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Impact of Under Voltage Load Shedding Approach for Voltage Security Control in Power Quality Environment



Abstract: - Contingencies in power system are an ever-present problem for electrical engineers. They may cause the system to have low voltages due to active and reactive power deficiencies. Engineers should consider the many solutions to approach this problem. The solution has to be appropriate to the contingency faced so as to be able to solve the issue without major damage to a power system. A drastic measure that can be used is by removing low voltage loads or 'shedding' the problematic loads. This method of Under Voltage Load Shedding is done by shedding or 'islanding' buses that have fallen to a predetermined minimum voltage for a predetermined time to prevent a cascade of blackouts in the widespread power system. The method to automate the process is by using two optimization techniques, Evolutionary Programming (EP) and Particle Swarm Optimization (PSO). This paper proposes a new hybrid algorithm, named Integrated Chaotic Swarm Based-Evolutionary Programming Optimization (ICSBEP) Technique for Voltage Security Control using Under Voltage Load Shedding (UVLS) approach. Voltage security is indicated by the reduction in voltage stability index, FVSI. In this study, EP, PSO and ICSBEP optimizations algorithms were developed and tested on a IEEE 30-bus reliability test system (RTS). Comparative studies were conducted to observe the advantages of the hybrid algorithm over traditional EP and PSO algorithms. The results obtained from the study can help manage the power quality of the system in ensuring that the customer receive secure electricity supply.

Keywords: load shedding; optimization techniques; evolutionary programming; particle swarm

1. Introduction

Voltage Security is the ability of a system to maintain the required level of voltage. it can be defined either as static, transient or dynamic [1]. Voltage security control is the steps that are taken to prevent a voltage collapse. Although voltage security, voltage control and voltage instability occur at a local level, the consequences would be able to cripple an entire power system. The methods that can be used to determine the voltage by determining the voltage performance index [2], the reactive power requirements [3], or by manually observing the voltage using Newton Raphson Method or Fast Decouple Method. A voltage collapse would only occur when a

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catastrophic outage occurs. Since it would require a heavily loaded and faulted power system to have multiple failures due to not meeting the reactive power demand, the schemes and mitigation techniques need to be equally as extreme. A form of voltage performance index would be to use Fast Voltage Stability Index (*FVSI*) because it can be used to detect sensitive branches in a power system that can lead to voltage instability [4]. *FVSI* has shown to also function well with load shedding techniques. *FVSI* has demonstrated an ability to locate the placement for UVLS for the most optimum solution [5].

Under Voltage Load Shedding (UVLS) approach is a final option that can be performed once all available voltage control techniques have been exhausted [2]. The UVLS sheds the buses that have fallen to a predetermined voltage for a predetermined time as to prevent a catastrophic failure in the power system. UVLS can be categorized as either centralized or decentralized [6]. Since UVLS requires removing loads to stabilize a system, it first is required to categorize the loads into three types, non-vital, semi-vital, and vital. Vital loads would consist of emergency services which under any contingency would never lose power. The order in which load is shed would be in the same order, non-vital followed by semi-vital and finally vital loads would be shed in the most serious of circumstances. The usage of UVLS in current power systems limited due to a preference of using Photovoltaic (PV) generation which is a common commercially used Distributed Generation (DG) [7]. The weakness of DG is the slow recovery speed of voltage during a voltage collapse at the cost of not deactivating the problem load. The use of algorithm to apply the Under Voltage load Shedding is a common practice. The ability of an engineer to supervise all the power stations is limited. By using modern Computational intelligence techniques or Artificial Intelligence (AI) such as Differential Evolution (DE), Genetic Algorithms (GA), Fuzzy Logic Control (FLC) and other Artificial Neural Networks (ANN) [8].

Evolutionary Computing (EC) is a traditional form of optimization programming. EC's roots can be traced to the 1950's but only showed prominence in the 1970's onwards due to increasingly powerful computer platforms and improvements to the methodology [9]. One of the most commonly used EC is Classical Evolutionary Programming or Evolutionary Programming (EP) which utilizes gaussian functions for the mutation process to achieve optimum result [10]. The main difference between EP and other members of EC family is that EP achieves its optimum results by simulating the evolutionary process of randomized mutation [11].

