Genetically Optimized Fuzzy Placement and Sizing of Capacitor Banks in Distorted Distribution Networks

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Abstract—A genetic algorithm (GA), in conjunction with fuzzy logic (FL) (approximate reasoning), is proposed for simultaneous improvement of power quality (PQ) and optimal placement and sizing of fixed capacitor banks in distribution networks with non-linear loads imposing voltage and current harmonics. Economic cost is defined as the objective function and includes the cost of power losses, energy losses, and that of the capacitor banks while the voltage limits, number/size of installed capacitors at each bus, and the PQ limits of harmonic standard IEEE-519 are considered constraints. Fuzzy approximate reasoning is used to calculate the fitness function in order to consider the uncertainty of decision making based on the suitability of constraints (S_{THD}, S_V) and the objective function (cost index) for each chromosome. Simulation results for the 18-bus and 123-bus IEEE distorted networks using the proposed GA–FL approach are presented and compared with those of previous methods. The main contribution is an improved fitness function for GA, capable of improving the objective function while directing the PQ constraints toward the permissible region using fuzzy approximate reasoning. This method leads to computing the (near) global solution with a lower probability of getting stuck at a local optimum and weak dependency on initial conditions while avoiding numerical problems in large systems.

Index Terms—Capacitor, fuzzy logic (FL), genetic algorithm (GA), harmonics, placement, power flow and optimization, power quality (PQ), sizing.

I. INTRODUCTION

THE problem of shunt capacitor allocation in distribution networks for reactive power compensation, voltage regulation, power factor correction, and power/energy loss reduction has been extensively researched and documented in literature [1]–[4]. However, limited attention is given to this problem in the presence of voltage and current harmonics.

With the increasing application of nonlinear loads and devices causing voltage and current harmonics in distribution networks, special attention should be paid to the placement and sizing of capacitors in such distorted systems. This is due to resonances, increased losses, extensive reactive power demand, and overvoltages at fundamental and harmonic frequencies.

Some recent publications have taken into account the presence of distorted voltages for solving the capacitor placement problem. These investigations include: exhaustive search [5], local variations [6], mixed integer-nonlinear programming [7],

[8], heuristic methods [9], maximum sensitivities selection [10]–[12], fuzzy set theory [13], [14], and genetic algorithms (GAs) [15]. Some of these documents [5]–[10], [13] ignore the couplings between harmonic voltages and currents. References [11], [12], [14], and [15] use a harmonic power flow that considers harmonic couplings caused by the nonlinear loads. Reference [8] addresses the problem under unbalanced three-phase conditions.

Most of these techniques are fast, but they suffer from the inability to escape local optimal solutions. Simulated annealing (SA), tabu search (TS), and GAs are three near global optimization techniques that have demonstrated fine capabilities for capacitor placement [1]–[4], but the computational burden is heavy.

Fuzzy logic (FL) has shown good results for capacitor bank allocation when combined with GAs under sinusoidal operating conditions [1], [2], [16], [17]. However, FL has been mainly used to select the most adequate buses for capacitor placement and, hence, to reduce the search space for GA under sinusoidal operating conditions [2].

This paper proposes a GA in conjunction with FL (GA–FL) to formulate the capacitor placement and sizing problem in the presence of voltage and current harmonics, taking into account a limited number of fixed capacitor banks at each bus. Operational and power-quality (PQ) constraints include the bounds of root mean square (rms) voltage THD_v, the number/size of installed capacitors, and harmonic parallel resonances. In the proposed method, the suitability of THD_v and voltage are defined for each chromosome based on fuzzy approximate reasoning. These variables represent the level of constraints satisfaction and are used with cost index (objective function) to determine the fitness function. Fuzzy approximate reasoning is used to calculate the fitness function considering the uncertainty of decision making based on constraints and objective function. This method improves the evolution process of GA, lowering the probability of getting stuck at local optimum and avoiding numerical problems [18]–[20].

