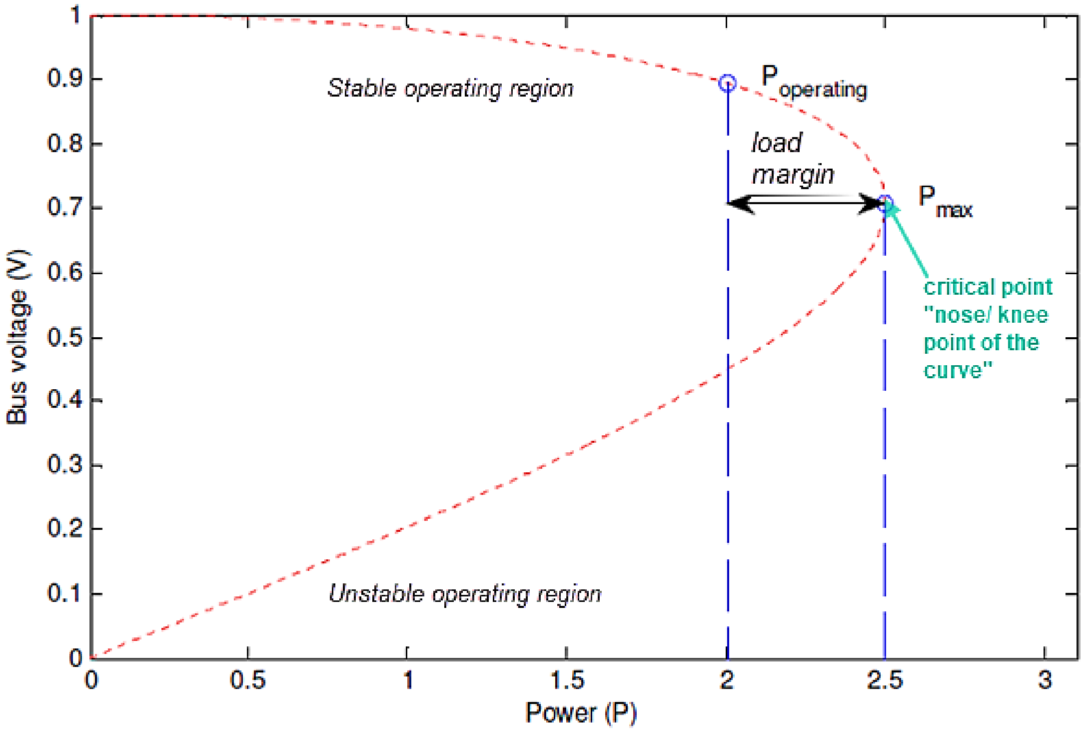

Figure 3: P-V Curve showing the SNB point

IV. Implementation of the Hybrid ABC-PSO Algorithm

The UVLS problem was solved through the framework of the ABC algorithm, which followed the following steps:

A: Initialization of data sets

Specifications for the base apparent power (100MVA), colony size (CS=100 bees), number of food sources (Food Number=50) and the problem dimension (D=14 buses) were defined. The iteration limit was also set to 100 to 200, and the fitness of the parameters was evaluated based equations (8) and (9):

$$fitness_i = \frac{1}{1 + OF_i} \qquad for\ OF_i \geq 0 \ \#(8)$$

$$fitness_i = 1 + abs(OF_i) \qquad for\ OF_i < 0 \ \#(9)$$

The PSO parameters to be initialized for the velocity computation were also initialized as: Coefficients c_1 and c_2 = 2 and Inertia weight w=1 [17].

B: Employed Bee Phase

The velocity and a food-finding method was used to find new solution positions. The new position was updated in an increment of +1 for each new best position was found. The new food source equation is given by Equation 10 for ABC optimization:

$$v_{i,j} = x_{i,j} + \varphi_{i,j} (x_{i,j} - x_{k,j}) \ \#(10)$$

Here, i represents the employee bee, j is the random index based on the problem dimension (D), k is the random neighboring index to i and φ is a random number between 0 and 1.

C: Scout Bee Phase

This phase is applied based on the number of solutions that can be improved. Each scout bee searches for the next food source randomly, independent of previous history and in incremental steps of the iteration counter. It is represented by the Equation 11 where r is a real number between 0 and 1, and d is the problem space dimension with minimum and maximum limits.

$$x_{i,d} = x_d^{min} + r\left(x_d^{max} - x_d^{min}\right) \#(11)$$

D: Hybrid of the Algorithm

The PSO algorithm came in to replace Equations 10 and 11 and is represented by Equations 12 and 13, that is, the new velocity and new position respectively.

$$v_{new}(t) = w_1 v_{old}(t-1) + c_1 r_1 (X_{best} - X_{old}) + c_2 r_2 (G_{best} - X_{old}) \#(12)$$

$$X_{new}(t) = X_{old}(t-1) + v_{new}(t) \ \#\# (13)$$

E: The Stopping Criteria

This was based on the maximum number of iterations and the set limit, computed from the employee bees (Food Number) and problem dimension (D) as the best food source and particle fitness were updated [14], [17].

The flow chart in Figure 4 shows how the hybrid algorithm that was implemented.

