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Review of Load Stability Techniques for Voltage Collapse on Electric Power System

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ABSTRACT

Nowadays, increase in transmission capacity of power system due to economic and environmental constraints has led to voltage collapse or instability which places limitation to power system operations. Thus,maintaining a stable operation of power system is one of the main challenges of electrical power system. Several computational, analytical and meta-heuristic techniques have been employed for analysis of voltage collapse in power system. These techniques help to identify load buses with high impact of voltage instability and the required generation reduction to maintain power balance within prescribed maximum and minimum allowable values.In these paper, different load stability techniques for voltage system collapse assessment has been reviewed and their corresponding limitations were analyzed. This analysis will play animportant role in determining the system operating limits and operating guidelines of powersystem.

Keywords: *Power System, Capacity limits, Voltage collapse, Analytical, Voltage Instability, Load Stability.*

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I. INTRODUCTION

In present deregulation the continuing growth in interconnections of power system industry has given rise to different forms of voltage collapse [1-3]. Voltage collapse is a consequential effect of instability which is the process by which voltage falls to a very low value as a result of series of events in a power system [2]. Interconnected power systems are increasingly experiencing voltage collapse or instability which poses a primary threat to power system stability, reliability and security. Excessive voltage decline can possibly leading to voltage collapse, by further tripping of more transmission facilities or generating units due to overloading [1, 4, 5].

Consequences of voltage collapse in power system include low voltage profiles, heavy reactive flows and inadequate reactive support. The consequences often require long system restoration, while large groups of customers are left without supply [6-9].In addition,a protection system and proper control may resolve the problem voltage collapse that occurs due to disturbance [3, 7].

Therefore these load stability techniquesfor voltage collapse assessment in power system plays important role in determining the system operating limits of power system.

a Operating States of Electric Power System

The power system operates in two important areas, namely normal and abnormal states. In thenormal operating state, the system is said to be secured and all constraints in Equations (1) to(4) are satisfied. Thus, under normal operating conditions of power systems, the following constraints must be satisfied [1, 6]:

$$\sum_{i=1}^{Ng} P_{Gi} = P_D + P_{Loss} \quad (1)$$

$$P_{Gi}^{Min} = P_{Gi} \le P_{Gi}^{Max} \; i = 1,2,.......Ng \quad (2)$$

$$V_k^{Min} \le V_k \le V_k^{Max} \; k = 1,2,......N_b \quad (3)$$

$$P_{km} \le P_{km}^{Min} \quad (4)$$

where; P_{Gi} is the real power generated, P_D total system demand , P_{Loss} total real power loss , V_k is the voltage magnitude,

However, in theabnormal operating, the operatingconditions of the system change and the variables like nodes voltages,real and reactivepower flows violate the constraints [2, 3].In addition, different operationalstates are defined as follows [4, 5, 8]:

i. Normal or secured state: In the normal state, all the constraints are satisfied and operatinglimit is within presented limits.

ii. Alert or critical state: It is a state symbolized by the satisfaction of all the constraints andby an insufficient level of stability margins.

iii. Emergency or unsecured state: It is a state where all the equality constraints are satisfiedand one constraint violated.

b. Load Stability Technique

Load Stability (LS) technique action against voltage collapseas it results in an instantaneous voltage stability enhancement. This technique is used tofind the weak bus for load shedding [4, 10, 11]. There are three main types of this techniquee; conventional, adaptive andcomputational intelligence LS [12].

II. RELATED WORKS

i. Conventional Load Stability Techniques

The stability techniques are of two types: Under-Frequency Load Stability(UFLS) and Under-Voltage Load Stability (UVLS). The UFLSdetermined amount of the load if the system frequency falls below its specified rangewhile UVLS is used to avoid a risk of voltagecollapse and for voltage restorer [9].

Verayiah*et al.* (2013) implemented under voltage load stability scheme to avert voltage collapse incidence from occurring in power system. The approach was implemented on IEEE 30-bus system. The weakest buses location was obtained using Voltage Stability Index (VSI). The results indicated that the approach can be used to identify the weak bus in a power system [10].

