A Fast and Scalable Genetic Algorithm-Based Approach for Planning of Microgrids in Distribution Networks

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Abstract

This paper proposes an optimization problem to partition a distribution grid, such that multiple feasible islands are planned and are capable to support their critical loads independently. It leverage the use of a multi-objective Genetic Algorithm (GA) approach to solve the problem. The proposed work has following major steps:

1) Formulates the optimization problem as node allocation and edge elimination and solves using Non-Dominated Sorting GA approach.
2) Evaluates the performance of the proposed technique with other GA and spectral clustering methods for varying size of test systems.

Optimization Problem

Objectives :

1) Edge Loss Minimization

$$\min \quad F_1 = \sum_{e_{i,j} \in \mathbb{E}} pf_{ij} \cdot X_{ij}$$

2) Similarly sized Partitions

$$\min \quad F_2 = \sum_{i=1}^{P-1} \sum_{j=i+1}^{P} |n'_i - n'_j|$$

3) Compact Partitions

$$\min \quad F_3 = \sum_{p=1}^{P} \delta_p,$$
$$\text{where } \delta_p = \begin{cases} x_p^U - x_p^L, & \text{if } x_p^U - x_p^L > y_p^U - y_p^L \\ y_p^U - y_p^L, & \text{if } y_p^U - y_p^L > x_p^U - x_p^L \end{cases}$$

4) Feasible Islands

$$F_4 = \frac{\max_{N_{sub}} \sum_{j \in \{1,..N_{sub}\}} A}{n(N)}$$
$$A = \left\{ \left[\sum_{i \in N_j} (g_{ij} - l_{ij}^c)\right]_+ + \sum_{i \in N_j} [v_{\max} - v_{ij}]_+ + \sum_{i \in N_j} [v_{ij} - v_{\min}]_+ \right\}$$

5) Path Redundancy

$$F_5 = \max \frac{\sum_{j \in N} \sum_{i \in N} 1/\sum_{k \in K} E(P_k(i,j))}{n(N)^2/2\hat{E}(P_k(i,j))}$$

Constraints:

Edge Elimination problem:

1) Upper/Lower Bounds on partitions $g_1 \equiv P^{\min} \leqslant P \leqslant P^{\max}$

2) Lower limit on no. of nodes in a partition $g_2 \equiv n_p^{\min} \leqslant n_p, \quad p = 1 \text{ to } P$

Node Allocation problem:

1) Node belongs to one partition $g_1 \equiv \sum_{p=1}^{z} X_{ip} = 1; i = 1 \text{ to } n$

2) Upper/Lower limits on nodes in a partition $g_2 \equiv n_p^{\min} \leqslant n_p \leqslant n_p^{\max}, \quad p = 1 \text{ to } P$

3) Nodes within a partition need to be contiguous

Proposed Approach

Non-Dominated Sorting Genetic Algorithm

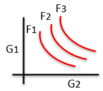
- Elitist Approach (considers the elite solutions in the next iteration).
- Provides a faster convergence to optimal pareto front.
- Maintains diversity in the non-dominated solution space.
- Parameter-independent in comparison to other Evolutionary Algorithms used for Multi-Objective optimal problems

NSGA-2 Algorithm and some terminology

Concept of Domination: A soln. X_1 dominates X_2 if:
a) if $G_j(X_1)$ is no worse than $G_j(X_2)$, for all j = 1,2,..m (m obj functions)
b) if $G_j(X_1)$ is strictly better than $G_j(X_2)$ for at least one objective

Non-Dominated Solution Set: The set of solutions which are non-dominated.
Ex: Say X_1 and X_2 are two solutions with two fitness G_1 and G_2 (min)
X_1 = 2 G_1= 23 G_2 = 45
X_2 = 3 G_1 = 34 G_2 = 23
X_1 and X_2 are non-dominated solution set.
This solution set is also called the **Pareto Optimal Set**

Now how to sort the solutions in the non-dominated set?
The idea is to segregate the solutions into multiple fronts, with the first one being the **Pareto Optimal Front**, which is F_1 in the figure (since we try to minimize G_1 and G_2).

