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Optimal Power Flow using Ant Colony Search Algorithm to Evaluate Load Curtailment Incorporating Voltage Stability Margin Criterion

K. Lenin, B. Ravindranath Reddy, M. Surya Kalavathi
Electrical and Electronics Engineering, Jawaharlal Technological University Kukatpally,
Hyderabad 500 085, India.

Article Info	ABSTRACT
	This paper proposes a method to compute load curtailment evaluation using ACSA based optimal power flow incorporating voltage stability margin criterion. In a deregulated environment, congestion alleviation could mean load curtailment in certain situations. The utilities would definitely prefer to curtail a load as lower as possible during a viability crisis situation. A criterion based on the voltage stability indicator is them incorporated as an additional constraint into the optimal power flow using ACSA algorithm and it is evaluated in a WSCC 9-bus test system.

Corresponding Author:

K. Lenin,
Research Scholar, Jawaharlal Technological University Kukatpally,
Hyderabad 500 085, India

1. INTRODUCTION

This chapter proposes a method to compute level curtailment evaluation using optimized based on ACSA computation incorporating the steady state voltage stability margin constraints.

A study state voltage stability indicator is first discussed for its applicability as a suitable indicator for representing stability margin from the collapse point the load curtailment formation is then evolved and described into the optimal power flow objective function. A criterion based on the voltage stability indicator is them incorporated as an additional constraint into the optimal power flow using ACSA algorithm and it is evaluated in a WSCC 9-bus test system.

In the recent years voltage stability issues have received considerable focus due to the several voltage stability crisis situations having occurred all around the globe. In the US these incidents have become more complicated with the ongoing process of deregulation. Economic competition, sometimes, results in paying less attention to security features of the overall system. Congestion management has become one of an important issue in the context of deregulation because of the increased demand and competition. In a deregulated environment, congestion alleviation could mean load curtailment in certain situations. The utilities would definitely prefer to curtail a load as lower as possible during a viability crisis situation. However, from the overall system viewpoint, any policy of load curtailment has definitely to incorporate voltage stability margin considerations. Thus, in the emerging deregulation market any control action has to incorporate security features to maintain an acceptable level of system reliability.

A power flow can have any number of operating limit violations. When such situations occur, the violations can be alleviated by appropriate or various corrective actions. The analytical process of evolving this procedure is known as Optimal Power Flow [1]. The current practice is to use the constraints based on

the operating limits imposed by bus voltages, branch flows, power transfers over interfaces, etc. The system troubles in contingency analysis are violations of such constraints. Controls may include generator, real power phase shifter angle, bus load-curtailment or all the three. The objective of the corrective action algorithm is to observe all constraints while minimizing the weighted sum of the control movement. The Newton based approach to OPF was proposed in [2]. In [3] the authors have formulated the OPF extension to take into effect the contingencies that occur in power systems. The non-solvability of the Newton process due to the singularity of the Jacobian matrix is got over by modifying the OPF through load shedding or by relaxing some in-equalities [4].

Methods to understand the voltage instability phenomenon and quantify the stability indices have been reported in works [5, 6, 7]. In [8] a voltage stability indicator has been discussed whose value changes between zero (no load) and one (voltage collapse). The indicator incorporates the effect of all other loads in the system on the evaluation of index at individual load buses. The overall voltage stability of the system could be identified by the largest value of the index evaluated amongst all the load buses. This indicator can also be used as a normalized quantitative measure, for estimation of the voltage stability margin from the operating point. In this paper, the authors have used this capability of the indicator. Works in the direction of developing algorithms to incorporate stability issues into power system operational analysis are going on. The reported work [9] attempts to formulate the incorporation of the transient angle stability, into an ACSA based OPF routine, as an additional constraint.

In this paper the authors have proposed and formulated an ACS algorithm to include the voltage stability margin feature into the load curtailment objective function of an OPF.

2. ACSA PARADIGM
2.1. Behavior of Real Ants

Ant colony search (ACS) studies are inspired from the behavior of real ant colonies that are used to solve function or combinatorial optimization problems. Currently, most work has been done in the direction of applying ACS to combinatorial optimization. The first ACS system was introduced by Marco Dorigo [10], and was called "ant system". Ant colony search algorithms, to some extent; mimic the behavior of real ants. As is well known, real ants are capable of finding the shortest path from food sources to the nest without using visual cues. They are also capable of adapting to changes in the environment; for example, finding a new shortest path once the old one is no longer feasible due to a new obstacle. The studies by ethnologists reveal that such capabilities are essentially due to what is called pheromone trails", which ants use to communicate information among individuals regarding path and to decide where to go. Ants deposit a certain amount of pheromone while walking, and each ant probabilistically prefers to follow a direction rich in pheromone rather than a poorer one.

