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Security Monitoring against Voltage Collapse through Ant Colony System

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Abstract—*Modern power systems are operated much closer to their stability limits owing to economical and environmental constraints. Deregulated operation has increased variability of loading patterns many folds compared to limited operating scenarios of vertically integrated power system. In the existing operational environment, online monitoring against possible voltage collapse has become all the more important. In the reported work voltage collapse margin (active and reactive) is estimated using ant colony optimization algorithm. The technique is inspired by foraging habits of ants. It has an edge over the existing method that it can optimize many independent parameters simultaneously. To evaluate the performance of this proposed method, IEEE 14 and IEEE 30 bus system is considered. Results obtained from study and conclusions drawn are also presented*

1. INTRODUCTION

In the current scenario, power demand levels in power system are continuously increasing and showing no sign of slowing down. As a result of increasing demand, bus voltages require more support from generator in order to maintain the voltage within specified limit. Due to economical and environmental constraint, system is not able to support this increasing demand, system bus voltage start to decrease suddenly below an unacceptable value and voltage instability occurs. Voltage collapse is culmination of voltage instability that can leads to large blackout.

There have been many studies conducted to identify and detect the closest voltage collapse point corresponding to current operating point, like direct method [1], [2] but it does not remain well condition at or around the critical point. The continuation power flow method [3] was introduced as an alternative to direct method, to-deal with numerical difficulties but limitation is that loading scenario remains in fixed direction at each of load buses. Other techniques based on genetic algorithm (GA) [4] was developed to detect the optimal solution but not feasible for practical system because loading variable λ^* is a scalar value means uniform loading of each buses. In this study, an algorithm based on Ant colony system is used. Ant colony system (ACS) [5], [6] is developed by M. Dorigo in 1996. It is inspired by foraging habits of ants in nature as described in section. It has major advantage of optimizing a large number of loading variables simultaneously, means λ^* becomes a vector of scalar values each associated with a single system parameter. So it is very fast computing and efficient method to detect the nearest voltage collapse point. Two case study involving IEEE 14 bus and IEEE 30 bus system is considered to describe the performance and advantage of proposed method.

2. VOLTAGE COLLAPSE

In electric power system, flow of electric power can be represented by set of power flow equation at equilibrium point containing load variable λ and state variable z.

$$\begin{aligned} &F(z,\lambda)=0 \\ &z=(|V_2|,\delta_2,........|V_n|,\delta_n) \\ &\lambda=(P_2,Q_2,........P_n,Q_n) \end{aligned} \quad (1)$$

Here (z_0,λ_0) is defined as current operating point. The loading variable λ_0 is obtained through load flow iterative technique, such as Gauss Siedel and Newton Raphson method. It is also assumed that λ_0 is chosen so that jacobian matrix $D_zF(z,\lambda)$ of the power system model evaluated at the point (z_0,λ_0) is nonsingular. Voltage collapse is commonly tied to saddle node bifurcation. Bifurcation occurs when slowly changing parameter causes sudden change to state variable [6]. In case of voltage collapse, slowly varying parameter λ^* and state variable that change drastically is bus voltage magnitude. Parameter λ^* is a scalar loading parameter which is applied to power system for load buses.

$$\lambda=\lambda^*\cdot\lambda_0 \quad (2)$$

In case of voltage collapse, bifurcation occurs at singularity point of jacobian matrix. Parameter λ^* applied to power system that result an equilibrium point (z_x,λ_x), such that jacobian is singular. At (z_x,λ_x) point jacobian matrix will have unique zero Eigen value with normalized right and left eigenvector v and w. Here our objective is to detect the point nearest to voltage collapse point (z_x, λ_x), that should be closest to current operating point, so every time singular value decomposition is needed to check the singularity of jacobian of the power system.

3. SINGULAR VALUE DECOMPOSITION

Singular value decomposition, or SVD, is a matrix decomposition method which is used many times throughout this study [7]. When $n \times m$ matrix A is decomposed using SVD, it is reduced to a diagonal matrix, Σ, by pre- and post-multiplying it by unitary, orthogonal matrices. That is, if Σ has a zero diagonal element, then A is not of full rank.

