

Optimization of Electric Power System with Transient Stability Constrained

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Abstract

In this paper optimization of electric power system with transient stability constraints is examined using Late Acceptance Hill Climbing Algorithm. The main aim is to minimize the total fuel cost while stability is maintained. The method is tested on two test cases: IEEE 9-bus system and IEEE 30-bus system. The results obtained shows that the system remain stable after the disturbance with minimum cost of operations and this established the effectiveness and efficiency of the algorithms when compared with those obtained by other algorithms given in the literature for the same test system. And the algorithms can be recommended for effective and accurate finding of global monetary and security solution for the power system.

Keywords: Cost; Large disturbance; Algorithm; Optimal Power Flow; Transient Stability.

Introduction

Transient Stability is the ability of power system to return to its normal conditions after a large disturbance due to the general situations like switching on and off of the circuit elements, sudden removal of the load, line switching, fault occurs in the system, sudden outage of a line and so on. Its takes into account constraints arising from the operation of the system under a set of postulated contingencies, Swing equation and limit of rotor angle deviation with respect to Center of Inertia and so on (Sauer and Pai, 1998; Kursat and Ulas, 2013).

Electric power system planning that helps the operator run the system optimally under specific constraints is known as Optimal Power Flow (OPF). It has been studied since its introduction in 1962 by Carpentier to minimize the total unit fuel cost, emission of pollutant, active power losses, and to enhance voltage stability, improve voltage profile under certain constraints. And because OPF is a very large, non-linear mathematical programming problem, it has taken decades to develop efficient algorithms for its solution. Many different mathematical techniques have been employed for its solution (Sauer and Pai, 1998; Abido, 2002).

Over the years, Transient Stability Constraints Optimal Power Flow (TSCOPF) model has been mostly handled as a deterministic optimization problem with pre-assumed conditions while uncertainties in real power grids, such as stochastic load injections, uncertain generations and protection device activation time, are seldom considered. The transient stability constraints consist of additional equality constraints which describes the dynamic behavior of rotor angle after undergoing severe disturbances and the additional inequality constraints which is a stability criterion indicating whether or not the system is stable after contingency. Several swarm intelligence algorithms have been adopted to generate a set of encouraging optimal solutions. Artificial bee colony (ABC) algorithm was used on TSCOPF by Kursat and Ulas (2013) while Kursat *et al.*, (2015), used a chaotic artificial bee colony (CABC) and solved for solution of security and transient stability constrained optimal power flow. (Mo *et al.*, 2007) proposed particle swarm optimization approach and compared with conventional OPF and genetic algorithm based.

Xia *et al.* (2014) divided TSCOPF into OPF and Stability analysis processes and solved iteratively by interior point method (IPM), incorporated TSC for each contingency into OPF model as a single stability constraint.

However, TSCOPF is still a difficult but important problem in power system planning and operation. Late Acceptance Hill Climbing (LAHC) is among the recently proposed algorithms that have shown the capability of producing good results. It is a powerful stochastic search technique that is based on the idea

of delays the comparison by comparing the new candidate solution with the one generated several iterations before. And because of its robustness and effectiveness, it has been successfully adapted, modified, hybridized and parallelized to solve many complex optimization problems like examination timetabling problem, traveling purchase problem. It is noteworthy that no studies have adopted the utilization of the LAHC algorithm for solving the TSCOPF problem (Abido, 2002). It was first introduced by Burke and Bykov (2008) for exam timetabling problems. Turkey *et al.*, (2016) used parallel late acceptance hill-climbing algorithm for the Google machine reassignment problem. Verstichel and Berghe (2009) applied late acceptance algorithm for the lock scheduling problem. Goerler and Schulte (2013) worked on an application of late acceptance hill-climbing to the traveling purchaser problem. Tierney (2013) used late acceptance hill climbing for the liner shipping fleet re-positioning problem, and Yuan *et al.*, (2015) used late acceptance hill-climbing algorithm for balancing two-sided assembly lines with multiple constraints. Bolaji *et al.*, (2018) uses late acceptance hill climbing algorithm for solving patient admission scheduling problem. In this paper, LAHC algorithm was adapted and used for solving Transient Stability Constrained Optimal Power Flow problem.