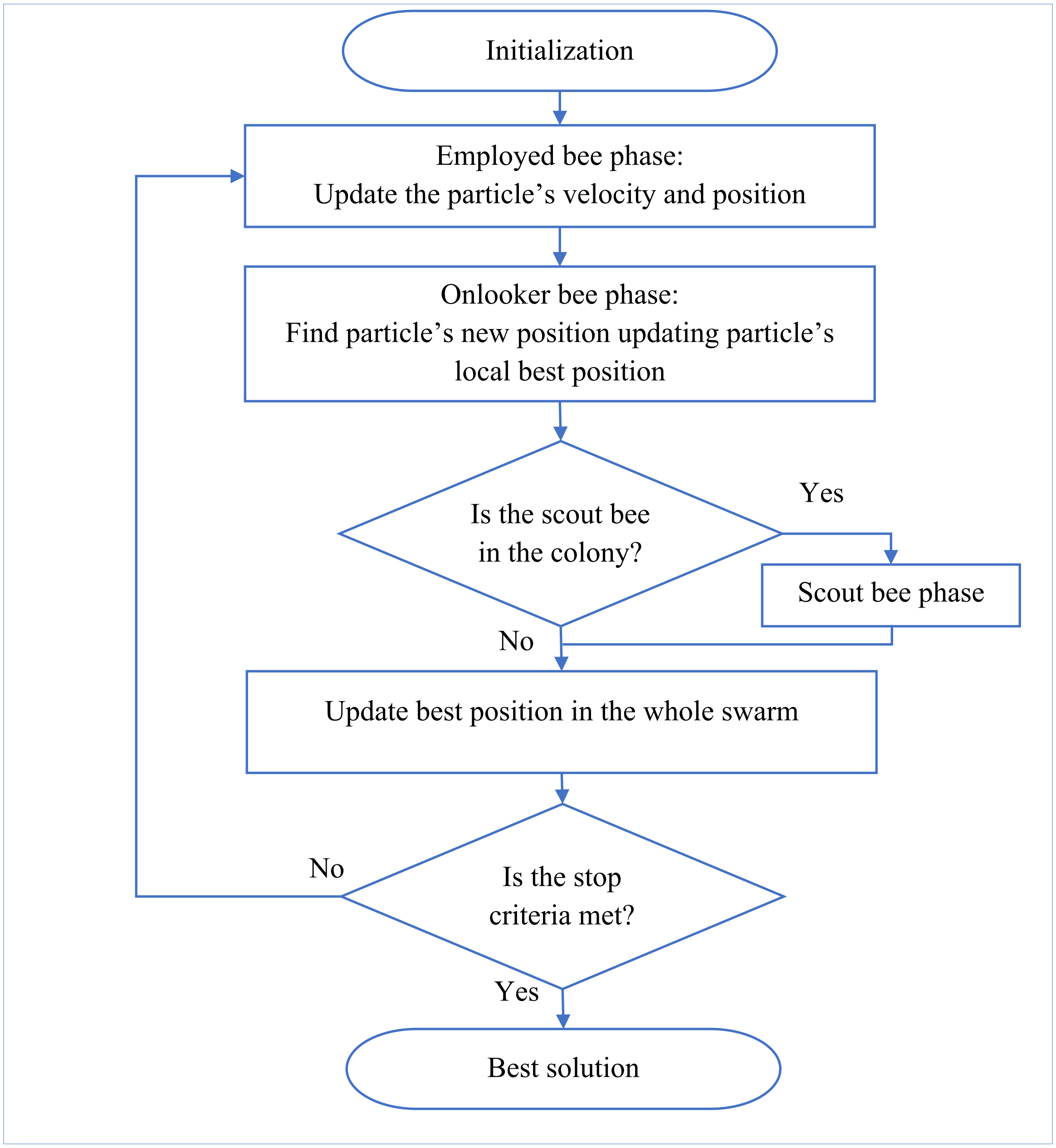

Figure 4: Flow Chart of the Hybrid ABC-PSO Algorithm

All data used was obtained from power flow analysis and time domain simulations done in both command prompt and the PSAT graphical user interface. All tests were done on an Intel core i7 processor with the following specifications: 2.5GHz CPU, 8GB RAM.

V. Results and Discussion

A. Effect of Load Characteristics on SNB Point

ZIP modelling as shown in Figure 5 affects the SNB point by slightly increasing the loading margin by 0.2, which is an 8.7% load increase. This was done to replicate voltage stability considerations in real life power systems whose loads are predominantly source-dependent. The interpretation in the physical components/ systems can be used for domestic, commercial or industrial application for Constant power loads using voltage exponents (0,0); Constant current loads using voltage exponents (1,1) and Constant impedance loads: voltage exponents (2,2).