In matrix notation, the $n \times m$ matrix A decomposed through singular value decomposition (SVD) may be expressed as-

$$A = U \cdot \Sigma \cdot V^T \tag{3}$$

The diagonal matrix Σ is a diagonal $p \times p$ matrix where $p = \min\{n, m\}$. If the rank of A is r, then the diagonal elements of Σ are ordered as

$$\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_r \geq \sigma_{r+1} = \ldots.. = \sigma_p = 0$$

and are called the singular values of matrix A.

In particular, the load flow Jacobian $J(X)$ will be analyzed using SVD in order to determine voltage collapse. It has been shown in [10] that $J + \Delta J$ is nonsingular if $\|\Delta J\| \langle \|J^{-1}\|^{-1} = \sigma_{\min}(J)$.

4. ANT COLONY SYSTEM

Ant colony system algorithm is introduced by M. Dorigo in 1996. The ACS metaheuristic is a multiagent system in which the behavior of each single agent called artificial ant, takes inspiration from the foraging habit of ants in nature. They used stigmergy type of communication in which the agents are stimulated by the performance, whatever they achieved. Ants lay down some quantity of substance called pheromone in the way to food source. To communicate the information among the individuals, regarding the path is decided by pheromone trail. The quantity of pheromone depends upon the length of food source and quality of discovered food source. Future ants in the colony perceive the presence of pheromone and tend to follow the path where concentration is higher. Thus, it reinforces the pheromone trail of the favorable path.

State transition rule used by ant in ant colony system, is given by (4), which gives the probability with which ant k in city i chooses to move to the

$$P_{i,j}^{k} = \begin{cases} \max\{[\tau(i,j)]^{\alpha} \cdot [\eta(i,j)]^{\beta}\} & q \leq q_0 \quad \text{biased} \\ P^{*} & \text{Otherwise exploration} \end{cases} \tag{4}$$

$$P^{*} = \frac{[\tau(i,j)]^{\alpha} \cdot [\eta(i,j)]^{\beta}}{\sum_{k \in allowedcity} [\tau(i,k)]^{\alpha} \cdot [\eta(i,k)]^{\beta}} \tag{5}$$

Where τ is the pheromone, η is the inverse of the distance between city i and city j, α and β is pheromone level importance and journey cost importance respectively.

Pheromone levels are updated to Pheromone levels are updated to increase the pheromone value associated with good solution and decrease with that those associated with bad solution through pheromone evaporation. This happen in two stage; global and local update, global updating rule is applied only to edges which belong to the best ant tour while local updating rule is applied to ants constructing a solution, its mathematical expression is given by (6) and (7) respectively.

$$\tau(i,j) = (1-\rho) \cdot \tau(i,j) + \rho \cdot \Delta\tau(i,j) \tag{6}$$

$$\tau(i,j) = (1-\mu) \cdot \tau(i,j) + \mu \cdot \Delta\tau(i,j) \tag{7}$$

Where

$$\Delta\tau(i,j) = \begin{cases} (L_{gb})^{-1} & \text{if } (i,j) \in \text{Tour done by ant } k \\ 0 & \text{Otherwise} \end{cases} \tag{8}$$

5. VOLTAGE COLLAPSE MARGIN ESTIMATION

In this study, ACS technique is utilized to detect the nearest voltage collapse point corresponding to actual loading of the power system because it has advantage of optimizing the many variables simultaneously. For this we have to create a space graph as shown in Fig. 1, which will define all possible paths for the virtual ants to travel on. This construction graph contains each element of λ^* (loading variable) as stages with the possible value of each element of λ^* for forming the states as shown in Fig.2. Here number of stages will be decided by number of load buses in the system and number of states of each stage is dependent on maximum value of load at each load bus. Once the space graph has been created, interconnection between the state j of k^{th} and state i of stage k^{th+1} are defined and initialized with the initial pheromone level.

Informally, ACS work as follows: m ants are initially distributed on the states of the first stage randomly. They start moving towards only one state of each stage using state transition rule, until each ant has visited each stage. This travelled path of an ant is referred as a solution. This solution generated by a given ant becomes the vector λ^* i.e. (each load buses has its individual loading parameter unlike the other techniques which is based on GA and direct method) not a scalar λ^*.