Ogbuefi*et al.* (2018) studied the incidence of power system voltage collapse on Nigeria power system using Fifteen (15) years data (2003-2017). The data were analyzed sequentially using simple statistics. The results shows that Nigeria national grid experienced an average of twenty eight (28) system collapse every year. The study suggested that power system needs total revamping to decrease the economic impact of the high incidence of system collapse in the country [12].

ii. Adaptive Load Stability Techniques

Adaptive load stability techniques are based onpower flow, power swing equation and stability indices [4, 8, 13].

a) Load flow analysis

Load flows are used to identify the need foradditional generation either capacitive or inductive. Inaddition, load flow analysis is at the heart of contingency analysis and the implementation ofreal-time monitoring systems [1, 4, 7, 8].

The most commonly used load flow analyses are the Gauss Seidel, the Newton-Raphson (NR) and Fast Decoupled.However, NR method is majorlyuseful for large network and has moderate computer storage requirements [8]. However, for estimation of proximity of voltagecollapse in power system Newton-Raphson load flow may fail to give optimum solution inmaximizing the load flow margin [6, 7].

b) Swingequation

The swing equation describes the behaviour of the electrical machine to disturbances in the power system [13]. This equation is given as for the case of synchronous machine connected to infinite bus, the angular position of the machine is given as machine acceleration torque, where the angular speed of rotation is constant as shown in Equations (5) to (7) [3, 13]:

$$T_a = T_m - T_e = J\,\frac{\partial^2\theta}{\partial t^2} = J\,\frac{\partial^2\delta}{\partial t^2} \qquad (5)$$

$$P_a = P_m - P_e = \omega J\,\frac{\partial^2\theta}{\partial t^2} = M\,\frac{\partial^2\delta}{\partial t^2} \qquad (6)$$

$$P_a = P_m - P_e = \frac{2H\partial^2\delta}{\omega\partial t^2} = \frac{H}{\pi f}\cdot\frac{\partial^2\delta}{\partial t^2} \qquad (7)$$

Where M is the angular momentum and it is assumed that the change in speed is small. H is the inertia constant and is equal to the kinetic energy of the generator divided by its powerrating. The typical machine has an inertiaconstant between 2 and 10 seconds.

Thus, stability analysis involves the solution of differential equation in Equation (7). Therefore, there are two significant aspects to stability using swing equations:The input mechanical power Pm and the output electrical power transferred to the load or network P_e [3. 13, 17].

c) Voltage stability indices

These are varieties of tools for assessing whether a system is voltage stable or not[1, 9]. These indices include:

i. Line Stability Index (LSI): The LSI is based on power transmission line concepts. [17]. The LSI is given as [18]:

$$LSI = \frac{4XQ_r}{|V_s|^2 Sin^2(\theta - \delta)} \leq 1 \qquad (8)$$

A line in the system is close to collapse when the *LSI*is close to one (1). However, if the *LSI* value is less than one (1), then the system is stable.where; Q_r is reactive power at receiving-end, θ is the transmission line angle, X is the line reactance, V_r is the sending-end voltage, V_s is the sending-end voltage, δ is a phase angle, δ_r is the receiving-end voltage phase angle,

ii. FastVoltage Stability Index (FVSI): The FVSI is also based on the concept of power flow[17].The FVSI is given as [2, 17]:

$$FVSI = \frac{4Z^2 Q_r}{V_s^2 X} \leq 1 \qquad (9)$$

The line with stability index value closest to one (1) is the most critical line connected to bus. where; P_s is the real power at sending-end, Q_s is the reactive power at sending-end,

iii. Line Stability Factor (LSF): The LSF index is based on the discriminant of the power quadratic equation set to be greater than or equal to zero. The lLSF is given as [18]:

$$LSF = 4\left(\frac{X}{V_s^2}\right)\left(\frac{X}{V_s^2} P_s + Q_r\right) \qquad (10)$$