II. NEWTON-BASED HARMONIC POWER FLOW

For modeling a distribution system with nonlinear loads at fundamental and harmonic frequencies, the formulation and notations of [21] and [22] are used. Linear loads are modeled as shunt admittances at harmonic frequencies [5]. Nonlinear loads with given v-i characteristics (either in the frequency or time domain) represent the coupling between harmonic voltages and currents. These loads are modeled as shunt harmonic current sources and are updated at every iteration of the harmonic power flow.

The system solution (with linear and nonlinear loads under balanced nonsinusoidal three-phase conditions) is achieved by forcing total (fundamental and harmonic) mismatch active and reactive powers as well as mismatch active and reactive fundamental and harmonic currents to zero using the Newton–Raphson method.

III. PROBLEM FORMULATION

Fixed capacitor banks are treated as variable shunt reactances with discrete values, and capacitor placement is possible for NC number of buses.

A. Constraints

Voltage constraints will be taken into account by specifying upper (e.g., $V^{\max} = 1.1$ p.u.) and lower (e.g., $V^{\min} = 0.9$ p.u.) bounds of rms voltage (n = total number of buses, i = bus number, h = harmonic order)

$$V^{\min} \leq \sqrt{\sum_h \left(V_i^{(h)}\right)^2} \leq V^{\max} \quad \text{for} \quad i = 1, \ldots, n. \quad (1)$$

The voltage distortion is considered by specifying the maximum total harmonic distortion (THD_v) of voltages

$$\text{THD}_{v,i} = \left(\left[\sqrt{\sum_{h \neq 1} \left(V_i^{(h)}\right)^2}\right] / V_i^{(1)}\right) \cdot 100\%$$
$$\leq \text{THD}_v^{\max} \quad \text{for} \quad i = 1, \ldots, n. \quad (2)$$

Bounds for (1) and (2) are specified by the IEEE-519 standard [23]. Let $u^{\max}$ denote the maximum number of capacitor units allowed at each bus. The number of capacitors at bus i is limited by

$$u = u_{fi} \leq u^{\max} \quad \text{for} \quad i \in \text{MC} \quad (3)$$

where u_{fi} denotes the number of fixed capacitor banks at bus i and MC is the set of possible buses for capacitor placement.

B. Objective Function (Cost Index)

The objective function ("$cost$") used for capacitor placement in the presence of harmonics is [5], [10], [14], and [15]

$$\min F = F_{loss} + F_{cap.} + F_{capacity}$$
$$= K_E T P_{loss}\left(V^{(1)}, \ldots, V^{(L)}, C\right) + \sum_{i \varepsilon MC} K_{cfp} C_{fi}$$
$$+ K_A P_{loss}\left(V^{(1)}, \ldots, V^{(L)}, C\right) \quad (4)$$

where

F_{loss} energy loss cost;

$F_{cap.}$ cost of fixed capacitors;

$F_{capacity}$ cost corresponding to power losses (e.g., used capacity of the system);

P_{loss} total system losses;

$V^{(h)}$ bus voltage vector at harmonic h;

L highest order of considered harmonics;

C size of connected capacitors;

T duration of load (h/yr);

MC set of possible shunt capacitor buses;

K_{cfp} cost per unit of fixed capacitance [15, Table I];

K_E cost per megawatt-hour (e.g., $K_E = 50$ U.S. $/MWh [10]);

K_A saving per megawatt for reduction in losses (e.g., $K_A = 120,000$ U.S. $/MW [10]).

Total losses can be computed using the Newton-based harmonic power-flow outputs

$$P_{loss} = \sum_{h=1}^{L} \left[\sum_{i=1}^{n} \sum_{j=1}^{n} V_i^{(h)} V_j^{(h)} Y_{ij}^{(h)} \cos\left(\theta_i^{(h)} - \theta_j^{(h)} - \delta_{ij}^{(h)}\right)\right] \quad (5)$$

where $V_i^{(h)}$ and $\theta_i^{(h)}$ are the magnitude and phase of the hth harmonic voltage at bus i, and $Y_{ij}^{(h)}$ and $\delta_{ij}^{(h)}$ are the magnitude and phase of the hth harmonic line admittance between buses i and j, respectively.

