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Original Article

Voltage Collapse Optimization for the Iraqi Extra High Voltage 400 kV Grid based on Particle Swarm Optimization

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Abstract *(The continuously ever-growing demand for the electrical power causing the continuous expansion and complexity of power systems, environmental and economic factors forcing the system to work near the critical limits of stability, so research's stability have become research areas worthy of attention in the resent day.*

The present work includes two phases: The first one is to determine the Voltage Stability Index for the more insensitive load bus to the voltage collapse in an interconnected power system using fast analyzed method based on separate voltage and current for PQ buses from these of PV buses, while the second phase is to suggested a simulated optimization technique for optimal voltage stability profile all around the power system. The optimization technique is used to adjust the control variables elements: Generator voltage magnitude, active power of PV buses, VAR of shunt capacitor banks and the position of transformers tap with satisfied the limit of the state variables (load voltages, generator reactive power and the active power of the slack bus).

These control variables are main effect on the voltage stability profile to reach the peak prospect voltage stable loading with acceptable voltage profile.

An optimized voltage collapse based on Particle Swarm Optimization has been tested on both of the IEEE 6 bus system and the Iraqi Extra High Voltage 400 kV Grid 28 bus. To ensure the effectiveness of the optimization technique a comparison between the stability indexes for load buses before and after technical application are presented. Simulation results have been executed using Matlab software).

Keyword: Voltage Stability Indicator; voltage collapse; Stability of Extra High Voltage Grid; PSO optimization technique.

I. Introduction

The fundamental objectives in the electric power industry are ensuring reliability, security and optimization [1]. The Continuous increase in power demand and the corresponding limits to expand the transmission systems due to economic and environmental constraints, power system operating close to the critical limits of stability. These extreme conditions can cause the collapse of voltages, so the stability of the system has become an urgent need to be taken into account [2].

Voltage stability is defined as capability of the system to ensure an acceptable level of voltage for each node in the system before and after being subjected to a disturbance, being subjected to a disturbance [3], while Voltage collapse is the operation that the consequence of events associated with voltage instability cause to unsatisfactory voltage profile in a large part of system. Increasing in demand load offset by excessively increasing in the reactive power required. Usually generators and compensation devices are responsible to cover the increased in the demand of reactive power but if absence of sufficient reserves to cover this increase, collapse voltages may occur and thus partially or entirely system may be blackouts. Hence set of procedures and precautions have been adapted to maintaining voltage stability. **A**utomatic **V**oltage **R**egulators-**AVRs**, **U**nder-**L**oad **T**ap **C**hangers-

ULTCs and compensation devices are good Solutions to keep the magnitude of bus voltage in suitable ranges [4].

Due to the voltage instability, many cases of blackouts in many countries of the world and their negative effects were Registered [5]. The voltage stability indices can be identified as continuous monitoring of the system, they could determine how far between operating point of a system and voltage stability boundary [6].

Previous studies that addressed voltage stability indices have been offered two analytical approaches such as static and dynamic. The static approach based on the traditional load flow model, achieves satisfactory results but does not take in consideration the dynamic side of the problem in which the power system is acting as a dynamic system and has an effect on instability voltage [2].

Many studies have based on the analysis of Jacobin matrix to predict the extent of the approaching system from the voltage collapse by eigenvalue calculations [7-8], the weaknesses of this approach lie in the sensitivity factors and the need for a long time during analysis huge systems [9]. According to the concept of impedance match techniques which summarized as follows: determine the v_{ph} and I_{ph} at any bus-bar then derive the equivalent of Thevenin impedance of the remaining part of the system. The possibility of the voltages collapse has been associated with verification matching case between each of the load impedance and equivalent Thevenin i.e ($Z_L = Z_{th}$) . the simplicity of this technology encouraged a large number of researchers to adopted in their researches [10]. Permeate this technique some of the adverse aspects that effect on the accuracy of predicting the collapse of voltages, one of it is the assumption that the parameters of the equivalent Thevenin is constant while they are continuous changes such as transmission lines off duty, the switching of shunt capacitor and the reserves of VAR [11]. In addition some studies [12-14] indicated that this technical have facing theoretical problems when applied to large system with multiple loads. Other research has relied on a dynamic approach in predict voltage collapse, In [5] Researcher adopted in its analysis on a correlation between (V-P) and (V-Q), which gave a complete picture for the dynamics of the system. Two of them to analyze the stability of each load node with symbol as $(VPI)_{bus}$ and $(VQI)_{bus}$ and the two others to analyze the stability of the transmission lines with symbol as $(VPI)_{line}$ and $(VQI)_{line}$ in a power system.

Many studies have been submitted some indicator that related with evaluate the instability of the voltage such as **V**oltage **I**nstability **P**roximity **I**ndex **-VIPI** , **V**oltage **C**ollapse **P**roximity **I**ndicator- **VCPI** [15] and the **P**ower **T**ransfer **S**tability **I**ndex – **PTSI** as a type of dynamic voltage collapse prediction [2]. They are based on many load flow solution and provide only comprehensive picture of the system.

Another study [16] presents an artificial bee colony algorithm to determine the optimal location for the injection DG. in the radial distribution system by identifying of the stability index for each node in the system (loss sensivity index), so the node with minimum possible value of (LSI) is the most sensitive to the breakdown voltages

Some research has proposed the use of neural networks as monitoring technique. A multilayer perceptron back propagation neural network has been adopted to identify the voltage stability index for load buses and hence predict the most load bus sensitive to the collapse of the voltages [17].

The current research included two phases of work, The first phase included applied a fast and accurate technique to determine the voltage stability index for all load buses of interconnected power system then identify the weakest one and their maximum loading limit (collapse voltage).

The second phase included enhancing voltage stability of the system by selecting a set of elements (control variables: independent variables) that an impact on voltage stability profile then adjust their values in order to achieve better stability of the system. this mechanism can be achieved by applying one of the modern optimization techniques (**P**article **S**warm **O**ptimization-**PSO**)] .

The optimum level of voltage stability profile is reached through minimizing voltage stability index for all load buses thus the system as a whole.