The process can he clearly illustrated by Figure 1 (a) ants are moving on a straight line that connects a food source to their nest. An ant:
- Ants deposit pheromone while walking.
- Probabilistically prefers to follow a direction rich in pheromone.

This behavior can be explained how ants can find the shortest path that reconnects a line that is broken by an obstacle in Figure 1 (b). On introducing, those ants are just in front of the obstacle and they cannot to continue to go. Therefore they have to choose between turning right or left. Half the ants choose to turn right and the other half choose to turn left. A similar situation arises on the other side of the obstacle Figure 1 (c). Ants choosing the shorter path will more rapidly reconstitute the interrupted pheromone trail compared with those choosing the longer path. Thus, the shorter path will receive a greater amount of pheromone per time unit and, in turn, a larger number of ants will choose the shorter path. Due to this positive feedback, all the ants will rapidly choose the shorter path Figure 1 (d). All ants move at approximately the same speed and deposit a pheromone trail at approximately the same rate. The time to go round the longer side of an obstacle is greater than the shorter. This makes the pheromone trail accumulate more quickly on the shorter side. Ants prefer higher pheromone trail levels causing this accumulation to build up still faster on the shorter path. This behavior of ants can be used to solve optimization problems and in particular the Traveling Salesman Problem (TSP). This is the problem of finding a shortest closed tour, which visits all cities in a given set once. This was the first problem solved by using the ant colony metaphor [10].
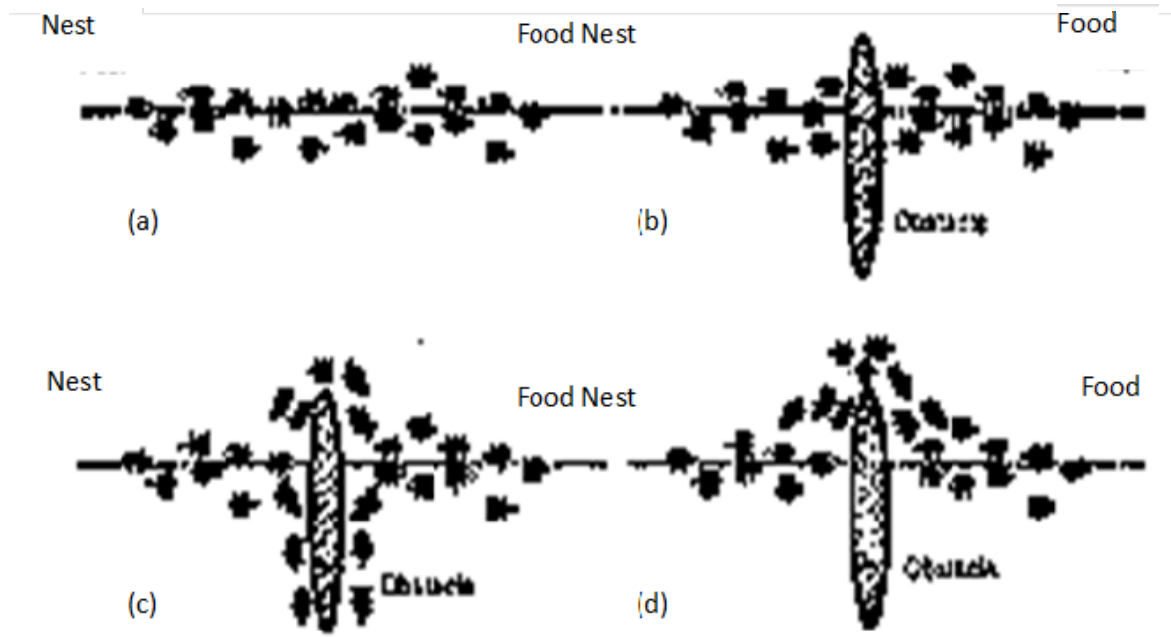
Figure 1. Behaviour of ants
(a) Real ants follow a path between nest and food source. (b) An obstacle appears on the path: ants choose whether to turn left or right with equal probability. (c) Pheromone is deposited more quickly on the shorter path. (d) All ants have chosen the shorter path.