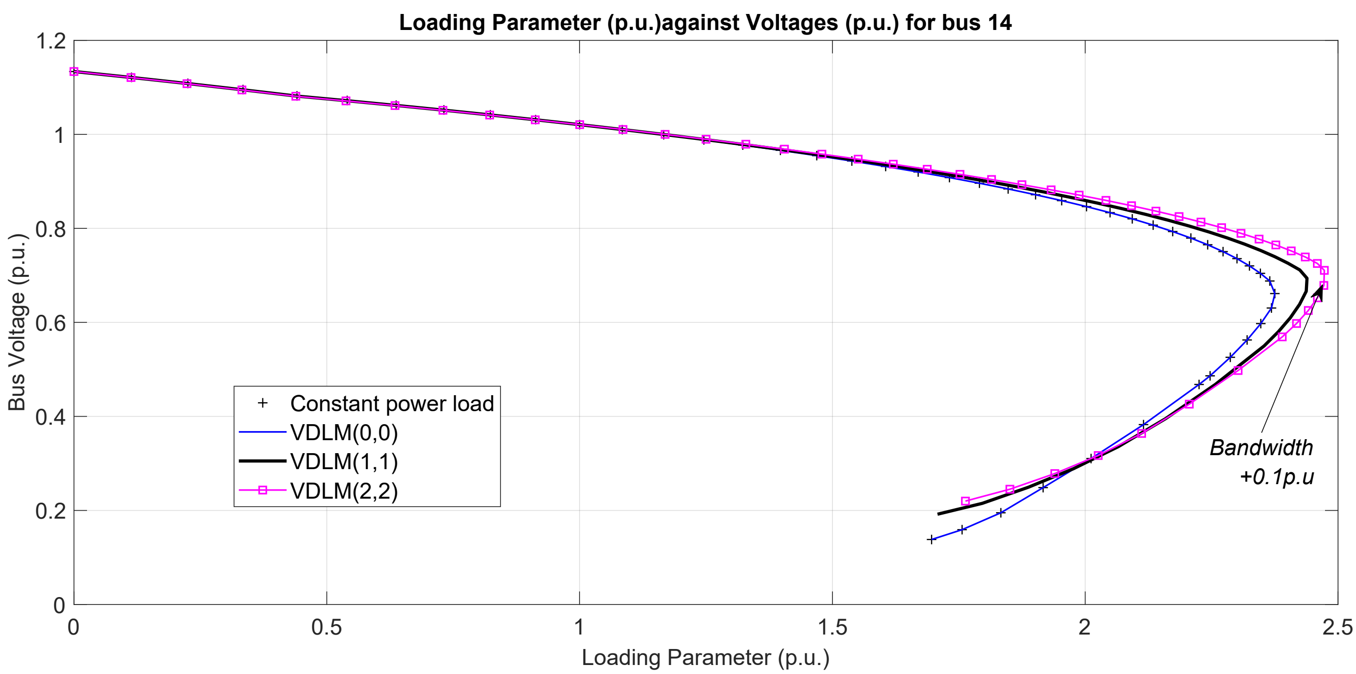

Figure 5: PV Curves with ZIP Model on Bus 14

B: Voltage Collapse Analysis

In order to determine the overloading conditions for the analysis, the system was loaded in steps of 5% until the occurrence of voltage collapse as shown in Figure 6. Bus 14 was picked for analysis being the weakest bus as it had the lowest Saddle Node Bifurcation (SNB) point when running the Continuation Power Flow for the test system as shown in Figure 6.

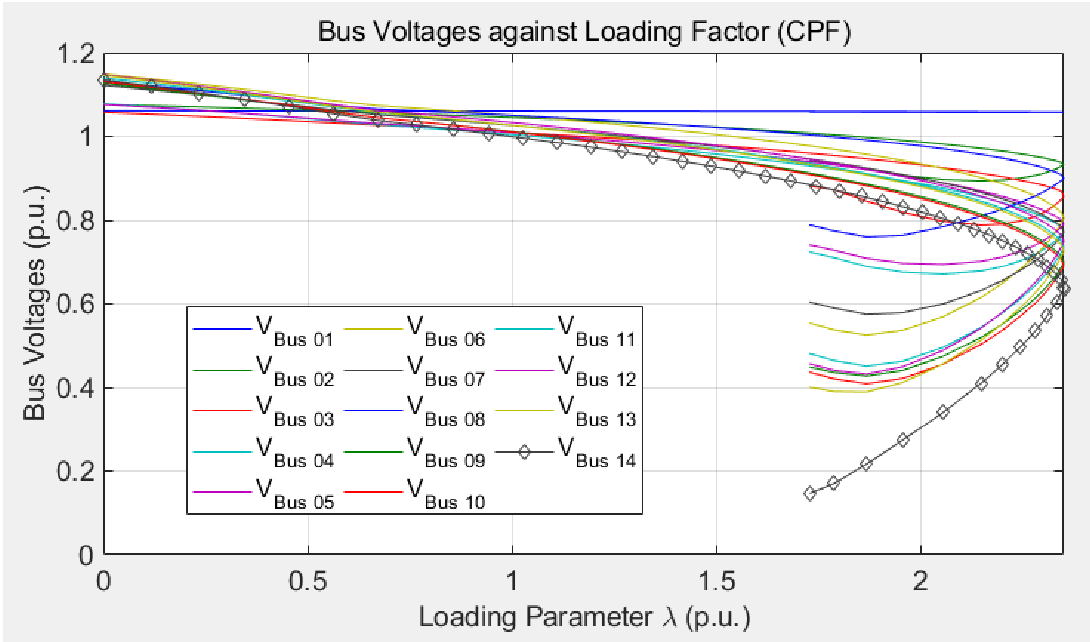

Figure 6: Continuation Power Flow analysis

The maximum loading parameter is 2.375p.u., representing a function of active & reactive power for each load. From the curves, bus 14 had the lowest PV curve, which peaked at approximately 0.65 per unit of voltage. Therefore, bus 14 was analyzed in time-domain as shown in Figure 7, where loads were increased in steps until attaining a point of voltage collapse. The fault created was a simultaneous loss in two transmission lines nearest the generators, i.e., between buses 1-2 and 2-5.

