Lecture Series on

Intelligent Control

Lecture 25

Evolutionary Algorithms: Applications

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Optimal Reactive Power Planning Using Evolutionary Algorithms:

A Comparative Study for Evolutionary Programming, Evolutionary Strategy, Genetic Algorithm, and Linear Programming

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Outline

1. Optimal Reactive Power Planning
2. Evolutionary Algorithms
   - Evolutionary Programming
   - Evolutionary Strategy
3. Genetic Algorithm
4. EAs for ORPP, ELD
5. Results
6. Conclusions

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Optimal Reactive Power Planning

Power System Collapse
- Heavy load
- Lack of reactive power
- Power interchanges

Optimal Reactive Power Planning (ORPP)

Minimize: operation cost + investment cost
- Determine ***locations*** of compensation devices
- Determine ***amounts*** of shunt VAR sources

While satisfying:
- Adequate voltage profile
- Real and reactive power balance (load flow)
- Variable limits (real and reactive power generations, tap-settings, etc.)

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Evolutionary Programming

Initialization: The initial population of control variables is selected randomly

Statistics: The maximum fitness f_{max}, minimum fitness f_{min}, the sum of fitnesses , and average fitness f_{avg}

Mutation: Each selected parent, P_i, is mutated and added to its population following the rule:

$$P_{i+m,j} = P_{i,j} + N(0, \beta\,(\overline{x}_j - \underline{x}_j)\frac{f_i}{f_{\max}}), \quad j = 1, 2, \ldots, n,$$

β : mutation scale in [0, 1], could decrease adaptively

n: number of components or variables

m: population size

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Evolutionary Programming

Competition: Several individuals (k) which have the best fitness are kept as the parents for the next generation.

Other individuals in the combined population of size ($2m$ - k) compete.

A weight value W_i of the i^{th} individual is calculated by the following competition:

$$W_i = \sum_{t=1}^{N} W_{i,t}$$

$$W_{i,t} = \begin{cases} 1 & \text{if } U_l < \dfrac{f_r}{f_r + f_i} \\ 0 & \text{otherwise,} \end{cases}$$

→ win (1) ; → loss (0)

N : *random competition number*

U_l : random number in $U(0,1)$

r: randomly chosen individual

Convergence test: $\{f_{avg} / f_{\max}\} \geq \delta$

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Evolutionary Strategy

Mutation process: Each selected parent, P_i, is mutated and added to its population following the rule,

$$P_{i+m,j} = P_{i,j} + N(0, \beta\, \nabla_{dev}), \quad j = 1, 2, \cdots, n,$$

n : the number of decision variables,
∇_{dev} : fixed, and its value depends on the size of decision variables.

Competition: Fitness of individuals of population size 2*m* are sorted in a descending order. The first *m* individuals are kept.

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Genetic Algorithm

Initial population generation: an initial population of binary strings is created randomly. Each of these strings represents one feasible solution to the search problem, i.e., a point in the search space or a domain satisfying constraints.

Fitness evaluation: $f = 1/(\alpha + C)$

Selection and reproduction: Fitness-proportionate reproduction through the simulated spin of a weighted roulette wheel

Crossover: head-tail crossover, tail-tail crossover

Mutation: sparingly

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Optimal Reactive Power Planning (ORPP) problem

Objective Functions

$$C_F = \sum_{i \in N_g} C_i\ (P_i)$$

$$C_i = \begin{cases} a_{i1} + b_{i1}P_i + c_{i1}P_i^2 & \text{if } \underline{P}_i \le P_i < P_{i1} \\ a_{i2} + b_{i2}P_i + c_{i2}P_i^2 & \text{if } P_{i1} \le P_i < P_{i2} \\ \cdots & \\ a_{im} + b_{im}P_i + c_{im}P_i^2 & \text{if } P_{im-1} \le P_i < \overline{P}_i, \end{cases}$$

N_g : the set of generators,
$C_i(P_i)$: cost of the i^{th} generator,
a_{ij}, b_{ij}, c_{ij} : cost coefficients of the i^{th} generator at the j^{th} power level,
P_i : the generated power of the i^{th} generator [MW],

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Optimal Reactive Power Planning (ORPP) problem

Investment Cost

$$c_I = \sum_{i \in N_C} \left\{ C_{fi} + C_{ci} \left| \bar{Q}_{ci} \right| \right\}$$

N_C : the set of compensators,
C_{fi} and C_{ci} : fixed and unit costs for investment,
$\bar{Q}_{ci}$: amount of Var source investment in discrete steps.