3.   ANT COLONY SYSTEM
3.1. ACS State Transition Rule
In ACS the state transition rule is as follows: an ant positioned on node r chooses the city s to move to by applying the rule given by Eqn. (1). $S =$

$$
\begin{cases}
\text{Amax}_{w \in J_{k(r)}}\{[\tau(r,u)].[\eta(r,u)]\}, \text{ if } q \le q_0, \text{ (exploitation)} \\
S, \text{ otherwise (biased exploration)} \\
\text{where} \\
q \text{ is a random number uniformly distributed in } \quad [0 \ldots 1] \\
q_0 \text{ is a parameter } (0 \le q_0 \le 1)
\end{cases}
$$

(1)

(2)

S is a random variable selected according to the probability distribution given.

The state transition rule used by ant system, called a random-proportional rule, is given by Eqn. (3), which gives the probability with which ant k in city r chooses to move to the city s.

$$
P_k(r,s) = \begin{cases} \dfrac{[\tau(r,s)] \bullet [\eta(r,s)]^{\beta}}{\sum\limits_{\mu \in J_k(r)} [\tau(r,u)] \bullet [\eta(r,u)]^{\beta}}, if \; s \in J_k(r) \\[6pt] 0, otherwise \end{cases}
$$

(3)

where:
  τ is the pheromone
  $_k(r)$ is the set of cities that remain to be visited by ant k positioned on city r (to make the solution feasible)
  β is a parameter, which determines the relative importance of pheromone versus distance ($\beta > 0$)
  $\eta =$ I/δ is the inverse of the distance δ (r,s)

3.2. ACS Global Updating Rule
Global updating is performed after all ants have completed their tours. The pheromone level is updated by applying the global updating rule of Eqn. (4)

$$\tau(r,s) \leftarrow (1-a).\tau(r,s) + \alpha.\Delta\tau(r,s) \tag{4}$$

where:

$\Delta\tau(r,s) =$

$$\begin{cases} (L_{gb})^{-1} & I\,f\,(r,s) \in \text{global-best -four} \\ 0\,, & \text{otherwise} \end{cases}$$

α is the pheromone decay parameter ($0<\alpha\ 1$) L_{gb} is the length of the globally best tour from the beginning of the trial.

3.3. ACS Local Updating Rule
While building a solution of the UC, ants visit edges and change their pheromone level by applying the local updating rule of Eqn. (5).

$$\tau(r,s) \leftarrow (1-p)\tau(r,s) +$$
$$p.\Delta\tau(r,s) \tag{5}$$

where
p is a heuristically defined coefficient ($O<p<1$)
$\Delta\tau(r,s) = \tau_0,$
τ_0 is the initial pheromone level

3.4. ACS Parameter Setting
In this program of the following sections the numeric parameters, except when indicated differently, are set to the following values: $\beta = 2$, $q_o = 0.9$, $\alpha = p = 0.1$, and $\tau_0 = (nL_{nn})^{-1}$, where L_{nn}, is the tour length produced by the nearest neighbor heuristic and n is the number of cities.

4. VOLTAGE STABILITY MARGIN CONSTRAINT
The transmission system can be represented using a hybrid representation, by the following set of equations

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix}$$

V_L, I_L are the voltage and current vectors at the load buses

V_G, I_G are the voltage and current vectors at the generator buses

$Z_{LL}, F_{LG}, K_{GL}, Y_{GG}$ are the sub-matrices of the hybrid matrix H.

The H matrix can be evaluated from the Y bus matrix by a partial inversion, where the voltages at the load buses are exchanged against their currents. This representation can then be used to define a voltage stability indicator at the load bus, namely L_j which is given by,

$$L_j = \left| 1 + \frac{V_{0j}}{V_j} \right| \tag{6}$$

where,

$$V_{0j} = -\sum_{i \in G} F_{ji} V_i \tag{7}$$

The term V_{0j} is representative of an equivalent generator comprising the contribution from all generators.

The index L_j can also be derived and expressed in terms of the power terms as the following.

$$L_j = \left| \frac{\overset{*}{S}_{j+}}{Y_{jj+} V_j^2} \right| \tag{8}$$

where,

$$S_{j+} = S_j + S_{jcorr} \tag{9}$$

* indicates the complex conjugate of the vector

$$S_{jcorr} = \left(\sum_{\substack{i \in Loads \\ i \neq j}} \frac{\overset{*}{Z}_{ji}}{\overset{*}{Z}_{jj}} \frac{S_i}{V_i} \right) V_j \tag{10}$$

$$Y_{jj+} = \frac{1}{Z_{jj}} \tag{11}$$

The complex power term component S_{jcorr} represents the contributions of the other loads in the system to the index evaluated at the node j.

It can be seen that when a load bus approaches a steady state voltage collapse situation, the index L approaches the numerical value 1.0. Hence for an overall system voltage stability condition, the index evaluated at any of the buses must be less than unity. Thus the index value L gives an indication of how far the system is from voltage collapse. This feature of this indicator has been exploited in our proposed algorithm to evolve a voltage collapse margin incorporated OPF routine using ACSA.