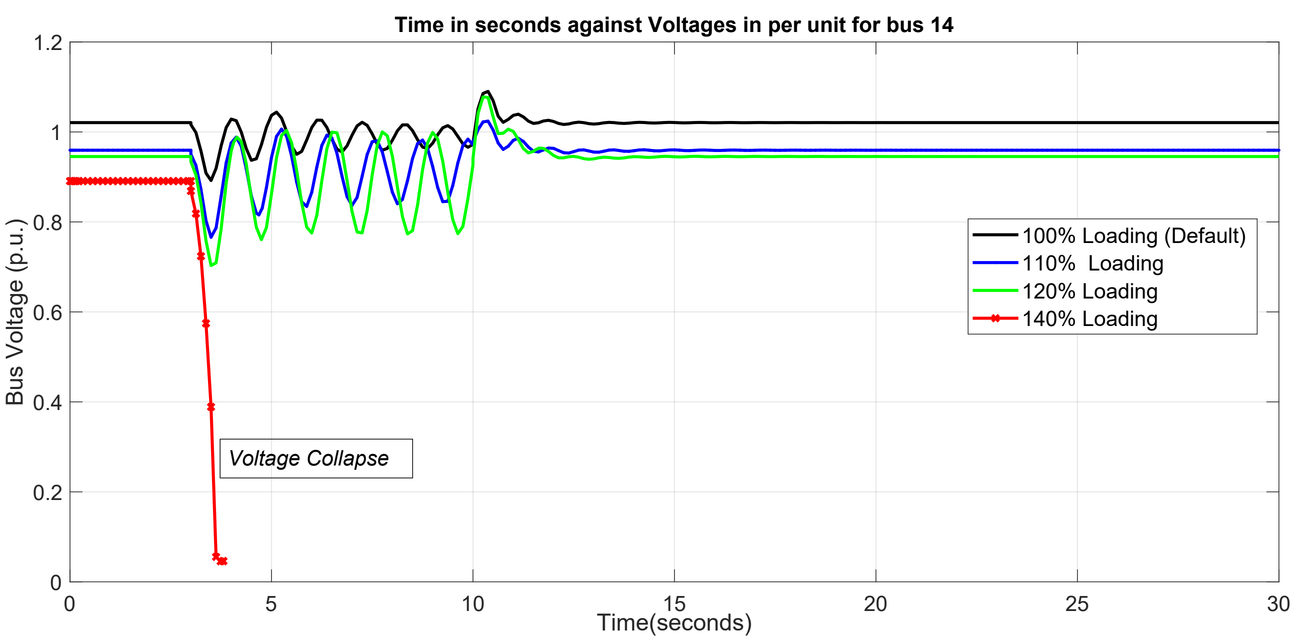

Figure 7: Voltage Collapse Simulations and Multiple Overload Conditions

Whenever a fault occurs in transmission lines, the load is normally redistributed to other lines during the outage period (until the fault is cleared, in this case at 10 seconds). The momentary shift in load causes more strain to the weak buses in a system. The weak buses in this study were computed using the Fast Voltage Stability Index (FVSI) at intervals as shown in Figure 8. The FVSI values rank the weakest of the 20 lines used in the supply of power between the buses.

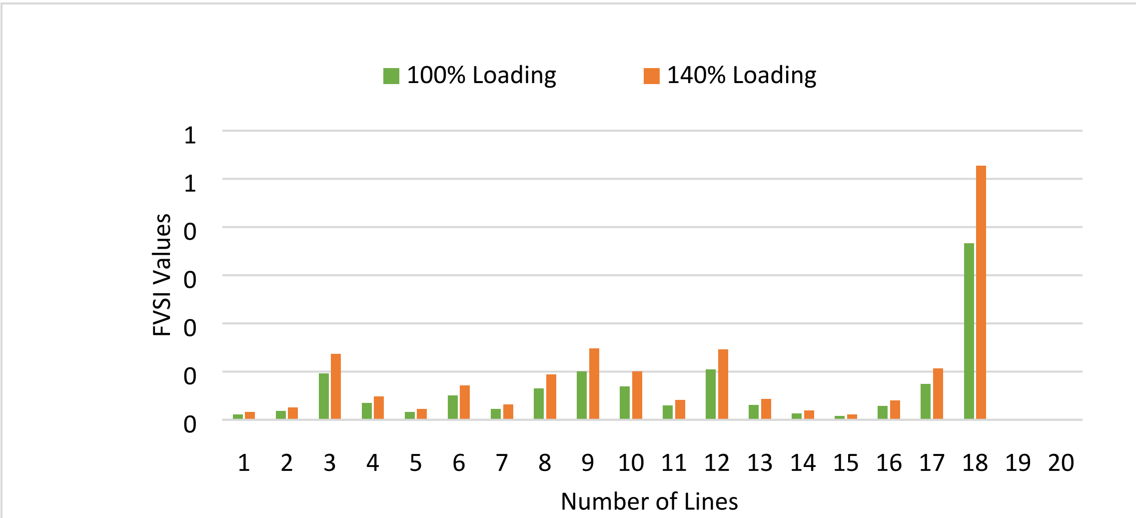

Figure 8: FVSI Values at 40% Overload

The total load demand of the system changes from 259MW and 81.4MVAr initially, up to a 362.6MW and 113.96MVAr load, whereby the voltage fails to recover after the fault occurrence at 3 seconds. The pre-fault voltage for bus 14 was 0.89p.u., which failed to sustain the load during fault, thus causing the voltage collapse in that bus. Similarly, the impact of the dynamic load modelling for the test system is represented in Figure 9, in which the power generated increased proportional to the load increment. This is due to the presence of Type 2 AVRs and Turbine Governors at the generators. A static system analysis ignores the action of dynamic components, although for long-term voltage stability, the parameter changes are said to be constant [1].