Model Formulation

The optimal electric power flow problem can be formulated as;

Minimize

$$f(x, u) \quad \text{Total cost} \quad (1)$$

subject to

$$g(x, u) = 0 \quad \text{Power flow equation} \quad (2)$$

$$h(x, u) \leq 0 \quad \text{Transmission line limits} \quad (3)$$

where equations (1), (2) and (3) are respectively the objective function, the equality constraint and inequality constraint.

Formulation of Electric Power System Problem with Transient Stability Constraints

Table 1: Nomenclature

f_i	Total cost
N_g	Total number of generators
P_{gi}	Active power generation of the i^{th} generator
a_i, b_i, c_i	Fuel cost coefficient of the i^{th} generator
N	Total number of system buses
P_{li}	Active load of i^{th} bus
Q_{li}	Reactive load of i^{th} bus
V_i	Voltage magnitude of the i^{th} bus
G_{ij}	Transfer conductance between bus i and j
B_{ij}	Transfer susceptance between bus i and j
θ_{ij}	Voltage angle difference between bus i and j
N_T	Total number of system buses
δ_i	Rotor angle of the i^{th} generator
w_i	Rotor speed of the i^{th} generator
w_0	Synchronous speed
M_i	Moment of inertia of the i^{th} generator
D_i	Damping constant of the i^{th} generator
P_{mi}	Mechanical input power of the i^{th} generator

P_{ei}	Electrical output power of the i^{th} generator
COI	Center of Inertia
$ \delta_i$	The maximum deviation of the i^{th} generator rotor angle from the COI
$-\delta_{COI} _{max}$	
δ_{max}	The maximum rotor angle allowable
N_{PQ}	Number of load buses
V_i^{lim}	Violated upper or lower limits of voltage magnitude
Q_{gi}^{lim}	Violated upper or lower limits of reactive power
P_{slack}^{lim}	Violated upper or lower limits of active power
K_P	Penalty weights of the active power output of the slack bus
K_Q	Penalty weights of the reactive power output of the generator bus
K_V	Load bus voltage magnitude
K_T	Transient stability limit

Using the parameters defined in table 1, the Transient Stability Constrained Optimal Power Flow problem to be considered is formulated as:

Minimize

$$f_i = \sum_{i=1}^{N_g} (a_i + b_i P_{gi} + c_i P_{gi}^2) \quad (4)$$

subject to: equality constraints

$$P_{gi} - P_{li} - V_i \sum_{j=1}^N V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0, \quad i = 1, 2, \dots, N \quad (5)$$

$$Q_{gi} - Q_{li} - V_i \sum_{j=1}^N V_j (G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij}) = 0, \quad i = 1, 2, \dots, N \quad (6)$$

inequality constraints

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}, \quad i = 1, 2, \dots, N_g \quad (7)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}, \quad i = 1, 2, \dots, N_g \quad (8)$$

$$V_i^{min} \leq V_i \leq V_i^{max}, \quad i = 1, 2, \dots, N \quad (9)$$

$$T_i^{min} \leq T_i \leq T_i^{max}, \quad i = 1, 2, \dots, N_T \quad (10)$$

and transient stability constraints

$$\delta_i = w_i - w_0 \quad (11)$$

$$M_i w_i = w_0 (P_{mi} - P_{ei} - D_i w_i) \quad (12)$$

$$\delta_{COI} = \frac{\sum_{i=1}^{N_g} M_i \delta_i}{\sum_{i=1}^{N_g} M_i} \quad (13)$$

$$|\delta_i - \delta_{COI}|_{max} \leq \delta_{max} \quad i = 1, 2, \dots, N_g \quad (14)$$

Fitness Value

A fitness function is a particular type of objective function that is used to summarize, as a single figure of merit, how close a given design solution is to achieving the set aims. Fitness functions are used in genetic programming and genetic algorithms to guide simulations towards optimal design solutions. The fitness value of the generator is calculated by adding the violation at the control variable to the fuel cost.

$$f(x, u) = f_i + K_v \sum_{i=1}^{NPQ} (V_i - V_i^{lim})^2 + K_Q \sum_{i=1}^{N_g} (Q_{gi} - Q_{gi}^{lim})^2 + K_p \sum_{i=1}^{NPQ} (P_{slack} - P_{slack}^{lim})^2 + K_T \sum_{i=1}^{NPQ} (|\delta_i - \delta_{COI}|_{max} - \delta_{lim})^2 \quad (15)$$

Late Acceptance Hill Climbing Algorithm (LAHC)