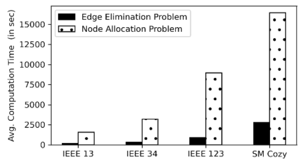


Algorithm 1 Pseudo-code for NSGA-2 [6]

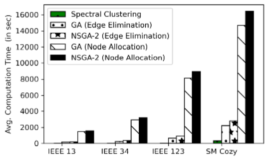
```
 1: while termination criteria do
 2:     R_t ← P_t ∪ Q_t
 3:     F ← non_dominated_sorting(R_t)
 4:     P_{t+1} ← φ; i ← 1
 5:     while |P_{t+1}| + |F_i| ⩽ N do
 6:         C_i ← crowd_sourcing_assignment(F_i)
 7:         P_{t+1} ← P_t ∪ F_i
 8:         i = i + 1
 9:     end while
10:     F_i ← sort(F_i, C_i, desc)
11:     P_{t+1} ← P_{t+1} ∪ F_i[1 : (N − |P_{t+1}|)]
12:     Q_{t+1} ← selection(P_{t+1}, N)
13:     Q_{t+1} ← mutation(Q_{t+1})
14:     Q_{t+1} ← crossover(Q_{t+1})
15:     t ← t + 1
16: end while
```

Numerical Results

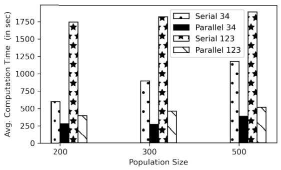
A. Comparison of Node Allocation & Edge Elimination Problem



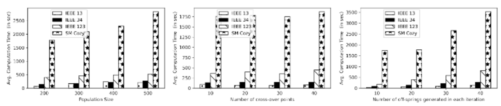
B. Comparison of NSGA-2 with other techniques



C. Improvement with Parallelization in solving NSGA-2



D. Genetic Algorithm Parameter Effects



E. Evaluation of the algorithm based on the following metrics

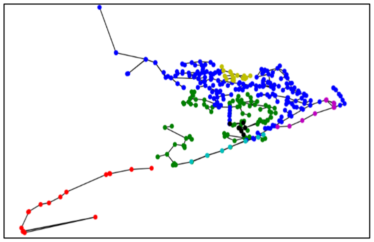
- Hypervolume (HV)
- Generation Distance (GD)
- Diversity Index(DI)
- Electrical Cohesive Index (ECI)
- Cluster Size Index (CSI)

Use Case	*Obj*	*Sol*	*HV*	*GD*	*DI*	*ECI*	*CSI*
IEEE 13	2	3	.019	2.7E-09	.57	.90	.269
	3	3	.003	1.2E-08	1.2	.89	.097
	4	5	0.0	3.9E-09	1.5	.89	.2
IEEE 34	2	37	.09	.0462	.32	.86	.15
	3	11	.05	.187	.78	.86	.063
	4	30	.01	.216	1.1	.87	.021
IEEE 123	2	57	.77	.26	.96	.90	.0092
	3	106	.61	.71	2.1	.87	4.9E-04
	4	200	.30	1.19	4.0	.79	5.5E-07
SM Cozy	2	35	.74	.41	1.4	.97	.067
	3	96	.44	0.73	2.5	.97	.011
	4	195	.033	1.13	3.7	.97	6.8E-05

F. Effect of selection of Fitness Function

Use Case	Scenarios	Solns	DI	ECI	CSI
IEEE 13	with F_4	5	1.508	0.88	0.20
	with F_5	4	1.413	0.91	0.25
	with F_4 and F_5	10	1.058	0.89	0.1
IEEE 34	with F_4	33	1.087	0.87	0.02
	with F_5	35	0.91	0.90	0.01
	with F_4 and F_5	186	0.94	0.84	0.004

A sample solution for a real distribution feeder in Colorado



Conclusions

1) Edge Elimination Problems are easier to solve than Node-Allocation Problems based on the computation time.
2) NSGA-2 is preferred over spectral clustering and GA technique.
3) Proposed solution is validated for topological and resilience objectives.
4) Evaluated the method for different distribution grids & a real distribution feeder.
5) Parallelization capability in the meta-heuristic approach helps in reducing computation time.

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