1. Voltage Stability Index

The analysis of voltage stability includes specify of an index defined as Voltage Collapse Proximity Indicator, VCPI. This index is a quantitative measurement for the distance between the operating point of the system and the critical limits for collapse voltage.

There are many approaches of identifying it. L-index method suggested in Kessel and Glavitsch [18] is one of these methods. It is depends on load flow analysis which is applicable for any system with multi buses [19].

According to the current Law of Kirchoff the relationship between the current and voltages for multi-bus electric power system can express as follows:

$$[I_{Bus}] = [Y_{Bus}][V_{Bus}] \qquad (1)$$

By separation load nodes i.e (PQ) buses from that for generator nodes i.e (PV and slack) buses we get:

$$\begin{bmatrix} I_l \\ I_g \end{bmatrix} = \begin{bmatrix} Y_{ll} & Y_{lg} \\ Y_{gl} & Y_{gg} \end{bmatrix} \begin{bmatrix} V_l \\ V_g \end{bmatrix} \qquad (2)$$

where I_l, V_l are the current and voltage across load nodes buses while I_g, V_g are for generator nodes. Through the reorganization of the equation (2) we get:

$$\begin{bmatrix} V_l \\ I_g \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_4 \end{bmatrix} \begin{bmatrix} I_l \\ V_g \end{bmatrix} \qquad (3)$$

where M_1, M_2, M_3, M_4 are sub matrices obtained from partial inversion of Y_{Bus}

$$M_2 = -[Y_{ll}^{-1}][Y_{lg}] \qquad (4)$$

Let L_k is voltage stability indicator of the kth bus, where k ∈ for any load bus

$$L_k = \left| 1 - \sum_{i=1}^{ng} M_{2ki} * \frac{V_i}{V_k} \angle\theta_{ki} + \delta_i - \delta_k \right| \qquad (5)$$

Practically indicators stabilizing voltages represented by (L_k) and its range value between zero (at no load condition) and one (at the full load condition). Any bus approaching the maximum value is the most closer to the limits of the collapse voltages i.e it's the weakest bus**.**

2. Mathematical model

Voltage Collapse Optimization is related with the limit of stability system. It is a part of the Optimal Power Flow OPF. Mathematically, the problem of the OPF can be expression as follows

$$\begin{cases} minimum\ f(x_1, x_2) \\ g(x_1, x_2) = 0 \\ h(x_1, x_2) \le 0 \end{cases} \qquad (6)$$

where f is the fitness function to reach minimum value; g is a function that representing to the equality limits of standard load flow equations; h is a function compatible with the limitations of system operating.

x_1 is the of state variables vector (dependent variables) including of active power generating at slack bus P_{G1}; voltage of the Load-bus V_L and reactive power outputs of generator Q_G.

x_2 is the control variables vector (independent variables) comprising of real power generator P_G at PV bus; voltage of the generator V_G; Shunt VAR of capacitance bank Q_C and the setting of transformer tap T_i.

The equality limitation corresponding with standard load flow equations. i.e. at each node the balance between active and reactive power can be expressed as follow:

$$P_i - V_i \sum_{j=1}^{NB} V_j \left(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij} \right) = 0 \qquad (7)$$

i = 1, 2,…. $NB - 1$ and $P_i = P_{Gi} - P_{Li}$

$$Q_i - V_i \sum_{j=1}^{NB} V_j \left(G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij} \right) = 0 \qquad (8)$$

i = 1,2,….NL and $Q_i = Q_{Gi} - Q_{Li}$

where P_i, Q_i are the injected active and reactive powers at bus *i*; $P_{Gi}; Q_{Gi}$ are the generation of active and reactive powers at bus *i*; $P_{Li}; Q_{Li}$ are the load active and reactive power at bus *i*; $G_{ij}; B_{ij}$ are the conductance and susceptance of the branch *i j* respectively; *NB*, *NB*-1 are the whole number of buses with and without slack bus respectively; *NL* is number of load buses.

The system operating limits that related with inequality constraints on control variables can be formulated as:

$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max}$ *i*=1,2,…..,*NG*

$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}$ i=1,2,…..,NG for PV bus

$T_i^{min} \le T_i \le T_i^{max}$ i=1,2,… .,NT

$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}$ i=1,2,…..,NC

where (V_{Gi}^{min},V_{Gi}^{max}),(T_i^{min},T_i^{max}), (Q_{Ci}^{min}, Q_{Ci}^{max}), (P_{Gi}^{min}, P_{Gi}^{max}) are the minimum and maximum voltage limit of generator i; tap changing limit of the transformer i; reactive power compensator of shunt injection capacitor i; are the generator real power limit at PV bus i respectively ; while NG, NT and NC are the generators number , regulating transformers number and shunt VAR of capacitance bank number sequentially.

The limits that related with inequality constraints on state variables can be formulated as

$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max}$ i=1,2,…….,NL

$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}$ i=1,2,…......,NG

$P_{Gs}^{min} \le P_{Gs} \le P_{Gs}^{max}$

where (V_{Li}^{min},V_{Li}^{max}),(Q_{Gi}^{min}, Q_{Gi}^{max}), (P_{Gs}^{min}, P_{Gs}^{max}) are the minimum and maximum limit for each of the voltage of load-bus i; reactive power of generator i and active power of slack generator respectively.

The fitness functions that considered in this article is maximum voltage Index (voltage collapse of the load bus).