IV. SOLUTION METHOD

This paper proposes a new hybrid approach based on GA and fuzzy approximate reasoning for the optimal placement and sizing of capacitor banks in distorted distribution networks with harmonic voltages and currents.

GAs use biological evolution and population genetics to search and arrive at a high-quality (near) global solution. The required design variables are encoded into a binary string as a set of genes corresponding to chromosomes in biological systems. Unlike the traditional optimization techniques that require one starting point, they use a set of points as the initial conditions. Each point is called a chromosome. A group of chromosomes (e.g., equal to 250 in this paper) is called a population. During each iterative procedure (referred to as a generation), a new population is generated using three GA operators (namely reproduction, crossover, and mutation).

Fuzzy set theory (FST) contains a set of rules which are developed from qualitative descriptions. When the suitability of THD_v and voltage and the cost of the distribution system are studied, an engineer can choose the most appropriate combination of capacitor banks. For example, it is intuitive that a distribution system with a high suitability of THD_v and voltage, having a low cost is highly desirable. Fuzzy rules are defined to determine the suitability of each chromosome (S_{chrom}) and may be executed with some degree using fuzzy inference. S_{chrom} is used as the fitness function in the GA to further improve the evolution process, reducing the probability of getting stuck at a local optimum.

A. Structure of Chromosomes

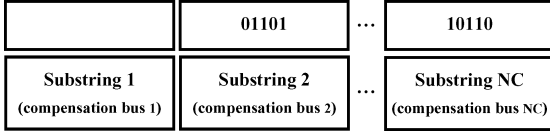In this work, the chromosome for GA consists of a sequence of NC substrings as shown in Fig. 1, where NC denotes the
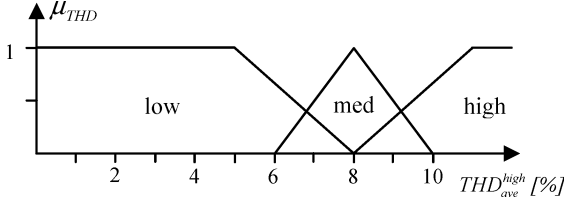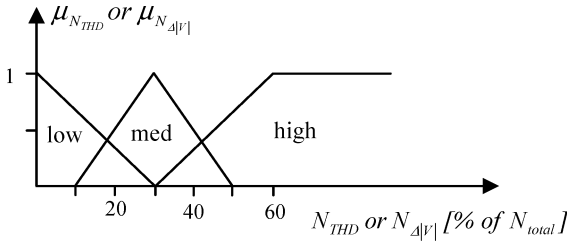
Fig. 1. Chromosome structure for the GA.

Fig. 2. Membership functions for the average of unacceptable (high) THD_v values (6).

Fig. 3. Membership functions for a number of buses with unacceptable THD_v or voltage.

TABLE I
DECISION MATRIX FOR DETERMINING SUITABILITY OF THD_v (AND V)

AND		$\mathit{THD_v}$ (or $\Delta|V|$)		
		low	med	high
N_{THD} (or $N_{\Delta|V|}$)	low	*high*	*med*	*med*
	med	*med*	*low*	*low*
	high	*med*	*low*	*low*

number of possible compensation buses for capacitor placement in the entire feeder. The binary substrings indicate the number of the installed capacitor units at the bus under consideration which is limited to $u^{\max}$.

B. Proposed Fuzzy Fitness (Suitability) Function

The suitability level of each chromosome (S_{chrom}) is computed by defining fuzzy membership functions for the suitability of total harmonic distortion $(\mu_{S_{\text{THD}}})$, voltage (μ_{S_V}), and cost index (μ_{cost}).

A fuzzy expert system (FES) uses the number of buses with high THD_v and the average of THD_v at these buses to determine the suitability of THD_v. A similar method is used to determine the suitability of voltage.