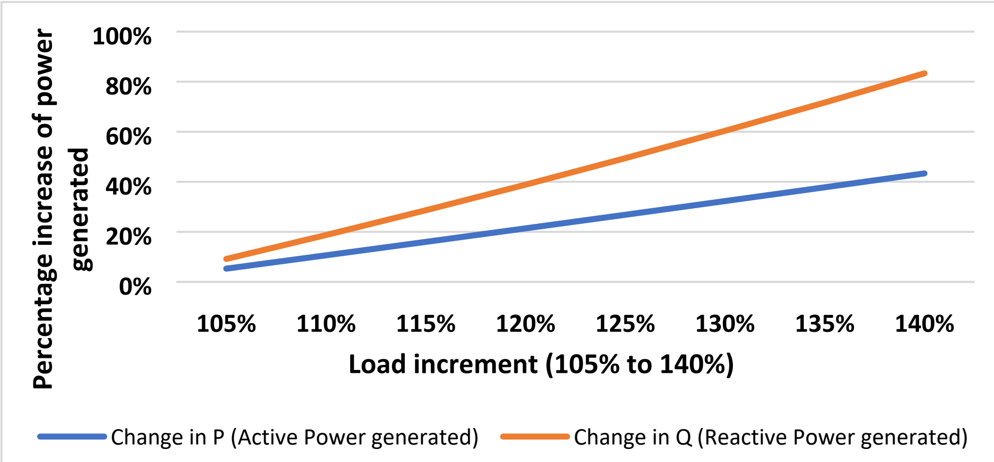

Figure 9: Dynamic behavior of the system during overload

The combination of all the above conditions were factored in the formulation of the hybrid load shedding algorithm.

C: Under Voltage Load Shedding

The expectations from the study were to obtain three outcomes, that is, the location, and amount of load to shed and voltage enhancement of the system.

1. Location of Load Shed

The use of voltage stability indices (VSIs) gives more optimized results for the location of load to shed as shown in Table 2, in which FVSI was used. For the implementation of the algorithm, the maximum FVSI value was set to 0.15, beyond which the bus was considered for load shedding.

Table 2: Location of Load Shed at Multiple Overloads

Overload condition	***No. of buses to load shed***	***Bus No. for UVLS***
105%	1	9
110%	1	9
115%	1	9
120%	3	13, 2, 9
125%	4	13, 2, 6, 9
130%	4	13, 2, 6, 9
135%	9	12, 13, 11, 10, 14, 9, 2, 4, 6
140%	9	12, 13, 11, 10, 14, 9, 2, 4, 6

The comparison for the FVSI ranking compared to studies in [18] show that the eigenvalue analysis shed one additional bus for the same system.

2. Amount of Load Shed

Figures 10 shows the amount of active power shed after the 140% loading considering load prioritization. The comparison of the active power with and without load prioritization is also shown in Figure 11. There is a 5.2$/MW cost saving when loads are prioritized for UVLS, and 85.5%, compared to 85.02%, of load is maintained post-contingency by considering load prioritization.