In order to avoid the outage limits of the state variables, the modify fitness function can be formulated as follow:

$$\min f = F + \lambda_v \sum_{i=1}^{NL} \Delta V_{Li}^2 + \lambda_Q \sum_{i=1}^{NG} \Delta Q_{Gi}^2 + \lambda_s \Delta P_s^2 \qquad (9)$$

$$\Delta V_{Li} = \begin{cases} V_{Li} - V_{Li}^{max} & (V_{Li} > V_{Li}^{max}) \\ 0 & (V_{Li}^{min} < V_{Li} < V_{Li}^{max}) \\ V_{Li}^{min} - V_{Li} & (V_{Li} < V_{Li}^{min}) \end{cases} \qquad (10)$$

$$\Delta Q_{Gi} = \begin{cases} Q_{Gi} - Q_{Gi}^{max} & (Q_{Gi} > Q_{Gi}^{max}) \\ 0 & Q_{Gi}^{min} < Q_{Gi} < Q_{Gi}^{max}) \\ Q_{Gi}^{min} - Q_{Gi} & (Q_{Gi} < Q_{Gi}^{min}) \end{cases} \qquad (11)$$

$$\Delta P_s = \begin{cases} P_s - P_s^{max} & (P_s > P_s^{max}) \\ 0 & P_s^{min} < P_s < P_s^{max}) \\ P_s^{min} - P_s & (P_s < P_s^{min}) \end{cases} \qquad (12)$$

where λ_v, λ_Q and λ_s are penalty factor of load-bus, reactive power of generator and active power of slack bus respectively while ΔV_{Li}, ΔQ_{Gi} , ΔP_{Gs} are the infringement in each of the voltage load-bus i; reactive power of generator i; active power of slack bus and F is the fitness Function (Voltage Collapse) [19, 20].

3. Particle Swarm Optimization (PSO)

PSO is subset of evolutionary computation based stochastic optimization technique. It described for the first time by James Kennedy and Russell C. Eberhart in 1995. The initial idea was inspired from two discrete notions: the first one attempt by some specialists in social psychology for modeling the movement of bird flocks and fish schools; and the other is field of evolutionary computation.

PSO has been initialized with a set of random agents or particles (possible solution) which form a swarm moving in the hyper-dimensional search space seeking to access the best solution (fitness function). Each particle represents a bird or fish in the swarm and treated as a point in a search space which regulates its movement depending on their own experience and the experience of adjacent particles.

Each particle keeps track of its coordinates in the search area toward the best solution; this value is called local or personal best position (*pbest)*. Furthermore each particle recognizes the best value so far in group *(gbest)* among all of the individual *pbests*. After determining *(pbest, gbest)*, each particle tries to accelerate its velocity and updating positions [21, 22, 23]

3.1The basic element of PSO technique

The essential elements of the PSO can be clarified as follows

***Particle s_{id}^{t}**

The control variables are represent in the form of a vector [S_1, S_2, S_3, S_4, … , S_n] where n is the number of control variables. Each control variables has a set of particles (candidates).

The set of particles of the first control variables S_1 are $\{s_{11}, s_{12}, s_{13}, \dots, s_{1D}\}$ where D is the number of particles in each control variables.

The set of particles of the second control variable S_2 are $\{s_{21}, s_{22}, s_{23}, \dots, s_{2D}\}$ and so on. At iteration t, the position of the particles, ${s_{id}}^t$ can be formulated as follow:

$$s_{id}^t = \begin{bmatrix} s_{11} & s_{12} & s_{13} & . & . & s_{1D} \\ s_{21} & s_{22} & s_{23} & . & . & s_{2D} \\ s_{31} & s_{32} & s_{33} & : & : & s_{3D} \\ . & . & . & . & . & . \\ s_{n1} & s_{n2} & s_{n3} & . & . & s_{nD} \end{bmatrix}^t \quad (13)$$

The vector $[s_{11}, s_{21}, s_{31}, \dots, s_{n1}]$ represent a first control variables and so on for generation the population of the swarm. Each control variables has a fitness function $f(s_{id})$ and this fitness function is related to the change of a specific particle s_{id} in this control variable [24].

A precise mechanism are adopted in this article to create the population of the swarm. The swarm's size can be select as a random value but in this article the size of the swarm N are determine according to the following equation.

$$N = n * D \quad (14)$$

where n is control variables number and D is the particles number in each control variables.

***Mechanism of the particles selection in the swarm population of PSO**

This mechanism depends on chosen a random reference control variable vector. In this article, the first control variables $[s_{11}, s_{21}, s_{31}, \dots, s_{n1}]$ are used as reference control vector. According to this control variable a first fitness function $f(s_{11})$ are calculated and related to the first particle s_{11}. In order to create another control variables vector, every particle in the reference control variable are varying between minimum and maximum value based to the input particles s_{id} keeping the other particle in the reference control variable constant. The second control variables vector will be as follow $[s_{12}, s_{21}, s_{31}, \dots, s_{n1}]$ where the particle s_{11} become s_{12} and the fitness function according to this control variables will be $f(s_{12})$. And so on as shown in Table (1) . The fitness function $f(s_{id})$ which is influenced by the particle s_{id} can be written as the matrix form of iteration t as in equation (15) [21]

Table 1
SWARM POPULATION

Vectors of control variables						Fitness function
X_1	X_2	X_3	.	.	X_n	
$\mathbf{s_{11}}$	s_{21}	s_{31}	.	.	s_{n1}	$f(s_{11})$
$\mathbf{s_{12}}$	s_{21}	s_{31}	.	.	s_{n1}	$f(s_{12})$
$\mathbf{s_{13}}$	s_{21}	s_{31}	.	.	s_{n1}	$f(s_{13})$
.	s_{21}	s_{31}	.	.	s_{n1}	.
.	s_{21}	s_{31}	.	.	s_{n1}	.
$\mathbf{s_{1D}}$	s_{21}	s_{31}	.	.	s_{n1}	$f(s_{1D})$
s_{11}	$\mathbf{s_{21}}$	s_{31}	.	.	s_{n1}	$f(s_{21})$
s_{11}	$\mathbf{s_{22}}$	s_{31}	.	.	s_{n1}	$f(s_{22})$
s_{11}	$\mathbf{s_{23}}$	s_{31}	.	.	s_{n1}	$f(s_{23})$
s_{11}	.	s_{31}	.	.	s_{n1}	.
s_{11}	.	s_{31}	.	.	s_{n1}	.
s_{11}	$\mathbf{s_{2D}}$	s_{31}	.	.	s_{n1}	$f(s_{2D})$
s_{11}	s_{21}	$\mathbf{s_{31}}$	.	.	s_{n1}	$f(s_{31})$
s_{11}	s_{21}	$\mathbf{s_{32}}$	.	.	s_{n1}	$f(s_{32})$
s_{11}	s_{21}	$\mathbf{s_{33}}$	.	.	s_{n1}	$f(s_{33})$
s_{11}	s_{21}	.	.	.	s_{n1}	.
s_{11}	s_{21}	.	.	.	s_{n1}	.
s_{11}	s_{21}	$\mathbf{s_{3D}}$	.	.	s_{n1}	$f(s_{3D})$
.	.	.	.	.	.	.
.	.	.	.	.	.	.
s_{11}	s_{21}	s_{31}	.	.	$\mathbf{s_{n1}}$	$f(s_{n1})$
s_{11}	s_{21}	s_{31}	.	.	$\mathbf{s_{n2}}$	$f(s_{n2})$
s_{11}	s_{21}	s_{31}	.	.	$\mathbf{s_{n3}}$	$f(s_{n3})$
s_{11}	s_{21}	s_{31}	.	.	.	.
s_{11}	s_{21}	s_{31}	.	.	.	.
s_{11}	s_{21}	s_{31}	.	.	$\mathbf{s_{nD}}$	$f(s_{nD})$