The value of *LSF* index should be maintained at less than 1, for stable system otherwise, system will collapse.

iv. Line Voltage Stability Index (LVSI):Is the relationship between line real power and the bus voltage. If the resistance of the transmission line is very close to zero, the index fail. The LVSI is given as [17]:

$$LVSI = \frac{4RP_r}{[V_s Cos(\theta - \delta)]} \leq 1 \qquad (11)$$

LVSI is more sensitive to δ since $Cos(\theta - \delta)$ is faster than $Sin(\theta - \delta)$ around 90^0 and a healthy line could be identified as a critical line.

v. Voltage Collapse Point Indicator (VCPI):This indicates closely, how far the bus is from its collapse point. The VCPI is as follows [9. 15]:

$$VCPI = \left| 1 - \frac{1}{V_r} \sum_{\substack{i=1 \\ i \neq r}}^{n} V_i \right| \qquad (12)$$

The value of *VCPI* determines the proximity to voltage collapse at a bus, when there is increase in power flow transfer, the value of the indices increases gradually and when it reaches 1, the voltage collapse occurs.

Various techniques of adaptive load stability techniques used by previous researchersto analyze the effect of voltage collapse on power system are reviewed and presented:Dey*et el.* (2010) presented a methodology for assessing the voltage stability using the concept of equivalence multi-bus power system of a two-bus network model. The approach was applied to a robust practical 203-bus Indian Eastern Grid system. The result shows that the approach could be able to assess voltage stability of any power system[13].

Mobarak and Hussein (2012) presented the dynamic analysis of voltage stability. The study searched for the effect of peak inrush current and its duration periods initiation of voltage instability, with lagging and leading load power factors at certain load buses and also, the fault duration required for voltage collapse. The result showed that, the fault duration which caused initiation of voltage collapse was affected by the cold inrush current magnitudes [14].

Althowibi and Mustafa (2013) analyzed the voltage stability in power systems using Voltage-Reactive (V-Q) and Voltage-Active (V-P) power relationships to prevent line outages and to avoid total system voltage collapse. The approach was tested on the IEEE 14-bus and 118-bus systems. These approaches proving a clear and complete picture of power flow dynamics systems [4].

Mobarak (2015) analyzed the voltage stability of a power system using constant load model. The simulation was done using Power World Simulator (PWS) Software and MATLAB Program, and applied on EIEG power system. The result shows that, the magnitude of the smallest eigen-value gave a measure of how close the system was to the voltage collapse [15].

Oluseyi*et al.* (2015) analyzed the voltage collapse on power system by carrying out load flow analysis on Nigerian 31-bus system using Newton Raphson iteration method. This study proved to be useful in determining what lines to take into utmost consideration in different transmission expansion planning schemes. The results showed that the Nigerian transmission network is a highly fragile grid system susceptible to a great number of collapses [16].

Samuel (2017) proposed a Line Stability Index (LSI) that was suitable for investigating the voltage stability condition of Power System Networks (PSN). The approach was tested on the IEEE 14-bus system and 28-bus, 330-kV Nigerian power grid and simulation in MATLAB environment. The result showed that the test system was stable [17].

Samuel *et al*. (2017) presented a Line Stability Index (NLSI) suitable for the prediction of voltage collapse in Power System Networks (PSN). This approach was tested on IEEE 14-bus system. The result showed that the test system was stable [18].

Braide and Diema (2018) analyzed the transient stability study of Nigeria 330 kV power system. The simulation was done using MATLAB. The analysis and investigation showed that fault protection scheme should have lower clearing time for an effective operating performance [19].

Idoniboyeobu*et al.* (2018) presented a novel approach for voltage collapse in power system using a probabilistic predictor-detector based on probabilistic Quadratic Line Voltage Stability Index (Q-LVSI).. The technique was applied on Nigeria power system network and a simulation was performed using MATLAB [20, 21].