A concern in the development of fuzzy expert systems is the assignment of appropriate membership functions which could
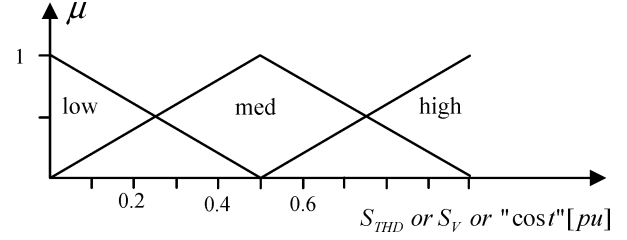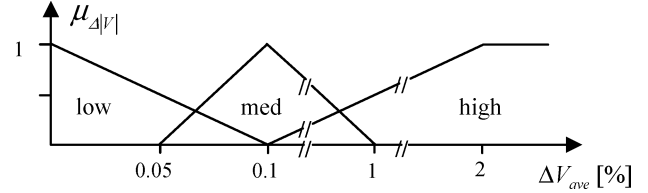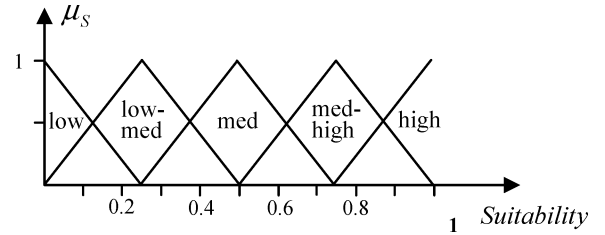

Fig. 4. Membership functions for the suitability of THD_v, V and "$cost$."

Fig. 5. Membership functions for the average of unacceptable voltage deviation values (8).

Fig. 6. Membership functions for S_{chrom}.

be performed based on intuition, rank ordering, or probabilistic methods. However, the choice of membership degree in the interval [0,1] does not matter, as it is the order of magnitude that is important [1], [24].

1) Suitability of $\text{THD}_v(S_{\text{THD}})$*:* For a given chromosome, define the average of unacceptable THD_v values

$$\text{THD}_{\text{ave}}^{\text{high}} = \sum_{j=1}^{N_{\text{THD}}} \text{THD}_j / N_{\text{THD}} \qquad (6)$$

where N_{THD} is the number of buses with high total voltage harmonic distortions (i.e., $\text{THD}_j > \text{THD}_v^{\max}$). The following steps are performed to compute S_{THD}:

• fuzzification of $\text{THD}_{\text{ave}}^{\text{high}}$ and N_{THD} (based on membership functions of Figs. 2 and 3, respectively) to compute the corresponding membership values (μ_{THD} and $\mu_{N_{\text{THD}}}$);

• fuzzy inferencing and defuzzification based on the decision matrix of Table I, the membership function of Fig. 4 and the Mamdani-max-prod implication method

$$S_{\text{THD}} = \sum \overline{y} \mu_{N_{\text{THD}}} \mu_{\text{THD}} / \sum \mu_{N_{\text{THD}}} \mu_{\text{THD}}. \qquad (7)$$

TABLE II
PROPOSED DECISION MATRIX FOR DETERMINING THE SUITABILITY OF A CHROMOSOME (S_{chrom})

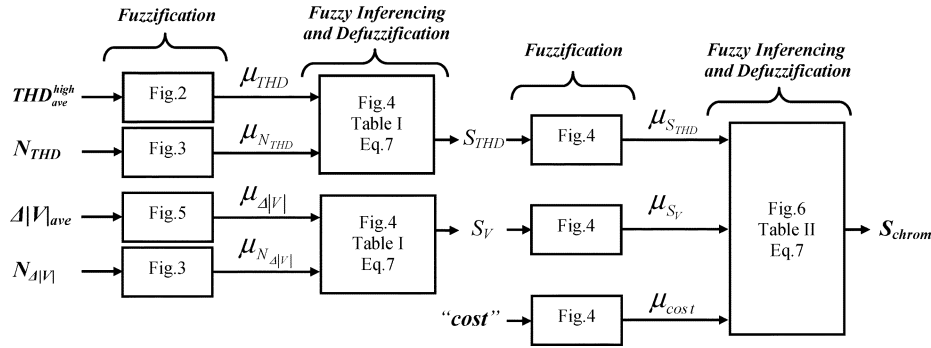| AND		S_{THD}								
		low			med			high		
		"cost"			"cost"			"cost"		
		low	med	high	low	med	high	low	med	high
S_V low		*low-med*	*low*	*low*	*med*	*low-med*	*low*	*med-high*	*med*	*low-med*
S_V med		*med*	*low-med*	*low*	*med-high*	*med*	*low-med*	*med-high*	*med*	*med*
S_V high		*med*	*low-med*	*low*	*med-high*	*med-high*	*med*	*high*	*high*	*med-high*