$$f(s_{id}^t) = \begin{bmatrix} f(s_{11}) & f(s_{12}) & . & . & . & f(s_{1D}) \\ f(s_{21}) & f(s_{22}) & . & . & . & f(s_{2D}) \\ f(s_{31}) & f(s_{32}) & : & : & : & f(s_{3D}) \\ . & . & . & . & . & . \\ f(s_{n1}) & f(s_{n2}) & . & . & . & f(s_{nD}) \end{bmatrix}^t \quad (15)$$

***Particle velocity $\mathbf{v_{id}^t}$**

In the swarm population, the particles velocity at iteration t can be express as follow:

$$v_{id}^t = \begin{bmatrix} v_{11} & v_{12} & v_{12} & . & . & v_{1D} \\ v_{21} & v_{22} & v_{23} & . & . & v_{2D} \\ v_{31} & v_{32} & v_{33} & : & : & v_{3D} \\ . & . & . & . & . & . \\ v_{n1} & v_{n2} & v_{n3} & . & . & v_{nD} \end{bmatrix}^t \quad (16)$$

v_{11} represent velocity of particle s_{11} and so on

**** Best local (individual) position*** **(** $\mathbf{pbest_{id}}$)

The best position that associated with the best value of the fitness function for each particle is represented the individual or local best position; which dependent on the experience owned by particle at iteration t

$$pbest_{id}^{t} = \begin{bmatrix} pbest_{11} & pbest_{12} & . & . & . & pbest_{1D} \\ pbest_{21} & pbest_{22} & . & . & . & pbest_{2D} \\ pbest_{31} & pbest_{32} & . & . & . & pbest_{3D} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ pbest_{n1} & pbest_{n2} & . & . & . & pbest_{nD} \end{bmatrix}^{t} \quad (17)$$

**** Best global position*** **(** $\mathbf{gbest_{i}}$**)**

is the preferable position among all of local best positions $pbest_{id}$ obtained so far. It a global best position associated with experience of neighboring particle.

$$gbest_{i}^{\ t} = \begin{bmatrix} gbest_{1} \\ gbest_{2} \\ gbest_{3} \\ . \\ . \\ gbest_{n} \end{bmatrix}^{t} \quad (18)$$

To clarify, $gbest_1$ represent the individual preferable position (global best position) of the first control variable i.e.

$$gbest_1 = \text{best among } \{pbest_{11}, pbest_{12}, \ldots, pbest_{1D}\}$$

****Velocity updating***

The id-th particle velocity is modified based on the following equation:

Inertia Personal Influence

$$v_{id}^{t+1} = wv_{id}^{t} + c_1 \times rand_1 \times (pbest_{id}^{t} - s_{id}^{t}) + c_2 \times rand_2 \times (gbest_{i}^{t} - s_{id}^{t}) \quad (19)$$

Social Influence

Inertia: regulates the particles movement in the same direction and velocity

Personal Influence: Improves the individual particles by return to a previous Position, since it is better than the current (i.e. Conservative).

Social Influence: regulates the individual particle follow the best neighbor's direction (i.e diversification).

$\mathbf{v_{id}^{t}}$**:** present velocity of particle id at t^{th} iteration.

$\mathbf{v_{id}^{t+1}}$**:** modified velocity of particle id at $(t+1)^{th}$ iteration.

w: inertia weight approach.

$\mathbf{c_1}$ **&** $\mathbf{c_2}$**:** acceleration positive constants for individual particles.

rand: regularly distributed random value between 0 and 1.

Inertia weight (w) that is mentioned in equation (19) can be mathematically modeled according to the following equation:

$$w = w_{max} - \left[\frac{w_{max} - w_{min}}{T}\right] * t \quad (20)$$

where

w_{max}= initial or max. weight = 0.9.

w_{min} = final or min. weight = 0.4.

T = maximum number of iteration.

t = currently iteration number.

Inertia weight (w) should be in the maximum value to assist the global search while and at the minimum value to assist the local search. By decreasing the inertia weight gradually from a maximum to a minimum range during the cycle of the search, the matching between global and local search will be achieved then the PSO run offers the best performance compared with invariable inertia weight settings.

If a particle exceeded the velocity limits, the algorithm will be set the particle velocity equal to the limit, as follow:

$$v_{id}^{t+1} = max.v_{id} \quad \text{if } v_{id}^{t+1} > max.v_{id} \quad (21)$$

$$v_{id}^{t+1} = min.v_{id} \quad \text{if } v_{id}^{t+1} < min.v_{id} \quad (22)$$

****Particle update*** $\mathbf{s_{id}^{t}}$ **:**

Update the position s_{id}^{t+1} for each particle using the updated velocities in (19) as in the following equation:

$$s_{id}^{t+1} = s_{id}^{t} + v_{id}^{t+1} \quad (23)$$

where

$\mathbf{s_{id}^{t}}$ **:** present position (searching point) of particle id at $(t)^{th}$ iteration.

s_{id}^{t+1}: new position (searching point) of particle id at (t+1)th iteration.