LAHC is among the newly proposed metaheuristic-based algorithm which belongs to the one-point solution technique. It does not employ external cooling scheduling like other metaheuristic technique, due to its robustness and effectiveness it has been successfully adapted to solve many complex optimization problems (Burke and Bykov, 2017). It consists of a standard hill climbing algorithm with one key difference; the acceptance criterion compares candidate solution to solution iterations ago, in addition to the solution from the previous iteration, (George *et al.*, 2016; Sauer and Pai, 1998). The computational procedure for solving the Transient stability constrained optimal power flow problem is presented as follows.

```
Pseudocode of LAHC
Generate an initial solution  $x$ 
Calculate initial fitness cost  $f(x)$ 
Set the initial number of steps  $l = 0$ 
For  $k \in [0, \dots, l - 1]$ ,  $f(k) - f(x)$ , do
Repeat
construct a candidate solution  $x'$ 
calculate its cost function  $f(x)$ 
 $v = i \text{ mod } l$ 
if  $f(x) \leq f(v)$ 
Then accept  $x'$ 
end if
Insert the cost value into the list  $f(v) - f(x)$ 
increment a number of steps  $l = l + 1$ 
until (termination criteria are met)
end for.
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Numerical Simulation and Results

To verify the effectiveness of the proposed LAHC algorithm, two cases of TSCOPF is tested namely IEEE 9-bus system and IEEE 30-Bus System (figures 1 and 2). The software used (MATPOWER) was developed with MATLAB is run on 2.4GHZ Intel Pentium(R) CPU 2020M processor and 4GB RAM. System bus and branch data are available on: [http://www.ee.washington.edu/research/pstca/\(03:46am; 14/7/18\)](http://www.ee.washington.edu/research/pstca/(03:46am; 14/7/18)).

Case A: WSCC 3-Generator, 9-Bus System

The widely used WSCC 3-Generator, 9-Bus System (figure 1) was first tested using the system data as given in Sauer and Pai (1998) and Kusart et al. (2015). The vector of control variables includes the generated active power, magnitude voltage of generators, transformer tap settings and the capacitor banks. The limits of the generator voltage magnitudes and the voltage magnitude of the other buses are sets as $[0.95p.u., 1.10p.u.]$, δ_{max} is set as 180° while the simulation time is taken as 5s.

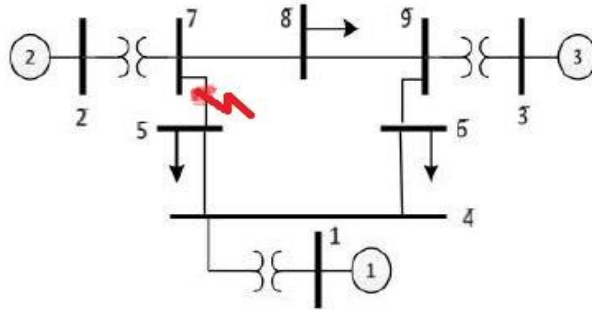


Figure 1: IEEE 9-bus system

The fault case for the test system is a 3-phase to ground fault at bus 7 and in line 7 – 5 in the system. The clearing time of the fault is 0.35s. The results obtained by LAHC algorithm are successful solutions (remain stable after the cost was minimized) while compared to those in literature as in table 2.