In the conventional optimal power flow approach, the objective is to minimize the total amount of load curtailment considering the load flow system constraints like line flow, voltage magnitude, the maximum active and reactive power generation etc. The control variables for the OPF evaluation are the real and reactive power generation of each generation bus and the real and reactive load at each load bus.

5. LOAD CURTAILMENT FORMULATION INCORPORATING VOLTAGESTABILITY MARGIN

The OPF using ACSA problem formulation which we have used is presented herewith. In order to keep the load power factor as a constant, we assume that when a certain amount of real load has been shed at one bus, the corresponding reactive load will also be shed in the same proportions.

Objective: $\displaystyle min \sum_{i=1}^{n} load\_curtail_i$

Subject to

$$P_{gi} - P_{li} - \sum_{j=1}^{n} |V_i| |V_j| (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) = 0 \tag{12}$$

$$Q_{gi} - Q_{li} - \sum_{j=1}^{n} |V_i| |V_j| (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) = 0 \tag{13}$$

$$P_{li} / P_{lireq} = Q_{li} / Q_{lireq} \tag{14}$$

$$0 \le P_{li} \le P_{lireq} \tag{15}$$

$$0 \le Q_{li} \le Q_{lireq} \tag{16}$$

$$|V_i|_{min} \le |V_i| \le |V_i|_{max} \tag{17}$$

$$P_{gi\,min} \le P_{gi} \le P_{gi\,max} \tag{18}$$

$$Q_{gi\,min} \le Q_{gi} \le Q_{gi\,max} \tag{19}$$

$$P_{ij}^2 + Q_{ij}^2 \le S_{ij\,max}^2 \tag{20}$$

$$L_i \le L_{crit} \tag{21}$$

Here,

$$load\_curtail_i = P_{lireq} - P_{li}$$

where,

P_{lireq} : real load demand at bus i

P_{li} : actual real load supply at bus i

n : total number of load flow buses in the system

P_{gi} : real power generation at bus i

Q_{gi} : reactive power generation at bus i

Q_{lireq} : reactive load demand at bus i

Q_{li} : actual reactive load supply at bus i

$|V_i|$: voltage magnitude at bus i

$|V_j|$: voltage magnitude at bus j

G_{ij}, B_{ij} : real/reactive part of the ij[th] element of the bus admittance matrix

δ_{ij} : angle difference between the voltage phasor at bus i and bus j

$P_{gi\,min,}P_{gi\,max}$: minimum/maximum real power generation at generation bus i

$Q_{gi\,min,}Q_{gi\,max}$: minimum/maximum reactive power generation at generation bus i

$|V_i|_{min},|V_i|_{max}$: minimum/maximum voltage magnitude at bus i

P_{ij}, Q_{ij} : real /reactive power flow through transmission line ij

$S_{ij\,max}$: maximum apparent power flow allowable through the ij[th] line L_i is the index L evaluated at the

i th bus other than the generation buses

L_{crit} is the threshold value of the index acceptable for the system

It can be observed in the OPF using ACSA formulation that it includes the power balance equations (7,8) generation limits (13, 14), line loading limits (15), voltage magnitude limits (12). For the load curtailment policy which we have adopted, i.e constant power factor, an additional constraint (5.9) has been added. To incorporate the feature of voltage stability margin into the ACSA based OPFs description the constraint (16) has been included.

6.   THE EFFECT OF INCORPORATING VOLTAGE STABILITY MARGIN ON LOAD CURTAILMENT EVALUATION

Case-1:

The WSCC 9 bus system is used as our test system (Figure 1) to illustrate how load curtailment evaluation is effected by our OPF algorithm which incorporates the steady state voltage stability margin criterion.

The network parameter for the WSCC 9 bus test system, on which we have chosen to implement our algorithm, is as shown in Table 1.
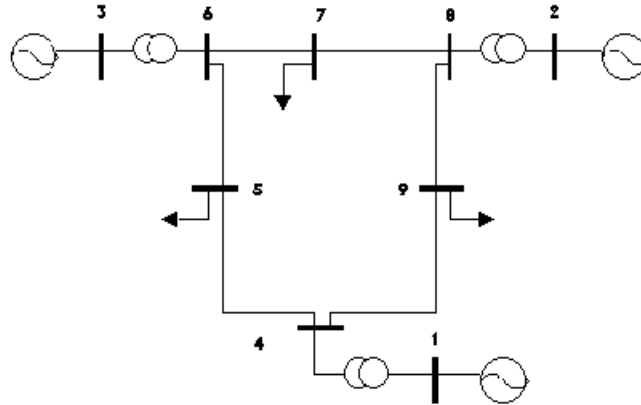