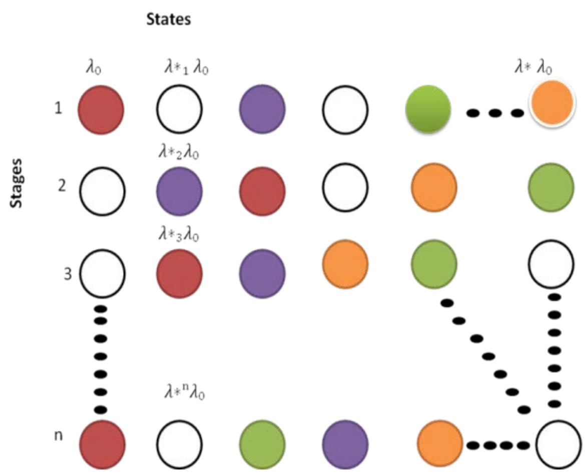

Fig. 1: Construction space graph

To travel on one state of next stage ants follow the transition rule as given in (4) and (5). Where q_0 is exploration factor, its range is $[0,1]$ that determines the balance between exploitation and exploration. Every time an ant in state i of stage k has to choose the state j of stage k^{th+1}, it samples a random number q, which is distributed in $[0,1]$. If $q \le q_0$, it exploits the states which are having the maximum probability, otherwise biased exploration.

Once all ants have generated a solution, fitness of the solution is calculated based on problem specific fitness function. Best solution is compared with the global best solution and updated as required. This process will be repeated predefined no of times or until fitness reaches a predefined value.

6. CASE STUDY AND RESULTS

6.1 IEEE 14 Bus System

The proposed technique is applied to 14 Bus systems. The following parameter is used in the ACS algorithm:

- Number of ants: 10
- Number of iteration: 50
- State maximum value: 0.55(p.u.)

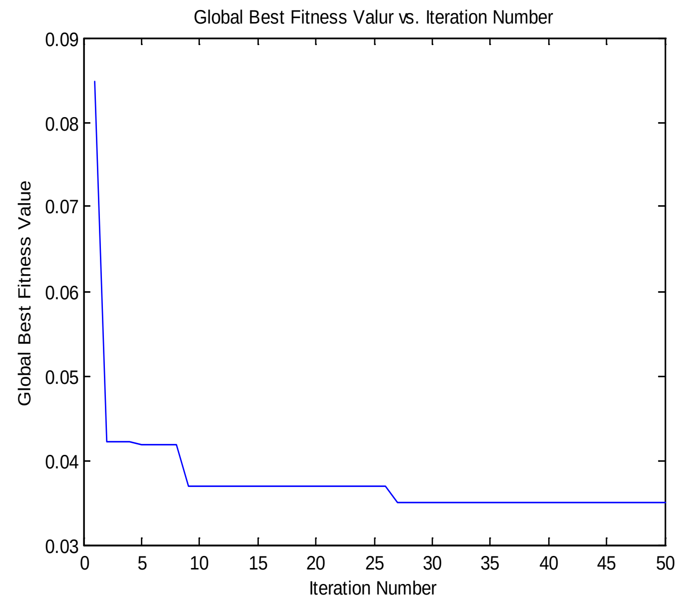

Fig. 2: Global Fitness Function Result (14 Bus Systems)

- State step size: 0.005(p.u.)
- Initial pheromone level: 0.5
- Exploration constant: 0.5
- Pheromone level constant (α): 1
- Journey cost importance (β): 0
- Global pheromone decay constant (μ): 0.1
- Local pheromone update constant (ρ): 0.01

Optimization results are summarized in table I and in Fig. 2.