Particle Swarm Optimization (PSO) Algorithm is an artificial intelligence algorithm that optimizes systems by performing calculations and is modelled to imitate the behavior of a swarm of animals [12]. The process begins with random positions and velocities for each particle which then begin to explore from the first iteration [13]. The Global Best among all particles, *Gbest*, and the Personal Best of a particle, *Pbest*, are recorded and updated for every following iteration. The advantage of PSO algorithm is that the particles imitate social behaviour by sharing information with particles in the region [14].

The weaknesses of each individual algorithm or AI can be compensated by Thus, a solution is always being developed. V. Tamilselvan and T. Jayabarathi [15] proposed a method of hybridizing GA and ANN with two stage process in which GA is used to prepare an optimization model and next is to generate a data set for an ANN based load shedding model. The usage of GA allows for a superior data set for the ANN load shedding model that will prevent an early convergence [15]. Thus, this paper proposes a new hybrid optimization technique that integrates EP and PSO, named Integrated Chaotic Swarm Based Evolutionary Programming (ICSBEP). This proposed ICSBEP optimization algorithm would be able to achieve voltage security in a system by shedding a load to reduce *FVSI*, which would be validated on a IEEE 30-Bus reliability test system (RTS). Through a comparative study conducted between EP and PSO, the effectiveness of ICSBEP can be shown.

2. Problem Formulation

The aim of UVLS is to shed the load to balance the rest of the system. The load shedding scheme can be used to alleviate the system's status in terms of voltage stability, losses and voltage control. In this study, UVLS is used to improve the voltage stability condition indicated by the reduction of voltage stability index. In this study, a pre-developed voltage stability index, termed as Fast Voltage Stability Index (*FVSI*) is used as a tool to indicate voltage stability. The function for measuring *FVSI* can be described as: -

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2X} \tag{1}$$

- FVSI* : Fast Voltage Stability Index
- Z* : Impedance of the Line
- Q* : Reactive power of receiving end
- V* : Sending end voltage
- X* : Reactance

FVSI has a range of $0 \leq FVSI \leq 1$. In this study, the value of *FVSI* has to be reduced below 0.5 to be considered stable. However, in other cases we can make a choice on the value of *FVSI* that needs to be achieved.

3. Optimization Techniques

The optimization techniques used are Evolutionary Programming (EP), Particle Swarm Optimization (PSO) and a newly proposed hybrid algorithm Integrated Chaotic Swarm Based Evolutionary Programming (ICSBEP).

A. Evolutionary Programming

Evolutionary Programming (EP) is a common form of optimization technique that finds the optimal solution by evolution of the population in repeated iterations. This process is achieved by calculating individual fitness and applying them to a mutation function, thus achieving a better result. In this paper, the objective of this study is to reduce the *FVSI* value to ensure voltage security improvement. The flowchart representing EP for solving UVLS problems is illustrated in Figure 1.

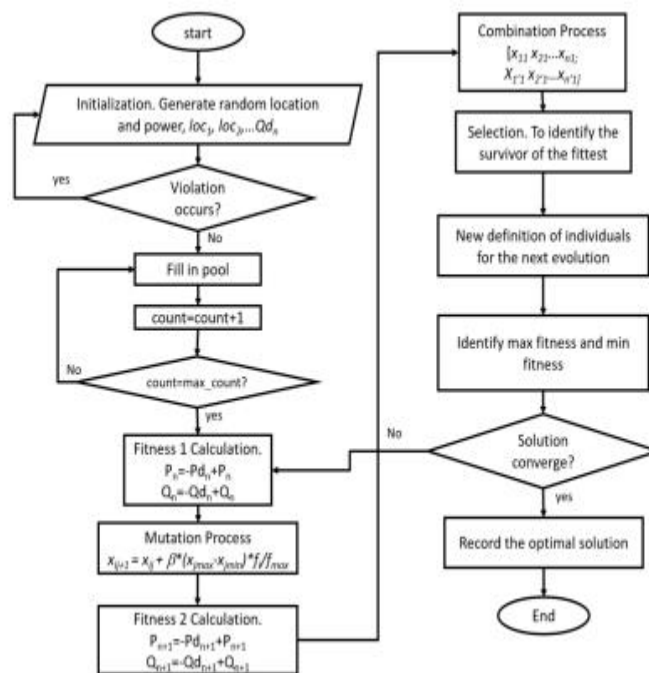


Figure 1: Flowchart for EP for load shedding

The steps of EP are:

Step 1: Initialization.