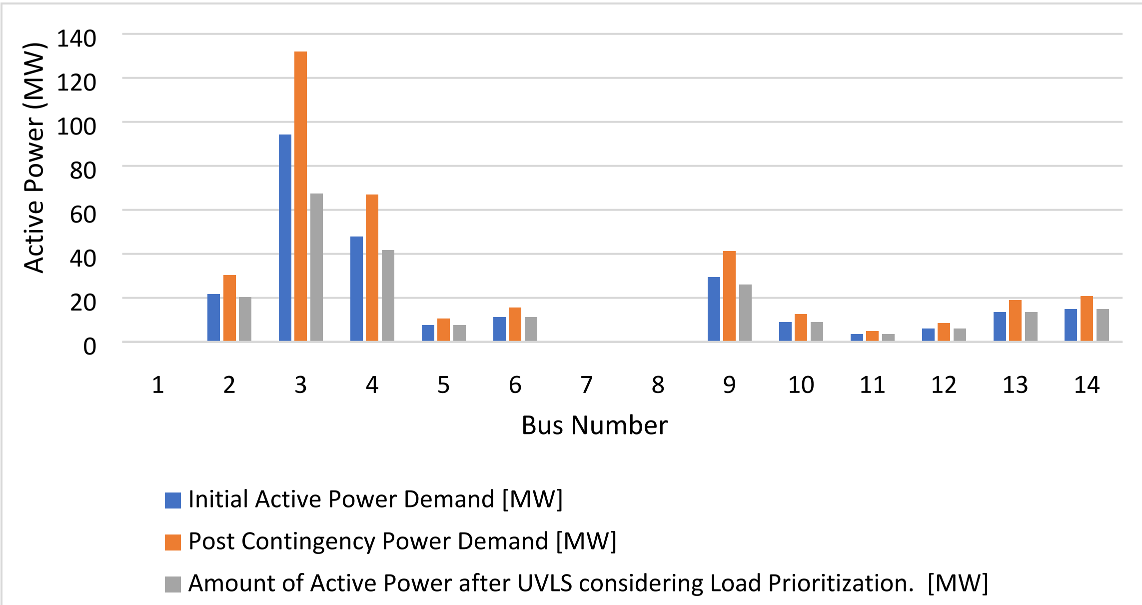

Figure 10: Amount of active power shed

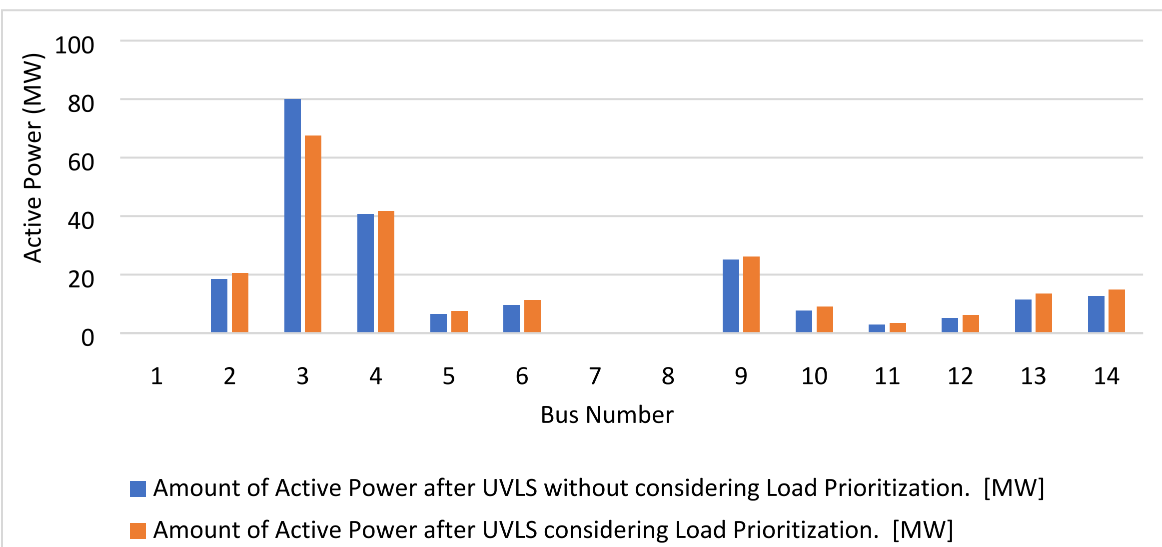

Figure 11: Amount of Active Power Post-Contingency considering Load Prioritization

3. Voltage Recovery

In order to perform UVLS, the criterion set up for decentralized relays, in which each relay remotely monitors a given bus is:

- When voltages drop to 90% and below, 5% of the load is tripped at the specified bus for 3.5 seconds.
- When the bus voltages drop lower than 92%, a 5% additional load is tripped for 5.0 seconds.
- When the bus voltages are still below 92% an additional load of 5% is tripped for 8.0 seconds [23].

Figure 12 shows the voltage profiles of the recovered system following the above UVLS criterion.

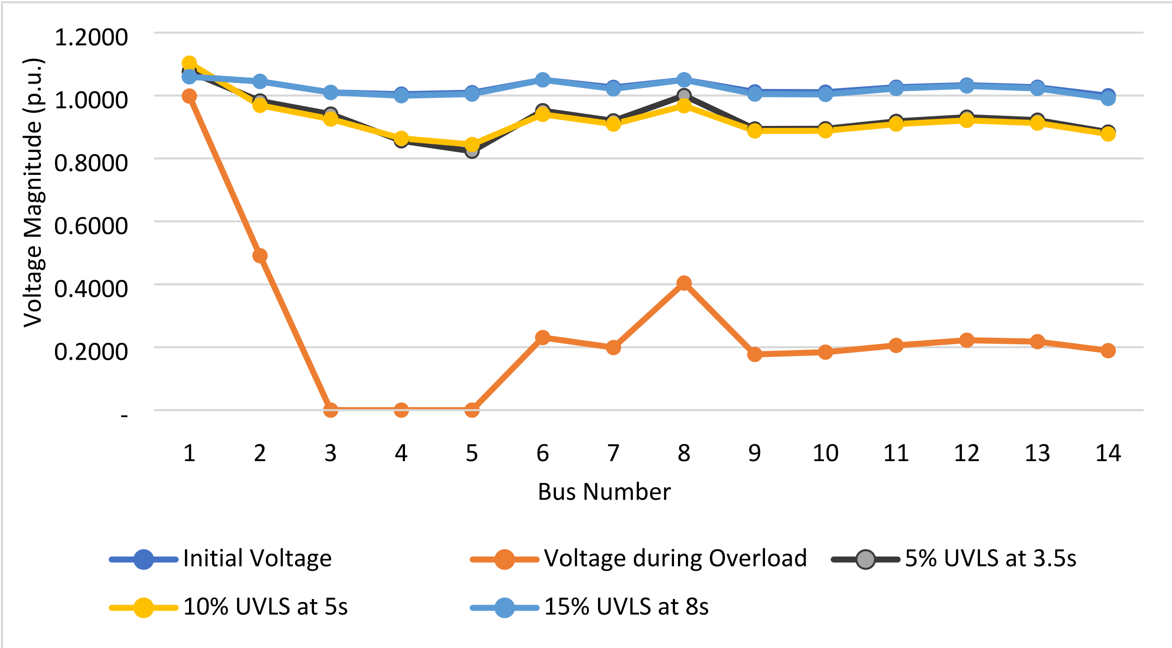

Figure 12: Voltage Recovery of the IEEE 14-bus System after UVLS.

The voltages were restored to almost the initial values, despite the minimal load shed. The range of voltages at each instance was recorded as:

- Initial bus voltage magnitude: 0.9995p.u. (bus 14) to 1.06p.u. (slack bus).
- Voltage during contingency: 0 p.u (buses 3-5) to 0.9983p.u. (slack bus).
- After 5% load shed: 0.823p.u (bus 5) to 1.0764p.u. (slack bus).
- After 10% load shed: 0.8444p.u. (bus 5) to 1.103 (slack bus).
- After 15% load shed: 0.9908p.u. (bus 14) to 1.06p.u. (slack bus).