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P-Q Decomposition

The P-module: $$C_P = \sum_{l \in N_l} d_l C_F^l,$$

C_F^l : the operation cost for load level *l*,
d_l : the duration of load level *l*,
N_l : the set of load levels.

Constraints: the real and reactive power balance, and Inequality constraints:

$$\underline{P}_{gi} \le P_{gi} \le \bar{P}_{gi}$$
$$\underline{Q}_{gi} \le Q_{gi} \le \bar{Q}_{gi}$$
$$\underline{T}_k \le T_i \le \bar{T}_k$$
$$\underline{V}_i \le V_i \le \bar{V}_i$$
$$\underline{Q}_{ci} \le Q_{ci} \le \bar{Q}_{ci}$$

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P-Q Decomposition

Soft constraints :

$$C_P = \sum_{l \in N_l} d_l \{ \; C_F^l + \sum_{i \in N_l} \lambda_{vi} (V_i - Sat(V_i))^2 + \sum_{i \in N_g} \lambda_{gi} (Q_{gi} - Sat(Q_{gi}))^2 \; \},$$

$$Sat(x) = \begin{cases} \underline{x} & \text{if } x < \underline{x} \\ x & \text{if } \underline{x} \le x \le \bar{x} \\ \bar{x} & \text{if } x > \bar{x} \end{cases}$$

The Q-module:

$$C_Q = C_P + C_I,$$

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P-Q Decomposition

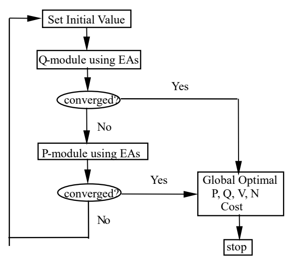

Fig. 1. Flow chart for ORPP by using EAs.

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Simulation Results

IEEE 30-bus system

TABLE I. SIMULATION PARAMETERS IN EP, ES, EP+ES AND GA

parameters	ES	EP	EP+ES	GA
number of parents	25	25	25	25
number of offspring	25	25	25	25
standard deviation	0.03	NA	EP(NA), ES(0.03)	NA

NA: Not Applicable

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Simulation Results

TABLE II. SIMULATION PARAMETERS IN GA

parameters	GA
mutation rate	0.01
crossover rate	0.8
abandoning rate	0.9
maximum generations	100
population size	25
control variables	6
parameter resolution	8 bits per substring
chromosome length	48
fitness function parameter α	0.01

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Simulation Results

TABLE III
COST COEFFICIENTS OF PIECEWISE QUADRATIC FUNCTION

U	GENERATION								cost coefficients		
	Min		P1		P2		Max	F	a	b	c
		F1		F2		F3					
1	50		100		190		200	1	0.000	1.900	0.00355
		1		2		3		2	0.000	2.000	0.00375
								3	0.000	2.200	0.00415
2	20		35		50		80	1	0.000	1.700	0.01700
		1		2		3		2	0.000	1.750	0.01750
								3	0.000	2.050	0.02350
3	15		30		50			1	0.000	1.000	0.06250
		1		2				2	0.000	1.200	0.08250
4	10		25		35			1	0.000	3.250	0.00834
		1		2				2	0.000	3.650	0.01234
5	10		20		30			1	0.000	3.000	0.02500
		1		2				2	0.000	3.300	0.03500
6	12		25		40			1	0.000	3.000	0.02500
		1		2				2	0.000	3.300	0.03500

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Simulation Results

TABLE IV. OPTIMAL OPERATION WITH INVESTMENT
(A) REAL POWER AND REACTIVE POWER DISTRIBUTION

Variable	LP	ES	EP	EP+ES
P_1	184.19	179.838	178.67	179.162
P_2	47.77	48.110	49.335	48.345
P_5	20.00	19.822	19.583	19.944
P_8	15.75	21.571	20.733	21.790
P_{11}	13.46	11.402	12.422	11.423
P_{13}	12.00	12.000	12.000	12.071
Q_1	27.71	8.861	13.027	12.409
Q_2	13.35	30.379	25.606	25.827
Q_5	30.12	30.136	30.060	30.753
Q_8	22.49	33.747	23.885	25.890
Q_{11}	29.58	13.826	18.934	17.064
Q_{12}	20.03	9.283	12.845	12.199
Loss	9.8+j44	9.3+j38.3	9.3+j38.7	9.3+j38.5