A random location for load shedding and amount of power to be removed for load shedding are generated. In this step, several random numbers are generated depending on the number of loads to be shed. Initialization is stopped when the population is assigned as the locations and sizing. The corresponding fitness values are also calculated in this phase. The general equation can be written as:

$$P = \{L_{1i}, L_{2i}, \dots, L_{ki}, x_{1i}, x_{2i}, \dots, x_{ki}\} \tag{2}$$

where L is location, x is control variables for sizing, i is the number of individuals and k is the number of individuals.

Step 2 : Fitness I Calculation

undergoes mutation using the gaussian equation as shown. Evolved offspring is produced.

Step 3 :

$$X_{i+m,j} = X_{ij} + N(0, \beta(X_{jmax} - X_{jmin}) (\frac{f_i}{f_{max}})) \tag{3}$$

Where:

$X_{i+m,j}$: parents of mutations (offspring)

X_{ij} : the parents

N : Random Gaussian parameter with mean μ and variance, γ^2

β : scale of mutations, $0 < \beta < 1$

X_{jmax} : for each vector the highest random number

X_{jmin} : the minimum random number of each vector

f_i : fitness the random number i^{th} ,

f_{max} : fitness of maximum random number

Step 4 : Calculate Fitness 2. The same calculations as in fitness 1 is undergone by the mutated offspring.

Step 5 : Combination. Initial and evolved offspring are combined. The combination is done by sorting output of fitness 1 and fitness 2 in a single matrix.

Step 6 : Selection. The best individuals of this iteration are chosen for the new generation. The best individuals would be the highest $FVSI$ to be compared to the original $FVSI$ and lowest location of load shed, lowest real power and lowest reactive power.

Step 7 : Repeat step 3-7 until convergence is achieved

Step 8 : Record the optimal solution

Step 9 : End the process

B. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an optimization algorithm that is able to achieve the optimum solution by imitating a swarm of animals. By defining the personal best of particles which is the individual parameters and the global best which would be the fitness of the equation. The coefficients of PSO are calculated according to Clerc and Kennedy which has the best chance of preventing an early convergence [16]. The flowchart representing PSO for solving UVLS problems is illustrated in Figure 2.

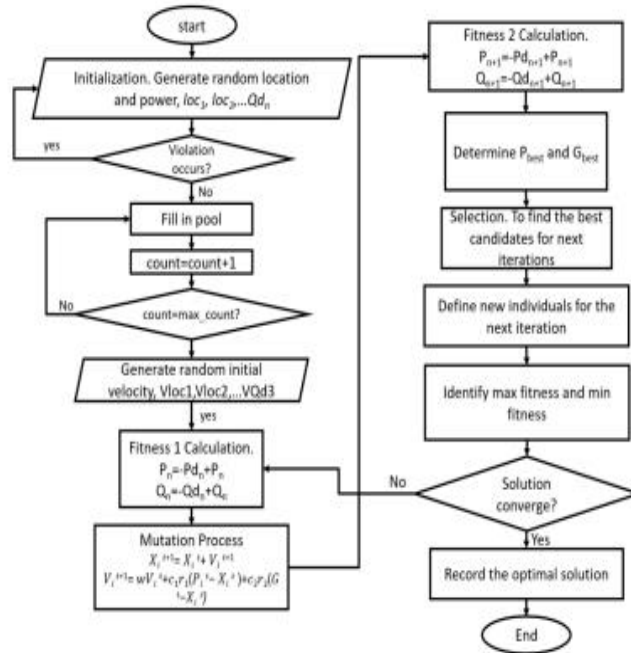


Figure 2: Flowchart for PSO for Load Shedding

The steps of PSO are:

Step 1 : Initialization.