Fig. 7. Proposed fuzzy expert system (FES) to determine the suitability of a chromosome (S_{chrom}) for capacitor placement from total harmonic distortion ($\mathrm{THD_v}$), voltage deviation ($\Delta|V|_{\mathrm{ave}}$), "cost," number of buses with unacceptable $\mathrm{THD_v}(\mathrm{N_{THD}})$ and unacceptable $|V|(\mathrm{N_{\Delta|V|}})$.

2) Suitability of Voltage (S_V): For a given chromosome, define the average of unacceptable voltage deviation values as

$$\Delta V_{\mathrm{ave}} = \frac{\sum_{j=1}^{N_{\Delta|V|}} \Delta V_j}{N_{\Delta|V|}},$$
$$\begin{cases} \Delta V_j = |V| - V^{\max} & (\text{if } |V| > V^{\max}) \\ \Delta V_j = V^{\min} - |V| & (\text{if } |V| < V^{\min}) \end{cases} \quad (8)$$

where $N_{\Delta|V|}$ is the number of buses with unacceptable values of voltage. $V^{\max} = 1.1$ p.u. and $V^{\min} = 0.9$ p.u. are upper and lower bounds of rms voltage, respectively. The following steps are performed to compute S_V:

- fuzzification of ΔV_{ave} and $N_{\Delta|V|}$ (based on membership functions of Figs. 5 and 3, respectively) to compute the corresponding membership values ($\mu_{\Delta|V|}$ and $\mu_{N_{\Delta|V|}}$);
- fuzzy inferencing and defuzzification (using the decision matrix of Table I, Fig. 4, and (7)) to determine the suitability of voltage (S_V).

3) Cost Index ("cost"): Compute the cost for all chromosomes ((4)) and linearly normalize them into the [0,1] range with the largest cost having a value of one and the smallest one having a value of zero.

4) Fitness (Suitability) of a Chromosome (S_{chrom}): The suitability level for a given chromosome is computed from S_{THD}, S_V, and "cost" using the following steps:

- fuzzification of S_{THD}, S_V and "cost" (based on Fig. 4) to compute the corresponding membership values ($\mu_{S_{\mathrm{THD}}}$, μ_{S_V} and μ_{cost});

- fuzzy inferencing and defuzzification [using the decision matrix of Table II, Fig. 6 and (7)] to determine the suitability of the chromosome (S_{chrom}).

C. Genetic Operators

Three stochastic transition rules are applied to each chromosome during the generation procedure to generate a new improved population from an old one.

1) Reproduction—a probabilistic process for selecting two parent strings from the population of strings on the basis of a "roulette-wheel" mechanism, using their fitness values.
2) Crossover—the process of selecting a random position in the chromosome and substrings (called the crossover point) and swapping the characters either right or left of this point with another similarly partitioned string. The probability of parent–chromosomes crossover is assumed to be between 0.6 and 1.0.
3) Mutation—the process of random modification of a string position by changing "0" to "1" or vice-versa, with a small probability. In this paper, the probability of mutation is assumed to be between 0.01 and 0.1.

V. SOLUTION METHODOLOGY

The shunt capacitor placement and sizing problem in the presence of linear and nonlinear loads is solved using the proposed GA–FL algorithm of Fig. 8, as follows:

Step 1) input system parameters and the initial population.