If a particle exceeds the allowable position limits in any dimension, the algorithm will be set the position of particle at the suitable limit, as follow:

$$s_{id}^{t+1} = \max . s_{id} \quad \text{if } s_{id}^{t+1} > \max . s_{id} \qquad (24)$$
$$s_{id}^{t+1} = \min . s_{id} \quad \text{if } s_{id}^{t+1} < \min . s_{id} \qquad (25)$$

***Local best position updating ($pbest_{i,d}{}^{t}$)**

Best position for the individual particle ($pbest_{id}{}^{t}$) can be updating based on its minimum fitness function. An update being in two stages

Firstly, the fitness function $f\left(s_{id}^{t+1}\right)$ for the updated position s_{id}^{t+1} (the new position) are calculated. Secondly:

If $f\left(s_{id}^{t+1}\right) < f(pbest_{id}^{t})$ then

$$f\left(s_{id}^{t+1}\right) = f\left(s_{id}^{t+1}\right) \ \& \ pbest_{id}^{t+1} = s_{id}^{t+1} \qquad (26)$$

If $f\left(s_{id}^{t+1}\right) \geq f(pbest_{id}^{t})$ then

$$f\left(s_{id}^{t+1}\right) = f(pbest_{id}^{t}) \ \& \ pbest_{id}^{t+1} = pbest_{id}^{t} \qquad (27)$$

*** Global best position updating ($gbest_{i}^{t}$)**

Firstly, based on the minimum fitness function for each control variable, the new global best position ($gbest_{i}^{t+1}$) are calculated. Secondly:

If($gbest_{i}^{t+1}$) $< f(gbest_{i}^{t})$ then

$$f(gbest_{i}^{t+1}) = f\left(gbest_{i}^{t+1}\right) \ \& \ gbest_{i}^{t+1} = gbest_{i}^{t+1} \qquad (28)$$

If $f(gbest_{i}^{t+1}) \geq f\left(gbest_{i}^{t}\right)$ then

$$f(gbest_{i}^{t+1}) = f\left(gbest_{i}^{t}\right) \ \& \ gbest_{i}^{t+1} = gbest_{i}^{t} \qquad (29)$$

****Stopping criteria***

The search will stopping if the number of iterations reach the maximum iteration T.

The modification of a searching point by PSO can be determined according to the flow chart in Figure (1).

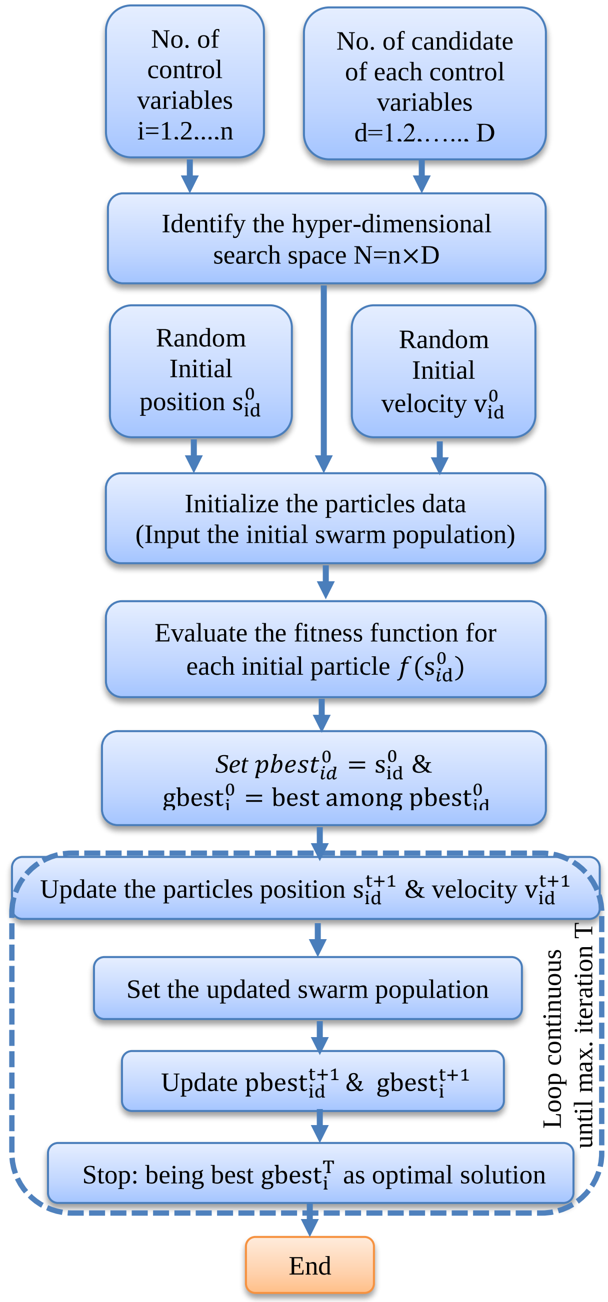

Figure (1)
Particle Swarm Optimization (PSO)

Result and Discussion

Two systems: IEEE 6 bus [25] and the Iraqi Extra High Voltage 400 kV Grid 28 bus [21] are used for identified the optimal value of the Voltage Stability Index (VSI) based on Particle Swarm Optimization (PSO). In this article the IEEE 6 bus in figure (2) has four type of the control variables: generator voltage magnitude, active power of PV bus, shunt VAR of capacitance bank and tap changing of the transformer while the Iraqi Extra High Voltage 400 kV Grid 28 bus has only two type of control variables: generator voltage magnitude and active power of PV bus as shown in figure (4).

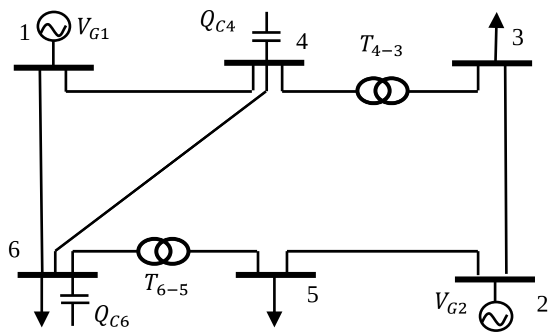

Fig. (2) The IEEE 6 bus system

Table (2) shows the Voltage Stability Index VSI of the IEEE 6 bus for the initial data (Tables A.2, A.2 , A.3 and A.4 in the Appendix). Also this table presents the optimal VSI based on PSO after 50 iteration for different candidate number D (different swarm population as in Table 1). The maximum optimal VSI that located at bus 3 for the candidate D=11 is the best over D=4 and D=20.