The set voltage range was 0.95p.u to 1.05p.u with an exception for the slack bus at 1.06p.u. The power generated post contingency was captured as 261.17MW and 54MVAr, in comparison to the initial 232.58MW and 40MVAr. This was a 15% increment in power generated as compensated by the AVRs and TGs.

4. Validation of Hybrid Algorithm

The validation of the algorithm was done in comparison with similar works in [16] and [18] as shown in Table 3. The active load post-contingency is given in comparison to existing algorithms, while considering the load prioritization.

Table 3: Comparing the performance of the Hybrid ABC-PSO algorithm

Bus No.	Base Load	GA	ABC-ANN	PSO-ANN	Proposed Algorithm
1	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.2170	0.1138	0.1987	0.1157	0.2045
3	0.9420	0.4940	0.8625	0.5023	0.6749
4	0.4780	0.4780	0.2784	0.2353	0.4163
5	0.0760	0.0760	0.0760	0.0760	0.0760
6	0.1120	0.1120	0.1120	0.1120	0.1120
7	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	0.0000
9	0.2950	0.2950	0.1787	0.5855	0.2608
10	0.0900	0.0900	0.0900	0.0900	0.0900
11	0.0350	0.0350	0.0350	0.0350	0.0350
12	0.0610	0.0610	0.0610	0.0610	0.0610
13	0.1350	0.0915	0.1350	0.1350	0.1350
14	0.1490	0.1490	0.1490	0.1490	0.1490

In the above results, buses 5-6 and 10 – 14 were restored to their base loads. Bus 3, assigned the penalty cost of commercial loads (12$/MW), had the most amount of load shed compared to bus 9, which was assigned to be a municipal load which has a higher penalty cost of 15$/MW. The prioritization of load saved an overall 5.2$/MW for the 40% overload contingency. At the same time, voltage stability was restored by simultaneously achieving optimal cost saving and optimal amount of load shedding.

VI. Conclusion

From this study, the first objective on the impact of load modelling shows that load modification on bus 14 gave an 8.7% bandwidth in loading margin. This shows that variation in systems' loads creates a difference in SNB points, which can cause delayed voltage collapse in cases where loads are dependent on voltage variations. In achieving optimal UVLS, load prioritization, as shown in the second objective function, creates an overall saving of 5.2$/MW as compared to UVLS without considering the load priority. The resulting amounts of load shed restored active power at 85.5% post fault compared to 77.04%, 84.03% and 80.96% in GA, ABC-ANN and PSO-ANN respectively. Lastly, voltage stability was restored in intervals of 3.5, 5 and 8 seconds, as per the decentralized relay settings. The average voltage profile was restored by 99.32% of the initial voltage profile before fault. Therefore, the novelty of this hybrid ABC-PSO algorithm was its ability to compute the multi-objective functions, giving a wider perspective on the UVLS problem. It proves that Computational Intelligence Techniques are useful in optimizing power system solutions.

VII. Acknowledgements

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VIII. References

[1] C. Taylor, *Power System Voltage Stability*. California: McGraw-Hill Companies, 1994.

[2] C. Zhai, H. Zhang, G. Xiao, and T. C. Pan, "A model predictive approach to protect power systems against cascading blackouts," *Int. J. Electr. Power Energy Syst.*, vol. 113, no. May, pp. 310–321, 2019.

[3] Prinesha Naidoo and R. Vollgraaff, "South Africa's record rolling blackouts raise recession risk," 2019.

[4] H. H. Alhelou, M. E. Hamedani-Golshan, T. C. Njenda, and P. Siano, "A survey on power system blackout and cascading events: Research motivations and challenges," *Energies*, vol. 12, no. 4, pp. 1–28, 2019.

[5] H. Shiraki, S. Ashina, Y. Kameyama, S. Hashimoto, and T. Fujita, "Analysis of optimal locations for power stations and their impact on industrial symbiosis planning under transition toward low-carbon power sector in Japan," *J. Clean. Prod.*, vol. 114, pp. 81–94, Feb. 2016.

[6] R. M. Larik, M. W. Mustafa, and M. N. Aman, "A critical review of the state-of-art schemes for under voltage load shedding," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 5, pp. 1–26, 2019.

[7] M. Usman, A. Amin, M. M. Azam, and H. Mokhlis, "Optimal under voltage load shedding scheme for a distribution network using EPSO algorithm," *Proc. - 2018, IEEE 1st Int. Conf. Power, Energy Smart Grid, ICPESG 2018*, no. September 2019, pp. 1–6, 2018.

[8] J. A. Laghari, H. Mokhlis, A. H. A. Bakar, and H. Mohamad, "Application of computational intelligence techniques for load shedding in power systems: A review," *Energy Convers. Manag.*, vol. 75, no. August 2003, pp. 130–140, 2013.

[9] A. P. Engelbrecht, *Computational intelligence: An introduction*. 2007.

[10] S. Jalilzadeh, S. H. Hosseini, and M. Derafshian-Maram, "Optimal Load Shedding to Prevent Voltage Instability Based on Multi-Objective Optimization Using Modal Analysis and PSO," *2010 Int. Congr. Ultra Mod. Telecommun. Control Syst. Work.*, pp. 371–376, 2010.

[11] A. El-zonkoly, M. Saad, and R. Khalil, "Electrical Power and Energy Systems New algorithm based on CLPSO for controlled islanding of distribution systems," *Int. J. Electr. Power Energy Syst.*, vol. 45, no. 1, pp. 391–403, 2013.