Figure 2. WSCC Nine-bus test system

Table 1. Line Parameters for the WSCC 9-bus System

Line	Resistance (p.u)	Reactance (p.u)	Susceptance (p.u)
1-4	0.0000	0.0576	0.0000
4-5	0.0170	0.0920	0.1580
5-6	0.0390	0.1700	0.3580
3-6	0.0000	0.0586	0.0000
6-7	0.0119	0.1008	0.2090
7-8	0.0085	0.0720	0.1490
8-2	0.0000	0.0625	0.0000
8-9	0.0320	0.1610	0.3060
9-4	0.0100	0.0850	0.1760

For this case we chose the following loading before running the OPF using ACSA based load curtailment algorithm. Load bus 5 was supposedly having a load demand of 150 + j 120 MVA, bus 7 a load demand of 100 + j 35 MVA and load bus 9 having demand of 125 + j 50 MVA. All the generator buses are taken to be PV buses with scheduled voltage at 1.0 p.u. The maximum and minimum acceptable voltage magnitudes at all load buses are taken as 1.1 and 0.9 p.u.

After running OPF using ACSA, without incorporating the voltage stability margin criterion as a constraint, the load curtailment value got is 26.51 +j 21.21 MVA. However, by introducing the voltage stability index L as an additional constraint as proposed in the paper, the curtailment value is 90.57 + j 72.45 if L_{crit} is chosen as 0.1 The curtailment is 36.45 + j 29.16 for L_{crit} taken to be 0.2. This brings out the fact that if one intends to operate the system far away from a possible voltage collapse situation, i.e lower L_{crit} value, it would be at the cost of a large load curtailment. However, if L_{crit} is taken as anywhere above 0.25 the load curtailment value obtained is 26.51 + j 21.21 which is the same as obtained using the conventional OPF algorithm. In this situation the lower limit of the allowable minimum voltage at bus 5 has hit its limit.

Thus, the proposed algorithm is able to incorporate both the features of voltage magnitude constraint and the voltage stability margin criteria. We summarize the results for the above case study in Table 2.

Table 2. Results for the Case-1 Scenario

Constraints Imposed	Curtailment (MVA) at BUS 5
Without Stability Index criteria	26.51 + j 21.21
Index L <= 0.1 at all load buses	90.57 + j 72.45
Index L <=0.2 at all load buses	36.45 + j 29.16
Index L <=0.25 at all load buses	26.51 + j 21.21

Case-2:

The same WSCC system as described in Case I, is used in this scenario too. In this case we will demonstrate how the new proposed algorithm evaluates the load curtailment in situations where line contingencies for a steady operating system occur.

For this case, load bus 5 is supposedly having a load demand of 120 + j 60 MVA, bus 7 a load demand of 100 + j 35 MVA and load bus 9 having demand of 125 + j 50 MVA. All the generator buses are taken to be PV buses with scheduled voltage at 1.0 p.u as before and the maximum and minimum acceptable voltage magnitudes at all load buses are taken to be 1.1 and 0.9 p.u.

When the line 5-6 is down it is observed that there is no load curtailment for the conventional OPF algorithm that does not include the voltage stability margin criteria. However, the curtailment as evaluated by the proposed algorithm taking L_{crit} as 0.2 comes out to be 5.8 + j 2.9 MVA. Similarly if a line 4-5 contingency happens then the curtailment evaluated by conventional OPF is 12.04 + j 6.02 MVA while the load curtailment evaluated by the proposed algorithm comes out to be 18.1 + j 9.05 MVA.

Thus it is observable from the results that incorporating the voltage stability margin feature into the load curtailment policy is effective during contingency conditions too. The result for this case is summarized in Table 3.

Table 3. Results for the Case-2 Scenario

Line Outage	Conventional power flow method Curtailment at BUS 5 (Without L Constraint)	Optimal power flow using ACSA Curtailment at BUS 5 (With L Constraint<=0.2)
5-6 out	No--curtailment	5.8 + j 2.9
4-5out	12.04+ j 6.02	18.1 + j 9.05

The load curtailment evaluation is effected by the proposed incorporation of the voltage stability margin index into the optimal power flow using ACS algorithm. The algorithm is also effective changing contingency evaluation also.

7.   CONCLUSION

The proposed algorithm has been tested on WSCC 9-bus test system. Algorithm reaches a best solution when compared to that of the conventional optimization method.

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