Bus 3 has the maximum VSI according to the initial case, while bus 3 and 5 have the maximum VSI after the optimization process based on PSO technique (optimal case). Also this Table shows that's PSO reduce the maximum value of the VSI from the initial value at 0.2878 to the optimal value at 0.2288.

Table (3) show that's IEEE 6 bus has 7 control variables: two generator voltages magnitude, one active power of PV bus, two VAR of capacitance bank and two tap changing of the transformers, also this table shows the minimum, maximum, initial and optimal values of these control variables based on PSO for minimum VSI.

Table (4) shows that the proposed algorithm PSO has better result over the other optimization techniques.

Figure (3) shows the VSI of the IEEE 6 bus at the load buses for the initial and optimal case.

This figure show that's bus 3 has maximum VSI before PSO optimization (initial) while bus 3 and 5 have the maximum VSI with the reduction after PSO optimization.

TABLE 2
VOLTAGE STABILITY INDEX VSI OF IEEE 6 BUS WITH DIFFERENT CANDIDATE D

Bus No.	Initial VSI	No. of candidate D for Optimal VSI		
		D=4	D=11	D=20
3	0.2878	0.2290	0.2288	0.2312
4	0.2111	0.1763	0.1766	0.1756
5	0.2775	0.2290	0.2288	0.2311
6	0.2575	0.2162	0.2166	0.2145

TABLE 3
CONTROL VARIABLES OF THE IEEE 6 BUS BASED ON PSO for VSI=0.2288 (D=11)

Control variables	Min. limits	Max. limits	Initial case	Optimal case
V_{G1}	1.0	1.1	1.05	1.1000
V_{G2}	1.0	1.15	1.1	1.1500
T_{6-5}	0.9	1.1	1.10	0.9000
T_{4-3}	0.9	1.1	1.025	0.9520
Q_{C4}	0	5	0	5.0000
Q_{C6}	0	5.5	0	5.5000
P_{G2}	10	100	50	43.213

TABLE 4
VSI OF IEEE 6 BUS

Technique	Optimization technique	Max. VSI
[25]	PSO	0.2340
[26]	Strength Pareto Evolutionary Algorithm	0.2304
Authors	Genetic Algorithm	0.2310
Proposed	PSO	0.2288

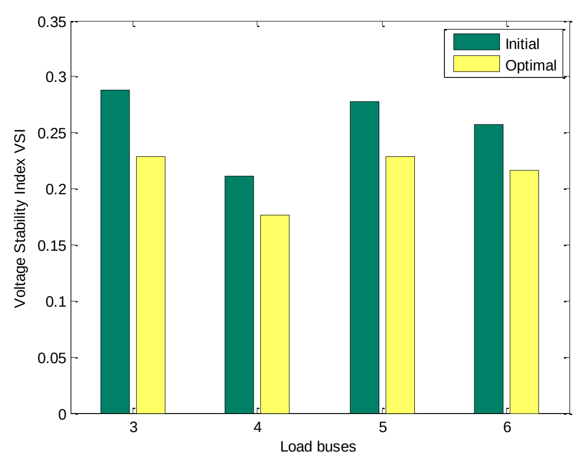

Figure (3) The initial and optimal VSI of the IEEE 6 bus

The Iraqi Extra High Voltage 400 kV Grid in figure (4) has 27 control variables: 14 generator voltage magnitude and 13 generator active powers.

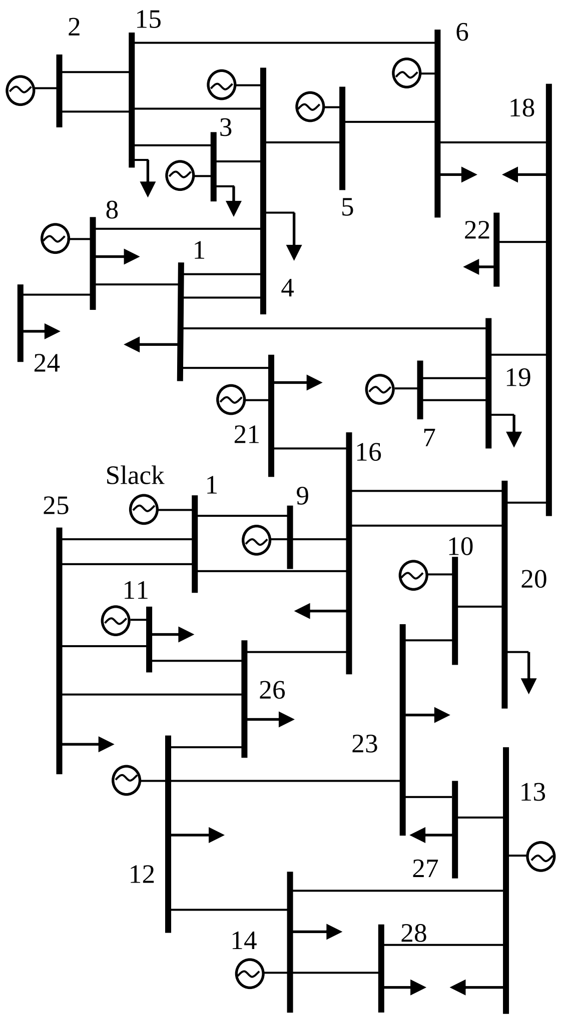

Figure (4) The Iraqi Extra High Voltage 400 kV Grid 28 bus

Table (5) shows the Voltage Stability Index VSI of the Iraqi Grid for the initial data (Tables A.5 and A.6 in the Appendix). This Table shows also the optimal VSI based on Particle Swarm Optimization PSO after 50 iteration for different candidate number D (different swarm population as in Table 1). The optimal maximum VSI for the three candidate D=4, D=11, D=20 is equally.