In this step, random variables are generated to represent the locations, sizing of load power to be curtailed. In this study, since three load buses are planned for the load curtailment scheme, nine variables will be required with size of population of 20. This is also called as 20 individuals for each random variable. If 3 load buses are randomly planned for the load shedding scheme.

$$A = \begin{bmatrix} l_{11} & l_{12} & l_{13} & P_{d11} & P_{d12} & P_{d13} & Q_{d11} & Q_{d12} & Q_{d13} \\ l_{21} & l_{22} & l_{23} & P_{d21} & P_{d22} & P_{d23} & Q_{d21} & Q_{d22} & Q_{d23} \\ l_{31} & l_{32} & l_{33} & P_{d31} & P_{d32} & P_{d33} & Q_{d31} & Q_{d32} & Q_{d33} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ l_{k1} & l_{k2} & l_{k3} & P_{dk1} & P_{dk2} & P_{dk3} & Q_{dk1} & Q_{dk2} & Q_{dk3} \end{bmatrix} \quad (4)$$

Step 2 : Fitness Calculation:

In this step, fitness value is calculated utilizing all the individuals contained in the parents' population. In this step, the fitness value is the power loss for the system. Thus, loss value will be calculated using all the individuals in equation (1). In order to do this, AC load flow process will be conducted. Since we have 20 individuals during the random number generation (called as initialization process); then, there will be 20 independent fitness values computed in this step. All the fitness values are tested using the constraint

violation test, which ensures that all fitness values are less than the pre-determined inequality quality constraint. In this case, the inequality constraint is $FVSI < FVSI_{init}$. 20 passed individuals sets containing all the control variables, which satisfied the inequality constraint will make sure the population pull is filled. In fitness calculation, all the random individuals generated during initialization process will be utilized. Apparently, all the fitness values in this step have already passed the constraint violation test during the initialization process.

Step 3 : Initialize v , p , P_{best} and G_{best} :

The initialized velocity, v and initialized position, p will be later utilized for the next process. P_{best} contains all the individuals with the top fitness values, which may have the matrix size of [20 rows by 9 columns for IEEE 30-Bus RTS], while the P_{best} only considered the individuals that give the top fitness value. In this case, the best fitness is the lowest power loss value. Random initial Velocity for all the parameters is generated. The random MATLAB coding is $rand(1,1)*0.25+0.5$. This step will generate a random number with a value between 0.5 and 0.75.

Step 4 : Generate P_{best} for each parameter and G_{best} , which is the $FVSI$ value in this cae.

Step 5 : Update Velocity and Breed Offsprings:

At this stage, velocity and position for each individual is calculated. In general, equations (5) and (6) can be used to do this.

$$X_{i,t+1} = X_{i,t} + V_{i,t+1} \tag{5}$$

$$V_{i,t+1} = wV_{i,t} + c_1r_1(P_{i,t} - X_{i,t}) + c_2r_2(G_t - X_{i,t}) \tag{6}$$

Step 6 Calculate Fitness 2.

: In this step, fitness values are calculated utilizing all the P_{best} values. The matrix size remained the same, but it will become [20 rows by 11 columns] if one column is used to note the individual number and the other column is meant for the fitness value.

Step 7 : Extract the Fitness 1 output and Fitness 2 output.

Step 10 : Compare Fitness 1 output and Fitness 2 output. The two fitness outputs are sorted to

Step 9 : Selection. The best candidates of Fitness 1 and Fitness 2 outputs are selected for next iteration

Step 10 : Repeat step 3-10 until convergence is achieved

Step 11 : Record the optimal solution

Step 12 : End the process

C. Proposed Integrated Chaotic Swarm Based Evolutionary Programming

Integrated Chaotic Swarm Based Evolutionary Programming (ICSBEP) is a newly developed optimization algorithm that combines the strength of EP and PSO. The population of parameters have their velocities and positions are updated using PSO equation. The EP segment of this algorithm comes from the combination and selection process for the next iteration. The benefit of this hybridization is that the combination process of EP takes less time to find the best positions and velocities for next iterations and the PSO mutation process is able to find the

optimum solution faster than the gaussian equation. The coefficients are the same as the other algorithms used. The flowchart representing the proposed ICSBEP for solving UVLS problems is illustrated in Figure 3.