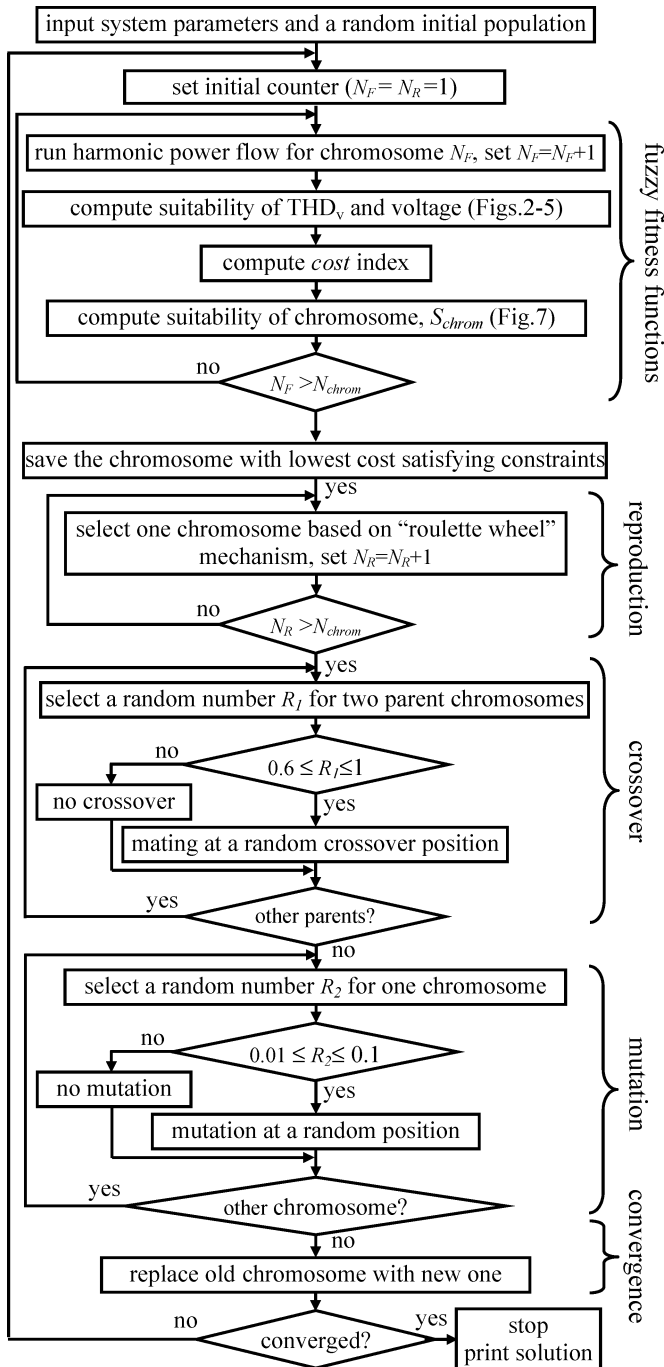Step 2) (**Fuzzy Fitness/Suitability**): Perform the following for all chromosomes (Fig. 7):

Fig. 8. Proposed GA–FL method for optimal placement and sizing of capacitor banks in the presence of harmonics.
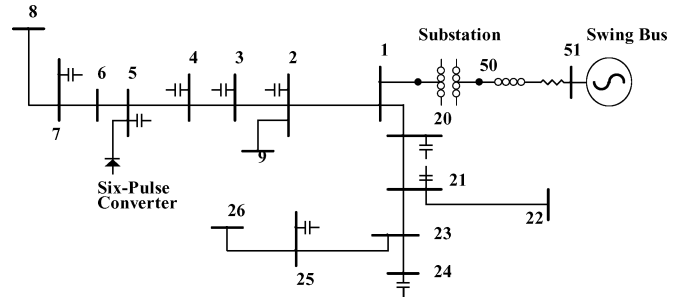

Fig. 9. Single-line diagram of the 18-bus IEEE distorted system [11], [12], [14], [15], [25] used for simulation and analysis.

offspring. Otherwise, transfer the chromosomes with no crossover.

Step 5) (**Mutation Process**): Select a random number for the mutation of one chromosome. If it is between 0.01 and 0.1, then apply the mutation process at a random position. Otherwise, transfer the chromosome with no mutation.

Step 6) (**Updating Populations**): Replace the old population with the improved population generated by Steps 2) to 5). Check all chromosomes and save the one with minimum cost, satisfying all constraints.