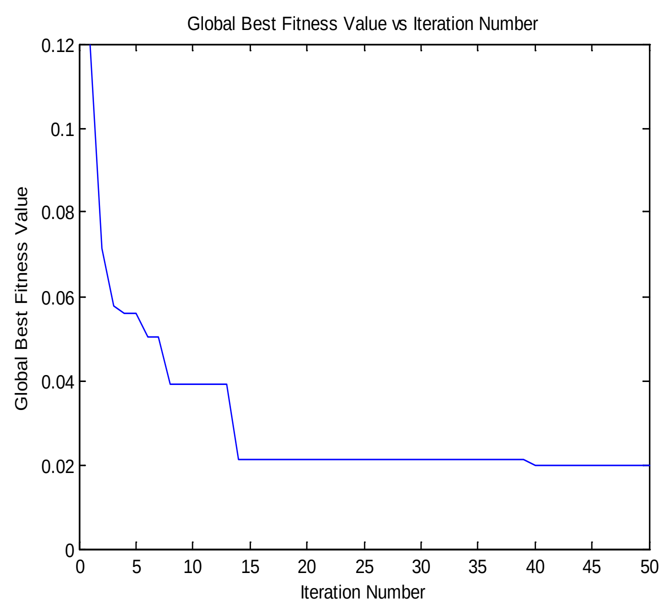

Fig. 3: Global Fitness Function Result (30 Bus -Systems)

It can be seen that buses 9, 10, 11, 14 are identified as a sensitive buses that are approaching voltage collapse due to load increase on the system. Bus 14 is identified as weakest bus with voltage of 0.5106 p.u. System independent parameters corresponding to solution and available power margin are shown in Fig. 5.

Table 1: Result of Nearest Voltage Collapse Point using Ant Colony System (IEEE 14 bus systems)

Bus No.	Voltage Magnitude (p.u.)	Voltage Phase (degree)	Load (M.W.)	Load (MVar)	Generation (M.W.)	Generation (MVar)
1	1.0600	0.0000	0.000	0.000	687.871	146.177
2	0.9950	-14.9403	21.700	12.700	40.000	261.537
3	0.9600	-31.4617	94.200	19.000	-0.000	121.835
4	0.8077	-32.3324	54.800	-46.900	0.000	-0.000
5	0.7863	-30.4727	50.100	7.500	0.000	0.000
6	1.0200	-74.6239	11.200	7.500	0.000	498.765
7	0.7863	-51.1121	0.0000	0.000	-0.000	-0.000
8	1.0400	-51.1121	0.0000	0.000	0.000	149.779
9	0.6455	-63.6253	54.500	47.600	0.000	-0.000
10	0.5924	-69.6827	46.000	48.3.00	0.000	-0.000
11	0.6949	-75.4791	53.000	50.300	0.000	-0.000
12	0.7825	-79.0815	53.600	49.600	0..000	-0.000
13	0.8013	-78.1649	51.500	35.800	0.000	-0.000
14	0.5106	-78.5326	51.400	39.5000	0.000	-0.000

From the results, it can be seen that optimization is capable of finding the loading parameter and the weakest bus that approaching the system to voltage collapse.

6.2 IEEE 30 Bus System

The proposed technique is applied to IEEE 30 Bus system [10]. The following parameter is used in the ACS algorithm:

- Number of ants: 10
- Number of iteration: 50
- State maximum value: $3.5 * \lambda_0$ (current operating point)
- State step size: 0.005(p.u.)
- Initial pheromone level: 0.5
- Exploration constant: 0.5
- Pheromone level constant (α): 1
- Journey cost importance (β): 0
- Global pheromone decay constant (μ):0.1
- Local pheromone update constant (ρ): 0.001

Optimization results are summarized in table II and in Fig. -3. It can seen from results obtained in table II that buses 25, 26, 27, 29, 30 are identified as sensitive buses, but bus 30 is the most sensitive and weakest bus with voltage of 0.5167 p.u. System loading parameter corresponding to the results summarized in table II and available power margin can be seen in fig. 6. This result