III. METHODOLOGY

This study based on review of different optimization used for voltage system collapse assessment in electrical power system

a) Genetic algorithm

Genetic Algorithms (GA) are heuristic probabilistic optimization techniques inspired by natural evolution process. They are considered when conventional techniques cannot achieve the desired speed, accuracy and efficiency [11, 21]. The GAare used for global function or control optimization [15, 18].

In GA, the fitness function is used instead of objective function as in the traditional optimization procedures [19].The fitness function ff is given as in Equation (13) [20]:

$$f = P_1\left(\sum h^2(x,u)\right) + P_2\left(\sum g^2(x,u)\right) \qquad (13)$$

where; f is the objective function; g is the power flow equations equality constraints; h is the system operating constraints .

In GA initial population is the first step, then, abinary string is associated to each member of the population. This string represents a solution of the problem. Crossover is responsible for the structure recombination (information exchange between mating chromosomes) and is usually applied with high probability (0.5–0.9). Mutation is used to avoid both premature convergence of the population and to fine-tune the solutions [2, 19].

b) Particle swarm optimization

Particle Swarm Optimization (PSO) algorithm is evolutionary computation techniques based on the movement and intelligence of swarms. PSO handles a population of individuals, in parallel where the optimal solution is searched. The individuals are called particles and the population is swarm [4, 15].

Each particle in the swarm represented by a vector of length *n* indicating the position and has a velocity vectorused to update the current position [15]. Each particle keeps track of its coordinates in the solution space which are associated with the best fitness value(personal best P_{best}.) While the best fitness value tracked by the PSO is the best value (global best G_{best}) [14].

The PSO algorithm consists of updating the velocities and positions of the particle, respectively as in Equations (14) and (15) [19, 21]:

$$v_m^{k+1} = wv_m^k + c_1 r_1 \left(P_{best(m)} - s_m^k\right) + c_2 r_2 \left(G_{best(m)} - S_m^k\right) \quad (14)$$

$$S_m^{k+1} = S_m^k + v_m^{k+1} \quad (15)$$

where; c_1, c_2 are acceleration coefficients, r_1, r_2 are random numbers between 0 and 1, v_m^k is current velocity of particle m and iteration k

c) Firefly algorithm

Firefly Algorithm (FA) is a nature inspired meta-heuristic algorithms which is inspired by the flashing behavior of fireflies and the phenomenon of bioluminescent communication.The algorithm works based on global communications among the fireflies and can find global and local optimal simultaneously [1, 20, 21].

There are three idealized rules by FA which based on flashing characteristics of real fireflies. These are as follow [8]:

i. Fireflies are unisex, move towards more attractive and brighter ones.
ii. The degree of attractiveness is proportional to its brightness
iii. The brightness or light intensity of a firefly is determined by the value of the objective function of a given problem.

Therefore, for a given medium with a fixed light absorption coefficient 'γ', the form of attractiveness function of a firefly is given as [17, 20]

$$\beta_r = \beta_0 * \exp\left(-\gamma r_{ij}^m\right) \text{with } m \geq 1 \quad (16)$$

The distance between any two fireflies i and j, at positions x_i and x_j, respectivelyis given as [21]:

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \quad (17)$$

The movement of a firefly i which is attracted by a more attractive firefly j is given as:

$$x_{i+1} = x_i + \beta_0 * \exp\left(-\gamma r_{ij}^2\right) * \left(x_j - x_i\right) + \alpha * \left(rand - \frac{1}{2}\right) \quad (18)$$

where: r is the distance between any two fireflies, β_0 is the initial attractiveness at $r = 0$, γ is an absorption coefficient, $x_{i,k}$ is the k^{th} component of the spatial coordinate x_i

d) Cuckoo search algorithm

Cuckoo Search Algorithm (CSA) is a nature inspired meta-heuristic algorithm based on the brood parasitism of somecuckoo species. This strategy is useful tominimize the risk of egg loss to other species, as the cuckoos can distribute their eggs amongst anumber of different nests [16, 17, 20, 21].