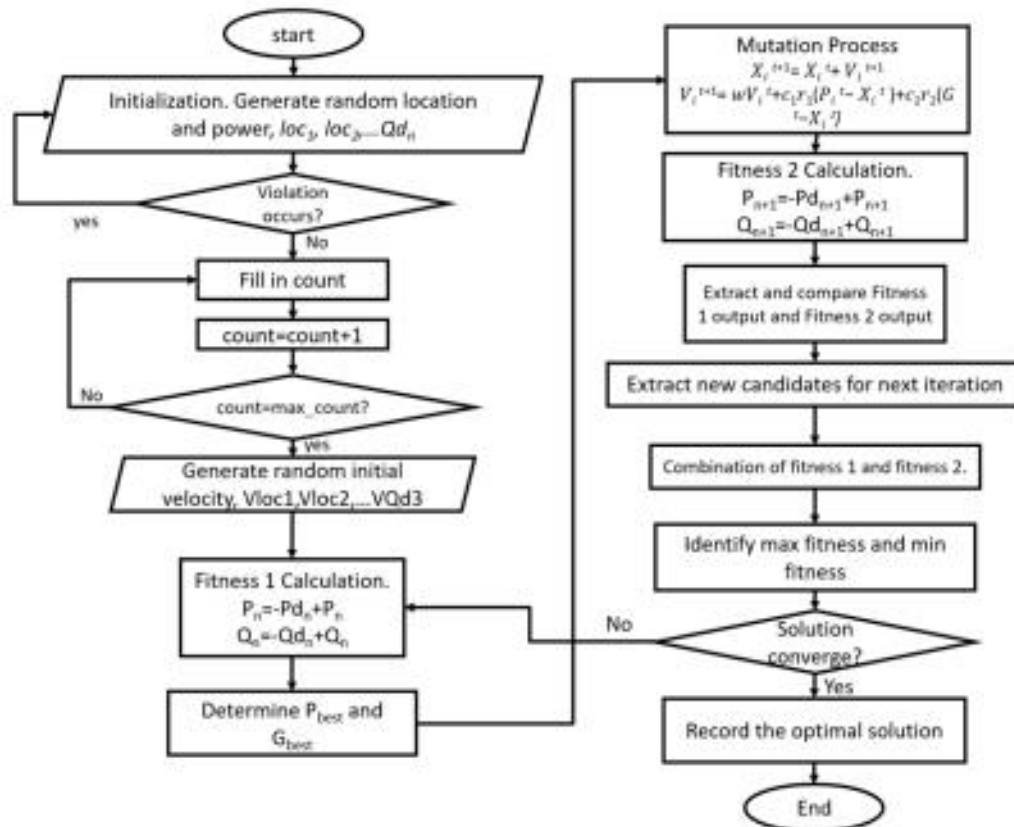


Figure 3: Flowchart for ICSBEP for Load Shedding

The steps for ICSBEP are given below: -

- Step 1 : Initialization. A random location for load shedding and amount of power to be removed for load shedding are generated.
- Step 2 : Initialization is stopped when the population reaches 20.
- Step 3 : Calculate Fitness 1. The fitness of the population is dependent of the *FVSI* value and the *FVSI* value can be reduced by performing load shedding involving the real power, P_d , and reactive power, Q_d , at optimal locations.
- Step 4 : Random initial Velocity for all the parameters is generated. The syntax is given as follows

$$Rand(1,1)*0.25+0.5$$
 This step will generate a random number with a value between 0.5 and 0.75.
- Step 5 : Generate personal best for each parameter and global best, which is the *FVSI* value.
- Step 7 : Calculate Fitness 2. The same calculations as in fitness 1 is undergone by the updated particles.

- Step 8 : Extract the Fitness 1 output and Fitness 2 output.
- Step 9 : Compare Fitness 1 output and Fitness 2 output. The comparison is done by sort the fitness 1 and fitness 2 outputs side by side.
- Step 10 : Selection. The best candidates of Fitness 1 and Fitness 2 outputs are selected for next iteration. The selection of best candidates is done by comparing the *FVSI* values either of the candidates and selecting which are better.
- Step 11 : Repeat step 3-10 until convergence is achieved.
- Step 12 : Record the optimal solution.
- Step 13 : End the process.

4. Results and Discussions

In this study, three cases implying load shedding schemes were conducted. The results of this study are presented and discussed in this section in terms of optimal locations and sizing of real and reactive power to be shed in the system. This study was conducted on IEEE 30-Bus Reliability Test System (RTS) under several cases. The cases are designed based 3 load shedding schemes as listed below.