[12] R. Verayiah, A. Mohamed, H. Shareef, and I. Zainal Abidin, “Review of Under-voltage Load Shedding Schemes in Power System Operation,” *Prz. Elektrotechniczny*, vol. 90, no. 7, pp. 99–103, 2014.

[13] D. P. Kothari and J. S. Dhillon, *Power System Optimization*, Second. New Delhi: PHI Learning Private Limited, 2010.

[14] R. Mageshvarana and T. Jayabarathib, “Steady State Load Shedding to Prevent Blackout in the Power System using Artificial Bee Colony Algorithm,” *J. Teknol. (Sciences Eng.*, vol. 8, no. 2, pp. 113–124, 2015.

[15] V. Tamilselvan and T. Jayabarathi, “A hybrid method for optimal load shedding and improving voltage stability,” *Ain Shams Eng. J.*, vol. 7, no. 1, pp. 223–232, 2016.

[16] R. M. Larik, M. W. Mustafa, M. N. Aman, T. A. Jumani, S. Sajid, and M. K. Panjwani, “An improved algorithm for optimal load shedding in power systems,” *Energies*, vol. 11, no. 7, pp. 1–16, 2018.

[17] T. T. Khuat and M. H. Le, “A Novel Hybrid ABC-PSO Algorithm for Effort Estimation of Software Projects Using Agile Methodologies,” *J. Intell. Syst.*, vol. 27, no. 3, pp. 489–506, 2018.

[18] V. Tamilselvan, “A hybrid PSO-ABC algorithm for optimal load shedding and improving voltage stability,” *Int. J. Manuf. Technol. Manag.*, vol. 34, no. 6, pp. 577–597, 2020.

[19] M. S. S. Danish, T. Senjyu, S. M. S. Danish, N. R. Sabory, K. Narayanan, and P. Mandal, “A recap of voltage stability indices in the past three decades,” *Energies*, vol. 12, no. 8, pp. 1–18, 2019.

[20] N. P. Memane, “Development of a Load Shedding Algorithm for Enhanced Provisioning of Electric Power,” Tshwane University of Technology, 2018.

[21] P. Roy and P. K. Chakrobarty, “Power System Analysis of The IEEE 14-Bus Test System Using PSAT and MATLAB.,” 2018.

[22] H. Saadat, *Power System Analysis*, 2nd, illustr ed. McGraw-Hill, 2002.

[23] C. Mozina, “Undervoltage load shedding,” *Power Syst. Conf. Adv. Metering, Prot. Control. Commun. Distrib. Resour. PSC 2007*, no. April 2007, pp. 39–54, 2007.

Appendix

System Data

IEEE 14 BUS TEST SYSTEM - BUS DATA							
Base MVA = 100							
Bus Number	Bus type	P(demand)	Q(demand)	Voltage magnitude	Voltage angle	Voltage limits	
[i]	1-PQ 2-PV 3-Slack	[MW]	[MVAr]	[p.u.]	[rad]	max	min
1	3	0	0	1.06	0	1.061	0.95
2	2	21.7	12.7	1.045	0	1.05	0.95
3	2	94.2	19	1.01	0	1.05	0.95
4	1	47.8	-3.9	1.00	0	1.05	0.95
5	1	7.6	1.6	1.00	0	1.05	0.95

6	2	11.2	7.5	1.05	0	1.051	0.95
7	1	0	0	1.00	0	1.05	0.95
8	2	0	0	1.05	0	1.051	0.95
9	1	29.5	16.6	1.00	0	1.05	0.95
10	1	9	5.8	1.00	0	1.05	0.95
11	1	3.5	1.8	1.00	0	1.05	0.95
12	1	6.1	1.6	1.00	0	1.05	0.95
13	1	13.5	5.8	1.00	0	1.05	0.95
14	1	14.9	5	1.00	0	1.05	0.95

IEEE 14 BUS TEST SYSTEM - GENERATOR DATA							
Bus no.	P (gen)	Q(gen)	Q(max)	Q(min)	V(gen)	P(max)	P(min)
[i]	[MW]	[MVAr]	[MVAr]	[MVAr]	[p.u.]	[MW]	[MW]
1	232.4	-16.9	10	0	1.06	332.4	0
2	40	42.4	50	-40	1.045	140	0
3	0	23.4	40	0	1.01	100	0
6	0	12.2	24	-6	1.05	100	0
8	0	17.4	24	-6	1.05	100	0

IEEE 14 BUS TEST SYSTEM - BRANCH DATA						
Line Number	From Bus	To Bus	Resistance R	Inductance X	Susceptance (B/2)	Transformer Tap Ratio
			[p.u.]	[p.u.]	[p.u.]	
1	2	5	0.057	0.1739	0.034	1
2	6	12	0.1229	0.2558	0	1
3	12	13	0.2209	0.1999	0	1
4	6	13	0.0662	0.1303	0	1
5	6	11	0.095	0.1989	0	1
6	11	10	0.0821	0.1921	0	1
7	9	10	0.0318	0.0845	0	1
8	9	14	0.1271	0.2704	0	1
9	14	13	0.1709	0.348	0	1
10	7	9	0	0.11	0	1
11	1	2	0.0194	0.0592	0.0528	1
12	3	2	0.047	0.198	0.0438	1
13	3	4	0.067	0.171	0.0346	1
14	1	5	0.054	0.223	0.0492	1
15	5	4	0.0134	0.0421	0.0128	1
16	2	4	0.0581	0.1763	0.0374	1
17	5	6	0	0.252	0	0.932
18	4	9	0	0.5562	0	0.969
19	4	7	0	0.2091	0	0.978
20	8	7	0	0.1762	0	1