Table 2: Optimal solutions of different methods for WSCC 3-Generator, 9-Bus System

Parameters	D.E	G. A	EPSO	IGSO	ABC	LAHC
G1 (MW)	130.94	120.12	118.55	113.66	117.69- j65.51	118.35
G2 (MW)	94.46	105.27	104.22	96.36	105.89- j41.88	98.25
G3 (MW)	93.09	92.55	95.19	88.11	94.23-j56.83	97.22
V1 (p.u)	0.959	1.050	1.048	0.994	1.025	0.954
V2 (p.u)	1.014	1.043	1.045	1.046	1.070	1.010
V3 (p.u)	1.047	1.037	1.041	1.050	1.070	1.024
Min. Cost(/hr)	1140.06	1134.37	1133.99	1141.63	1133.18	1133.09
Max. Cost(/hr)	1140.65	1136.21	1134.61	1141.77	1138.80	1138.25
Avg. Cost(/hr)	1141.57	1141.82	1135.67	1141.11	1135.99	1135.67

From the result, the system remains stable after the disturbance (it didn't go beyond $\delta_{max} = 180^\circ$).

Case B: IEEE 9-Generator, 30-Bus System

The IEEE 30-bus system consists of 41 transmission lines, 9-generators and 4-transformers (figure 2). The line and bus data are adopted from Kursat (2015). The total load demand is 189.2 MW for active load and 107.2 MVar for the reactive load. The vector of control variables includes the generated active power, magnitude voltage of generators, transformer tap settings and the capacitor banks. The IEEE 30-bus system was solved using the proposed LAHC approach. The fault case studied for the test system is single contingency consisting of a 3-phase to ground fault at bus 2 of line 2-5.

Case A: The fault clearing time is taken as 0.18s δ_{max} is set as 100° and simulation period is 5secs.

Case B: The fault clearing time is taken as 0.35s δ_{max} is set as 120° and simulation period is 5secs. All the generators remain stable during the simulation period and the result obtained for the proposed algorithm were compared with those in the literature.

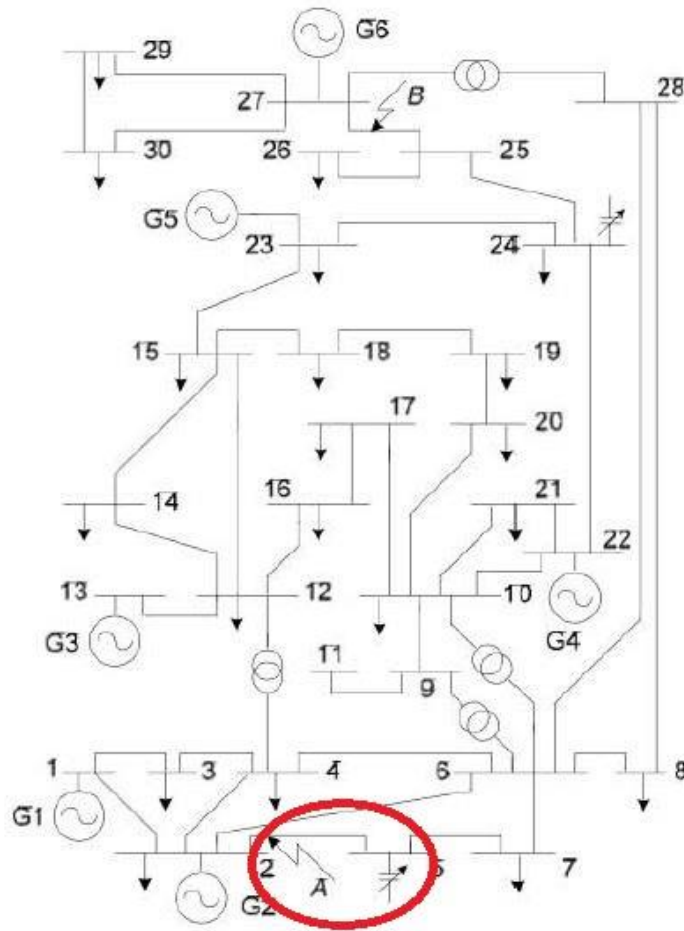


Figure 2: IEEE 30-Bus System

Table 3: Optimal Solutions of different methods for a IEEE 30-Bus System

PARAMETERS	G.A	PSO	EPNN	ABC	LAHC
Pg1 (MW)	41.88	43.63	48.95	42.65	46.35
Pg2 (MW)	56.38	58.05	38.41	60.14	62.24
Pg3 (MW)	22.94	23.29	23.34	17.96	19.35
Pg4 (MW)	37.63	32.49	24.65	24.68	26.29
Pg5 (MW)	16.70	17.04	17.61	15.00	18.53
Pg6 (MW)	16.53	17.54	38.99	31.64	15.65
T1 (p.u)	1.01	1.01	1.01	1.0104	1.02
T2 (p.u)	0.95	0.96	0.98	1.0115	1.011
T3 (p.u)	1.00	1.01	1.03	0.9822	0.995
T4 (p.u)	0.97	0.97	1.04	0.9968	1.02
Min. Cost(/hr)	585.62	585.17	585.12	576.76	576.69
Max. Cost(/hr)	585.71	585.69	586.73	581.98	582.36
Avg. Cost(/hr)	585.66	585.34	585.84	579.37	579.53

From the result, the system remains stable after the disturbance.