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Simulation Results

(B) BUS VOLTAGES

Bus V (p.u.)	LP	ES	EP	EP+ES
V_1	1.0903	1.084	1.084	1.083
V_2	1.0616	1.064	1.063	1.062
V_3	1.0508	1.050	1.050	1.049
V_4	1.0425	1.043	1.042	1.042
V_5	1.0289	1.032	1.030	1.030
V_6	1.0340	1.037	1.036	1.035
V_7	1.0234	1.027	1.025	1.025
V_8	1.0294	1.038	1.033	1.033
V_9	1.0006	1.028	1.019	1.022
V_{10}	1.0032	1.014	1.010	1.013
V_{11}	1.0584	1.055	1.056	1.056
V_{12}	1.0111	1.019	1.018	1.019
V_{13}	1.0380	1.032	1.035	1.035
V_{14}	1.0000	1.010	1.008	1.010
V_{15}	0.9992	1.011	1.009	1.011

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Simulation Results

(C) TAP-SETTINGS, CAPACITIVE VARS, AND COSTS

Variable	LP	ES	EP	EP+ES
N_{11}	1.0155	1.0290	1.0223	1.0165
N_{12}	0.9940	1.0337	1.0199	1.0261
N_{15}	1.0320	1.0298	1.0286	1.0277
N_{36}	0.9930	1.0274	1.0176	1.0152
Q_{c15}(Mvar)	3.05	6.5218	4.7253	4.7541
Q_{c17}(Mvar)	2.89	6.4387	4.4645	4.4418
Q_{c20}(Mvar)	2.79	6.8332	5.0405	5.0644
Q_{c21}(Mvar)	4.73	6.6059	4.7493	4.7540
Q_{c23}(Mvar)	2.96	6.4141	4.4747	4.4762
Gen. cost ($/hr)	801.87	801.125	801.58	801.41
Inv. cost ($/hr)	0.75	1.05	0.75	0.75
Total ($/hr)	802.62	802.175	802.33	802.16

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Simulation Results

TABLE VI. COMPARISON OF EA'S FOR P-OPTIMIZATION

Method	EP	ES	EP+ES	GA
P1[MW]	177.92	177.93	177.13	178.46
P2[MW]	48.587	48.887	49.664	47.891
P3[MW]	19.975	19.996	19.996	20.879
P4[MW]	22.739	22.467	22.775	23.086
P5[MW]	12.613	12.355	12.103	10.703
P6[MW]	11.745	11.776	11.753	12.328
Loss[MW]	9.995	10.013	9.985	9.944
Total cost	803.87	803.86	803.87	803.64
Generations	60	37	36	63

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Simulation Results

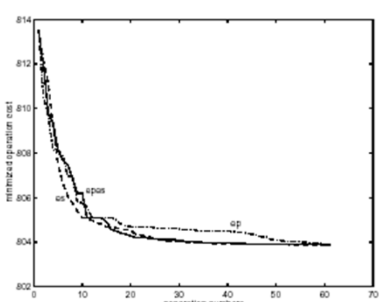

Fig. 2. Convergence comparison for EAs in the P-module

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Simulation Results

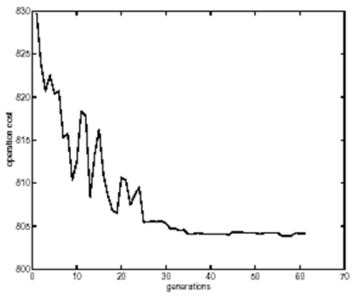

Fig. 3. Convergence characteristics of GA in the P-module

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Conclusions

EAs Compared to LP:

- Total cost lower slightly, power loss lower
- P- and Q-modules are easily formulated
- More computation time

Comparison of EAs:

- EP: more generations to converge, but less likely to fall into a local minimum
- ES: less generation to converge, higher probability to fall into local minimum
- EP+ES: close to the ES convergence, but improved robustness in finding the global minimum
- GA: similar to EP

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