The best o-ne is at candidate D=4 because it take less time through the execution the program (less swarm population). Table (5) show that's the maximum VSI at the initial case before the optimization is 0.0886 at bus 27 (AMR4) and this value is reduced to the optimal value at 0.074 according to the PSO optimization technique at bus 27 also.

TABLE 5
VOLTAGE STABILITY INDEX VSI OF THE IRAQI EXTRA HIGH VOLTAGE 400 BUS kV WITH DIFFERENT CANDIDATE D

Bus No.	Bus Name	Initial case	No. of candidate D for Optimal VSI		
			D=4	D=11	D=20
15	MSL4	0.0260	0.0247	0.0242	0.0233
16	BGS4	0.0193	0.0168	0.0166	0.0175
17	BGW4	0.0432	0.0375	0.0367	0.0397
18	BGE4	0.0319	0.0272	0.0272	0.0290
19	BGN4	0.0110	0.0094	0.0093	0.0101
20	AMN4	0.0256	0.0221	0.0220	0.0232
21	BGC4	0.0393	0.0342	0.0336	0.0359
22	DYL4	0.0406	0.0347	0.0347	0.0369
23	KUT4	0.0474	0.0404	0.0404	0.0404
24	QIM4	0.0338	0.0288	0.0288	0.0302
25	BAB4	0.0095	0.0084	0.0084	0.0087
26	KDS4	0.0236	0.0207	0.0206	0.0216
27	AMR4	0.0886	0.0740	0.0740	0.0740
28	BSR4	0.0133	0.0112	0.0112	0.0112

Figure (5) shows the VSI of the Iraqi Extra High Voltage 400 kV Grid at the load buses for the initial and optimal case. This figure show that's bus 27 (AMR4) has the maximum Voltage Stability Index before and after the optimization process.

Table (6) show that's, the Iraqi Grid has 27 control variables: 14 generator voltages magnitude and 17 active power of PV bus, also this table shows the minimum, maximum, initial and optimal values of the control variables based on PSO at D=4 for minimum VSI

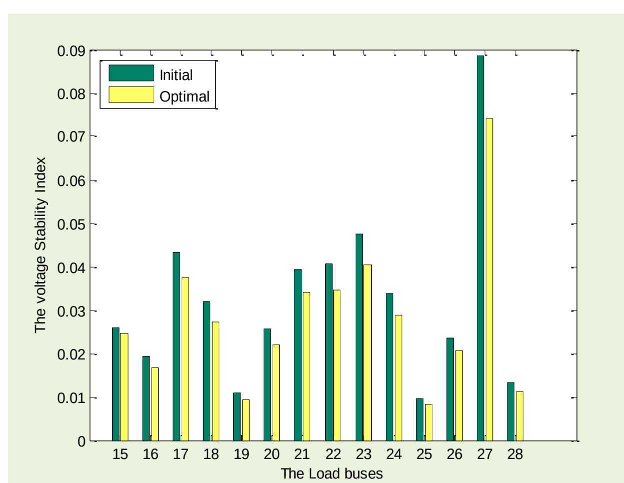

Figure (5) The initial and optimal VSI of the Iraqi Extra High Voltage Grid 400 kV

TABLE 6

CONTROL VARIABLES (C.V.) OF THE IRAQI EXTRA HIGH VOLTAGE 400 kV GRID

Name of C.V.	Min. limits	Max. limits	Initial C.V.	Optimal C.V.
V_{G1}	1.00	1.10	1.0400	1.1000
V_{G2}	1.00	1.10	1.0150	1.0350
V_{G3}	1.00	1.10	1.0100	1.0391
V_{G4}	1.00	1.10	1.0200	1.0455
V_{G5}	1.00	1.10	1.0200	1.0000
V_{G6}	1.00	1.10	1.0170	1.0698
V_{G7}	1.00	1.10	1.0100	1.1000
V_{G8}	1.00	1.10	1.0200	1.1000
V_{G9}	1.00	1.10	1.0200	1.1000
V_{G10}	1.00	1.10	1.0300	1.1000
V_{G11}	1.00	1.10	1.0250	1.0906
V_{G12}	1.00	1.10	1.0200	1.1000
V_{G13}	1.00	1.10	1.0100	1.1000
V_{G14}	1.00	1.10	1.0096	1.1000
P_{G2}	130	988	690	130.00
P_{G3}	250	750	250	472.85
P_{G4}	120	1320	406	120.00
P_{G5}	120	636	591	120.00
P_{G6}	50	260	240	50.00
P_{G7}	180	910	735	360.32
P_{G8}	60	660	203	114.96
P_{G9}	50	500	369	169.31
P_{G10}	250	1320	478	339.88
P_{G11}	250	1250	600	830.97
P_{G12}	210	840	775	840.00
P_{G13}	100	440	332	440.00
P_{G14}	50	250	208	250.00

5. Conclusion

Identify the most critical load buses which have the maximum Voltage Stability Index (VSI) is very important and effective in power system to represent the voltage collapse of the busses (worse case). This article presents the Particle Swarm Optimization (PSO) to adjust the control variables for minimize the fitness function: the Voltage Stability Index (collapse case).

Two systems are used in this article: the first one is the IEEE 6 bus and the second is the Iraqi Extra High Voltage 400 kV Grid 28 bus. The buses 3 in IEEE 6 bus system and bus 27 (AMR4) in the Iraqi Extra High Voltage 400 kV Grid are the most critical buses that have the highest value of the Voltage Stability Index respectively.

PSO technique reduce the Voltage Stability Index by 20.5% in IEEE6 bus and 16.47% in the Iraqi Extra High Voltage 400 kV Grid.

The article present a specific mechanism for prepared the swam population.

The proposed algorithm present PSO at different swarm population (different candidate of each control variables D) and provides better results when compare with other optimization techniques.

All the programs in this article are written by the authors on Matlab software.