Case 1 : 3-Load shedding Scheme

Case 2 : 5-Load shedding Scheme

Case 3 : 7--Load shedding Scheme

The results for Case 1 are tabulated in Table 1, solved using three optimization techniques namely EP, PSO and ICSBEP. It is shown that the final *FVSI* for ICSBEP is lower than the EP and PSO. In all three optimization techniques, the voltage security are stable indicated by the *FVSI* value is less than 0.5. Our proposed ICSBEP managed to reduce the *FVSI* value from 0.9183 to 0.1296. This value is significantly lower than the results solved using EP and PSO. When compared to EP and PSO; great difference in value of *FVSI* with 0.4186 and 0.1354 respectively are shown. This indicates the merit of ICSBEP over the traditional EP and PSO. The locations for load to be shed, solved using ICSBEP are Bus 28, Bus 14 and Bus 26 in IEEE 30-Bus RTS. Using EP, the locations are Bus 14, Bus 18 and Bus 19; while PSO gives Bus 4, Bus 14 and Bus 23.

Table 1: Case 1: Results for Optimal Locations in 3-Load shedding Scheme

Method	EP	PSO	ICSBEP
<i>Location 1</i>	14	4	28
<i>Location 2</i>	18	14	14
<i>Location 3</i>	19	23	26
<i>Initial FVSI</i>	0.9183	0.9183	0.9183
<i>Final FVSI</i>	0.4186	0.1354	0.1296

Table 2: Case 1: : Optimal Sizing for 3-Load shedding Scheme

Method		<i>Loc 1</i>	<i>Loc 2</i>	<i>Loc 3</i>
EP	P_d	17.91	2.09	4.53
	Q_d	29.88	2.91	19.48
PSO	P_d	0.90	3.28	19.34
	Q_d	13.45	49.41	26.14
ICSBEP	P_d	3.67	21.38	6.43
	Q_d	27.42	-21.49	55.05

The results for sizing of the loads to be shed involving 3 locations with real and reactive power to be shed are tabulated in Table 2. For ICSBEP, the amount of real power to be shed at Buses 28, 14 and 26 are 3.67 MW, 21.38 MW and 6.43 MW as shown in the table. The amount of reactive power to be shed are 27.42 MVAR, -21.49 MVAR and 55.05 MVAR. The negative value indicates that this load needs to be connected at this bus to improve voltage security in the system. The results for EP and PSO involving these two parameters can be seen in the same table.

Table 3: Case 2: Results for optimal locations in 5-Load shedding Scheme

Method	EP	PSO	ICSBEP
<i>Location 1</i>	14	14	14
<i>Location 2</i>	28	24	16
<i>Location 3</i>	24	21	15
<i>Location 4</i>	16	25	28
<i>Location 5</i>	18	28	24
<i>Initial FVSI</i>	0.9655	0.9655	0.9655
<i>Final FVSI</i>	0.2359	0.1380	0.1263

Table 3 tabulates the results for load shedding for Case 2. In case 2, it is shown that ICSBEP outperforms EP and PSO again in terms of achieving the lowest *FVSI* value. In this case, 5 locations were involved for load shedding. ICSBEP managed to reduce the *FVSI* value from 0.9655 to 0.1263, indicating significant voltage security improvement. This requires load shedding at Buses 14, 16, 15, 28 and 24. The amount of real and reactive power are tabulated in Table 4. The amount of real power to be shed at the mentioned buses are 18.91 MW, 22.91 MW, 16.37 MW, 11.12 MW and 28.42 MW. The corresponding reactive power to be shed are 57.97 MVAR, 23.04 MVAR, 32.81MVAR, 26.18 MVAR and -44.0 MVAR as tabulated in Table 4. Negative MVAR value implies that at this bus, there should not be reactive power to be shed but to be absorbed. The detailed locations to undergo load shedding solved using EP and PSO can also be referred to Table 3, while the amount of load to be shed can be seen in Table 4.