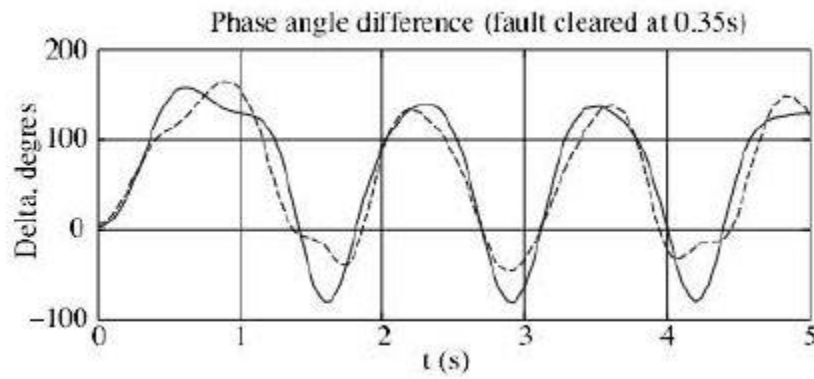
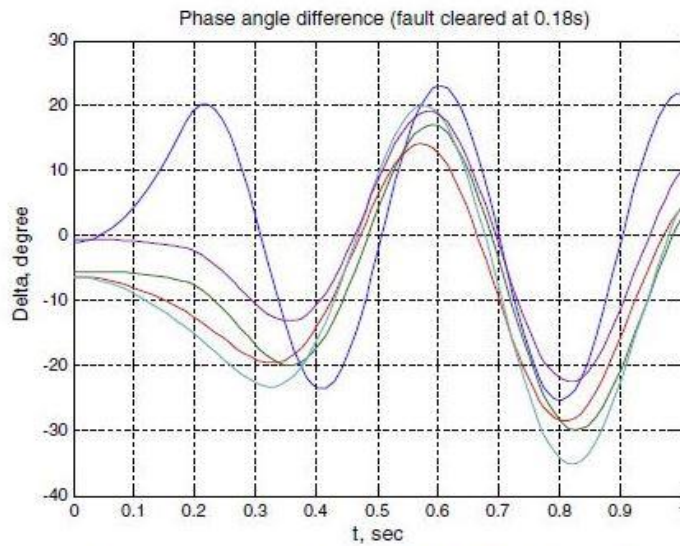


Figure 3: Average rotor angles for the fault at bus 7



Relative rotor angles obtained by LAHC algorithm

Figure 4: Relative rotor angles

Discussion of Results

From figure 3, the thick line and the dotted line shows the stability at generator 2 and generator 3 respectively and it remains stable after the disturbance, (it didn't go beyond $\delta_{max} = 180$). While in figure 4 the lines in the different colours represent stability at generators 2-6. It remains stable after the disturbance at bus 2, (it didn't go beyond $\delta_{max} = 100$). In the 9-bus system; A 3-phase to ground fault at bus 7 and line 7-5 was considered, δ_{max} is set as 180° while the clearing time is taken as 0.35s, the total cost reduced when the proposed algorithm reaches an optimum at the 28th iteration while the system remains stable and the total cost minimized. Tables 1 and 2 shows the comparative results obtained by GA, PSO, EPNN, ABC and the LAHC algorithms for 9-bus system and 30-bus system respectively. In Table 1, the minimum total cost obtained is the lowest compared with other algorithms while the average total cost of LAHC is \$1135.67 which is better than the results obtained by D.E, EPSO, IGSO and ABC.

In the 30-bus system; A 3-phase to ground fault at bus 2 and line 2-5 with two cases were considered (case A: δ_{max} is set as 80° while the clearing time is taken as 0.18s. From case B: δ_{max} is set as 60° while the clearing time is taken as 0.35s.). The results from the two cases are the same but with different number of iterations.

In table 2 the minimum total cost obtained is the lowest compared with other algorithms while the average total cost of LAHC is \$579.56 which is better than the results obtained by GA, PSO and EPNN on comparison.

Conclusions and Recommendations

In this work, optimization of electric power system with transient stability constraints was considered, LAHC algorithm was proposed to solve TSCOPF problem. The efficiency and accuracy of the proposed algorithm was demonstrated by Two test systems and 2 fault cases; WSCC 9-bus system and IEEE 30-bus system. The solutions obtained by the algorithm are better when compared with solutions obtained by other methods mentioned in the literature. Thus, the LAHC algorithm is efficient and accurate in solving the TSCOPF problem and can be applied to find power systems global solution which is monetary and stability.

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