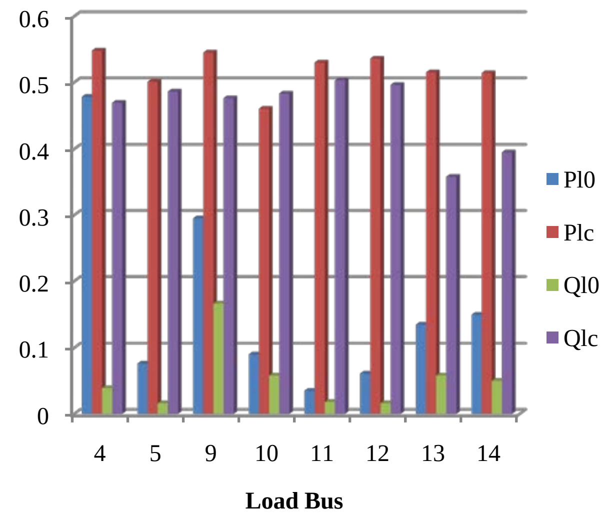

Fig. 5: Estimated bus loading margin (active and reactive) for IEEE 14 bus system

This result is more realistic in comparison to results obtained from other technique.

Where Pl_0, Ql_0 is current active loading point and current reactive loading point, respectively. And Pl_c, Ql_c is point, nearest to voltage collapse point which is obtained through the application of λ^*, respectively.

Table II: Result of Nearest Voltage Collapse Point using Ant Colony System (IEEE 30 bus systems)

Bus No.	Voltage Magnitude (p.u.)	Voltage Phase (degree)	Load (M.W.)	Load (MVar)	Generation (M.W.)	Generation (MVar)
1	1.0600	0.0000	0.000	0.000	646.506	93.039
2	0.9930	-13.5807	21.700	12.700	40.000	132.278
3	0.9115	-21.3746	7.400	1.200	-0.000	0.000
4	0.8919	-26.2780	22.600	1.600	-0.000	0.000
5	0.9600	-31.0652	94.200	19.000	-0.000	93.357

6	0.9013	-30.7199	0.000	0.000	-0.000	0.000
7	0.8940	-33.0562	77.800	30.900	-0.000	0.000
8	0.9600	-32.9637	30.000	30.000	0.000	208.799
9	0.8829	-44.8780	0.000	0.000	-0.000	0.000
10	0.8240	-52.8871	10.800	7.000	-0.000	19.000
11	1.0320	-44.8780	0.000	0.000	0.000	73.966
12	0.8709	-52.1202	36.200	22.500	0.000	0.000
13	1.0210	-52.1202	0.000	0.000	0.000	109.457
14	0.8134	-56.6504	21.200	1.600	0.000	-0.000
15	0.7944	-56.4605	28.200	7.500	-0.000	0.000
16	0.8305	-53.7698	8.500	1.800	0.000	0.000
17	0.8059	-54.3019	29.000	15.800	0.000	0.000
18	0.7647	-58.5460	8.200	0.900	0.000	-0.000
19	0.7558	-58.8460	24.500	8.400	0.000	-0.000
20	0.7698	-57.6421	7.200	0.700	0.000	0.000
21	0.7704	-55.5162	57.500	31.200	0.000	0.000
22	0.7715	-55.4231	0.000	0.000	-0.000	0.000
23	0.7502	-57.8492	8.200	1.600	-0.000	0.000
24	0.7118	-57.7900	23.700	16.700	-0.000	4.300
25	0.6723	-55.7298	0.000	0.000	-0.000	0.000
26	0.5879	-57.7203	8.500	7.300	0.000	0.000
27	0.6904	-53.2301	0.000	0.000	-0.000	0.000
28	0.8828	-32.6633	0.000	0.000	-0.000	-0.000
29	0.5807	-63.4581	7.400	0.900	-0.000	0.000
30	0.5167	-72.3387	30.600	1.900	0.000	-0.000

7. CONCLUSION

In this paper, Ant Colony Optimization based algorithm is used to detect the nearest voltage collapse point corresponding to current operating point. Two case studies involving IEEE 14 bus system and IEEE 30 bus system show that proposed method has advantage of optimizing large no of variable simultaneously. In other technique load is changing in same direction at each load buses but in practical scenario, load can change in either way. So this proposed method is also useful at energy management center for online monitoring of the system against voltage collapse for ever changing loading pattern. Although nearest voltage collapse point is approximate but its accuracy can be increased by reducing increment in load levels. Thus by increasing the number of states, that results in increased execution time. However acceptable level of accuracy can be achieved at reasonable computation burden.

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