Table 4: Case 2: Optimal Sizing for 5-Load shedding Scheme

Method		<i>Loc 1</i>	<i>Loc 2</i>	<i>Loc 3</i>	<i>Loc 4</i>	<i>Loc 5</i>
EP	P_d	22.04	5.66	26.82	15.52	26.26
	Q_d	17.11	23.07	27.46	0.38	10.04
PSO	P_d	18.77	36.70	19.2	27.56	32.76
	Q_d	41.37	18.79	4.00	33.34	35.29
ICSBEP	P_d	18.91	22.91	16.37	11.12	28.42
	Q_d	57.97	23.04	32.81	26.18	-44.0

A further load shedding scheme was implemented to the system involving 7-load shedding scheme. The results for the optimal location for 7-load shedding scheme are tabulated in Table 5. On the other hand, the results for the optimal sizing of loads to be shed are tabulated in Table 6.

Table 5: Case 3: Results for optimal locations in 7-Load Shedding Scheme

Method	EP	PSO	ICSBEP
<i>Location 1</i>	14	17	14
<i>Location 2</i>	21	25	21
<i>Location 3</i>	15	15	29
<i>Location 4</i>	25	29	18
<i>Location 5</i>	29	21	15
<i>Location 6</i>	18	20	25
<i>Location 7</i>	17	14	20
<i>Initial FVSI</i>	0.9655	0.9655	0.9655
<i>Final FVSI</i>	0.4573	0.3109	0.2374

In Table 6, the implementation of 7-load shedding, solved using ICSBEP managed to reduce the *FVSI* value from 0.9655 to 0.2374 as shown in the table. This requires 7 loads to undergo load shedding scheme involving Buses 14, 21, 29, 18, 15, 25 and 20, if solved using ICSBEP. The optimal locations solved using EP are Buses 14, 21, 15, 25, 29, 18 and 17; while using PSO the optimal locations are Buses 17, 25, 15, 29, 21, 20 and 14 as shown in Table 5. Solving this problem, revealed that ICSBEP managed to achieve the lowest *FVSI* value worth 0.2374, implying its superiority over EP and PSO. EP and PSO exhibit higher *FVSI* values. The optimal sizing of real power to be shed at Buses 14, 21, 29, 18, 15, 25 and 20 are 22.80 MW, 24.43 MW, 20.16 MW, 12.18 MW, 8.38 MW, 18.40 MW and 29.83 MW. The corresponding reactive power to be shed at these buses are 20.44 MVAR, 34.57 MVAR, 17.23 MVAR, 10.68 MVAR, 41.39 MVAR, 18.11 MVAR and 1.24 MVAR respectively as indicated in Table 6. These values would be beneficial to power system operators for their load shedding scheme if implemented on IEEE 30-Bus RTS as the test model. The results solved using other techniques are also tabulated in the same table.

Table 6: Case 3: Optimal Sizing for 7-Load shedding Scheme

Method		<i>Loc 1</i>	<i>Loc 2</i>	<i>Loc 3</i>	<i>Loc 4</i>	<i>Loc 5</i>	<i>Loc 6</i>	<i>Loc 7</i>
EP	P_d	2.18	22.40	16.56	28.96	21.29	7.81	15.15
	Q_d	24.66	24.42	16.54	20.02	20.67	8.24	15.65
PSO	P_d	5.95	20.74	14.86	7.73	15.58	28.42	3.23
	Q_d	8.44	17.00	5.97	25.50	18.32	0.21	24.83
ICSBEP	P_d	22.80	24.43	20.16	12.18	8.38	18.40	29.83
	Q_d	20.44	34.57	17.23	10.68	41.39	18.11	1.24

5. Conclusion

This paper has presented the impact of under voltage load shedding approach for voltage security control in power quality environment. In this study a new optimization technique termed ICSBEP was derived to alleviate the setback experienced by the traditional EP and PSO. Results from the study validated in IEEE 300-Bus RTS managed to achieve the lowest *FVSI* value worth 0.1296 from 0.9183 for 3-load shedding scheme, 0.1263 from 0.9655 for 5-load shedding scheme and 0.2374 from 0.9655 for 7-load shedding scheme. In all load shedding schemes, ICSBEP outperformed EP and PSO. This revealed its superiority over EP and PSO as the standalone optimization technique. Further load shedding scheme can also be explored involving more loads to be shed. The developed ICSBEP optimization engine can also be utilized or applied for solving other optimization problems subject to considerable amendments in the optimization engine.

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