Thethree idealized rules for implementation of CSA are [18]:

i. Cuckoos choose random nest for laying their eggs..
ii. By applying selection process, only eggs with highest quality are passed tothe next generation.
iii. The number of available host nests is fixed. Host bird discovers cuckoo egg withprobability *pd*ε [0, 1]. If cuckoo egg is disclosed by the host, it may be thrown away, or abandon.

Based on the above rules, the system equation for CSA is established using local random walk and global random walk, controlled by a switching parameter *Pa* .The current state and the probability of transition as in Equations(19) and (20) respectively [19, 20]:

$$x_i^{t+1} = x_i^t + \alpha s \otimes H\left(p_a - \varepsilon\right) \otimes \left(x_j^t - x_k^t\right) \quad (19)$$

$$x_i^{t+1} = x_i^t + \alpha \otimes Levy(s, \lambda) \quad (20)$$

where; p_a is the switching parameter, x_i^t and x_j^t are the upper and lower bounds of i^{th} and j^{th} component respectively, H is a standard uniform random number on the open interval (0, 1), s is the number of the current generation, α indicates the step size or coefficient of step length,

e) Salp swarm algorithm

Salp Swarm Algorithm (SSA) is an intelligent evolutionary optimization algorithm based on the swarming mechanism of salps in oceans [19]. In SSA, the leader is the salp at the front of chain and whatever remains of salps are called followers [3, 18, 21].The population represents the salp chain and each solution in the population represents the position of a salp. Each solution is evaluated using a fitness function and the best solution is denoted as the food target [1, 19].

Equations (21) to (23)are used to update the positions of salps.

$$x_n^1 = \begin{cases} F_n + c_1\left(\left(u_n - l_n\right)\cdot c_2 + l_n\right) \; c_3 \geq 0 \\ F_n - c_1\left(\left(u_n - l_n\right)\cdot c_2 + l_n\right) \; c_3 < 0 \end{cases} \qquad (21)$$

$$c_1 = 2e^{-\left(\frac{4a}{A}\right)^2} \qquad (22)$$

$$x_n^i = \frac{1}{2}\left(x_n^i + x_n^{i-1}\right) \qquad (23)$$

where; c_1 is a time varying parameter, c_2 and c_3 are uniform random numbers, $i \geq 2$ and x_n^i depicts the position of the i^{th} follower at the n^{th} dimension,

f) Whale optimization algorithm

Whale Optimization Algorithm (WOA) is a simple, robust and swarm based stochastic optimization algorithm works based on the behavior of humpback whales in hunting [13, 20, 21].

In the context of WOA, a swarm refers to a number of potential solutions to the optimization problem, where each potential solution is referred to as a search agent[18].

In order to perform optimization, Equations (24) to (26) are used to update the behavior, position and distance of the WOA [18, 21]:

$$D = \left|\vec{C}.\vec{X}^*(t) - X(t)\right| \qquad (24)$$

$$X(t+1) = \vec{X}^*(t) - \vec{A}.D \qquad (25)$$

$$\vec{X}(t+1) = X_{rand} - \vec{A}.\vec{D} \qquad (26)$$

Where; $\overline{A}$ and $\overline{C}$ are coefficient vectors, t indicates the current iteration, $\overline{X}$ is the best solution, X is the position vector, D is best solution obtained. It is worth mentioning here that X^* should be updated in each iteration,

IV. CONCLUSION

This paper has successfully reviewed and presentedthe strengths and weaknesses of various techniques used by previous researchers for voltage collapse analysis on electrical power system in order to provide effective solutions for the reliable functioning ofthe power system. Each technique has tried to solve the problem with various objectives and constraints. But, most of the techniques used conventional power flow model to represent the system steady state and this might not always be appropriate, especially as the system approached critical condition.

However, application of computational intelligence techniques such as GA, PSO, CSA, FA, SSA,WOA among others have been proved by researches as capable tools for predicting voltage collapse in complex network system.

Thus, this research paper will help power system engineerto determining themaximum load-ability of the load buses vulnerable to voltage collapse in powersystem.

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