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Appendix

Table A.1 State variable constraints of IEEE 6 bus

	Minimum limit	Maximum limit
PQ bus voltage	0.9	1.10

Table A.2 Line data of IEEE 6 bus

Branch No.	From bus	To bus	Branch impedance p.u	Transformer Tap
1	1	6	0.123+j0.518	1
2	1	4	0.080+j0.370	1
3	4	6	0.097+j0.407	1
4	5	2	0.282+j0.640	1
5	2	3	0.723+j1.050	1
6	6	5	0.000+j0.300	1.025
7	4	3	0.000+j0.133	1.100

Table A.3 Bus data of IEEE 6 bus

Bus No.	Bus type	Bus voltage p.u	Angle degree	Load		Generator		Shunt injection capacitance Q_C MVAR
				P_L MW	Q_L MVAR	P_G MW	Q_G MVAR	
1	Slack	1.05	0	0	0	0	0	0
2	PU	1.10	0	0	0	50	0	0
3	PQ	1	0	55	13	0	0	0
4	PQ	1	0	0	0	0	0	0
5	PQ	1	0	30	18	0	0	0
6	PQ	1	0	50	5	0	0	0

Table A.4 State variable constraints of the Iraqi Extra High Voltage 400 kV

	Minimum limit	Maximum limit
PQ bus voltage	0.9	1.10

Table A.5 Bus data of the Iraqi Extra High Voltage 400 kV

Bus No.	Bus Name	Bus type	Bus voltage p.u	Load		Generator	
				P_L MW	Q_L MVAR	P_G MW	Q_G MVAR
1	MUSP	Slack	$1.040∟0^o$	206	56	0	0
2	MMDH	PV	$1.015∟0^o$	0	0	690	0
3	NENWG	PV	$1.010∟0^o$	150	75	250	0
4	BAJP	PV	$1.015∟0^o$	125	93	406	0
5	BAJG	PV	$1.020∟0^o$	0	0	591	0
6	KRK4	PV	$1.017∟0^o$	130	10	240	0
7	QDSG	PV	$1.010∟0^o$	0	0	735	0
8	HDTH	PV	$1.020∟0^o$	200	50	203	0
9	MUSG	PV	$1.020∟0^o$	0	0	369	0
10	KUTP	PV	$1.030∟0^o$	0	0	478	0
11	KHRPG	PV	$1.025∟0^o$	0	0	600	0
12	NSRP	PV	$1.020∟0^o$	423	101	775	0
13	HRTHP	PV	$1.010∟0^o$	155	72	332	0
14	KAZG	PV	$1.0096∟0^o$	200	101	208	0

15	MSL4	PQ	$1\angle 0^{o}$	650	302	0	0
16	BGS4	PQ	$1\angle 0^{o}$	0	0	0	0
17	BGW4	PQ	$1\angle 0^{o}$	576	302	0	0
18	BGE4	PQ	$1\angle 0^{o}$	849	295	0	0
19	BGN4	PQ	$1\angle 0^{o}$	413	149	0	0
20	AMN4	PQ	$1\angle 0^{o}$	127	56	0	0
21	BGC4	PQ	$1\angle 0^{o}$	50	182	0	0
22	DYL4	PQ	$1\angle 0^{o}$	84	22	0	0
23	KUT4	PQ	$1\angle 0^{o}$	260	108	0	0
24	QIM4	PQ	$1\angle 0^{o}$	109	40	0	0
25	BAB4	PQ	$1\angle 0^{o}$	308	185	0	0
26	KDS4	PQ	$1\angle 0^{o}$	213	152	0	0
27	AMR4	PQ	$1\angle 0^{o}$	311	161	0	0
28	BSR4	PQ	$1\angle 0^{o}$	455	145	0	0

Table A.6 Line data of the Iraqi Extra High Voltage 400 kV

No. of branches	From bus	To bus	Resistance p.u	Reactance p.u	Half line charging Susceptance (p.u)	Length of the line km
1	15	2	0.00144	0.01177	0.364390	63
2	15	2	0.001440	0.011770	0.364390	63
3	15	3	0.001777	0.016154	0.478634	82
4	15	4	0.004200	0.03437	1.064260	1
5	15	6	0.004984	0.045310	1.342510	230
6	3	4	0.003294	0.029940	0.887224	152
7	4	5	0.000020	0.000200	0.005840	1
8	4	17	0.004830	0.043930	1.301650	223
9	4	17	0.004960	0.045110	1.336670	229
10	4	8	0.003450	0.031320	0.928080	159
11	5	6	0.001800	0.016350	0.484470	83
12	6	18	0.004960	0.045110	1.333667	233
13	17	19	0.000930	0.008470	0.250990	43
14	17	21	0.000607	0.005516	0.163436	28
15	17	8	0.005049	0.045901	1.360021	233
16	16	20	0.000820	0.007490	0.221810	38
17	16	20	0.000820	0.007490	0.221810	38
18	16	21	0.000953	0.008660	0.256820	44
19	16	1	0.001220	0.010150	0.318970	53.5
20	16	9	0.001094	0.009106	0.286176	48
21	16	26	0.003080	0.027950	0.828270	141.9
22	18	19	0.000290	0.002620	0.077630	13.3
23	18	20	0.000430	0.003940	0.116740	20
24	18	22	0.000870	0.007880	0.233480	40
25	19	7	0.000150	0.001380	0.040860	7
26	20	10	0.002427	0.022064	0.653744	112
27	23	10	0.001734	0.015760	0.466960	80
28	23	12	0.004320	0.039280	1.163900	199.4
29	23	27	0.004790	0.043540	1.289980	221
30	8	24	0.002920	0.023910	0.740350	128
31	1	9	0.000125	0.001043	0.032791	5.5

32	1	25	0.000810	0.006730	0.211650	35.5
33	1	25	0.000810	0.006730	0.211650	35.5
34	25	11	0.000898	0.007360	0.227000	39.4
35	25	26	0.002330	0.019350	0.608120	102
36	11	26	0.002267	0.018500	0.575200	99.45
37	26	12	0.003830	0.034850	1.032560	176.9
38	12	14	0.004390	0.039930	1.183160	202.7
39	27	13	0.002900	0.026400	0.782160	134
40	13	14	0.001180	0.010760	0.318700	54.6
41	13	14	0.001180	0.010760	0.318700	54.6
42	3	28	0.000672	0.006107	0.180947	31
43	14	28	0.000563	0.005122	0.151762	26