Step 7) (**Convergence**): If all chromosomes are the same or the maximum number of iterations is achieved ($N_{\max} = 40$), then print the solution and stop, else go to Step 2).

VI. APPLICATION OF THE METHOD

A. Simulation of the 18-Bus IEEE Distorted System

The proposed GA-FL method (Fig. 8) and previous capacitor placement techniques (MSS [10], [11], MSS-LV [12], fuzzy [14], genetic [15]) are applied to the 23-kV, 18-bus distorted IEEE distribution system. Line and data specifications are given in [25]. A single-line diagram of the system is shown in Fig. 9. The six-pulse rectifier (with $P = 0.3$ p.u. $= 3$ MW and $Q = 0.226$ p.u. $= 2.26$ MVAr) causes a maximum voltage THD_v of 8.486% (column 2 of Table III).

Simulation results for the MSS, MSS-LV, fuzzy and genetic algorithm (GA) are listed in columns 3 to 6 of Table III, respectively. Among these previously proposed algorithms, the GA approach results in a near global solution with the best yearly benefit of U.S.$ 18 949 (column 6 of Table III). Note that MSS (a local search algorithm) results in a higher benefit (i.e., U.S.$ 20 653 per year) but it does not limit THD_v to the desired level of 5% (column 3 of Table III).

The proposed GA–FL approach of Fig. 8 is also applied to this system for optimal placement and sizing of capacitor banks. The results show a yearly benefit of U.S.$ 19 550 (last row of Table III) and the maximum voltage THD_v is limited to 4.98% (column 7 of Table III). Compared to the GA approach, the total annual benefit is increased by U.S.$ 600 (i.e., 3.2%) and the total allocated capacitance is decreased by 0.015 p.u.

B. Simulation of the 123-Bus IEEE Distorted System

The GA [15] and proposed GA–FL (Fig. 8) methods are applied to the 4.16-kV, 123-bus distorted IEEE radial distribu-

Step 2A) Run the harmonic power flow.

Step 2B) Compute suitability of THD_v and voltage [Figs. 2–5, Table I and (6)–(8)].

Step 2C) Compute the cost index.

Step 2D) Compute the suitability of chromosome S_{chrom} [Fig. 6, Table II, and (7)].

Step 3) (**Reproduction Process**): Select a new combination of chromosomes by spinning the "roulette wheel."

Step 4) (**Crossover Process**): Select a random number for mating two parent chromosomes. If it is between 0.6 and 1.0, then combine the two parents and generate two

TABLE III
SIMULATION RESULTS OF MSS [11], MSS-LV [12], FUZZY SET [14], GENETIC ALGORITHM [15] AND THE PROPOSED GA–FL APPROACH FOR THE 18-BUS, DISTORTED IEEE DISTRIBUTION SYSTEM OF FIG. 9 (PER UNIT $VA = 10$ MVA, PER UNIT $V = 23$ kV, swing bus voltage $= 1.05$ p.u.)

optimization method	before * optimization	local optimization			(near) global optimization	
		after MSS** optimization	after MSS-LV** optimization	after fuzzy** optimization	after GA** optimization	after GA-FL** optimization
capacitor bank locations [pu]	Q2 = 0.105	Q2 = 0.030	Q2 = 0.120	Q2 = 0.015	Q2 = 0.030	Q2 = 0.030
	Q3 = 0.060	Q3 = 0.090	Q3 = 0.060	Q3 = 0.030	Q3 = 0.000	Q3 = 0.000
	Q4 = 0.060	Q4 = 0.180	Q4 = 0.180	Q4 = 0.060	Q4 = 0.165	Q4 = 0.195
	Q5 = 0.180	Q5 = 0.240	Q5 = 0.240	Q5 = 0.240	Q5 = 0.330	Q5 = 0.300
	Q7 = 0.060	Q7 = 0.120	Q7 = 0.120	Q7 = 0.210	Q7 = 0.105	Q7 = 0.105
	Q20= 0.060	Q20= 0.090	Q20= 0.090	Q20= 0.090	Q20= 0.060	Q20= 0.090
	Q21= 0.120	Q21= 0.120	Q21= 0.120	Q21= 0.120	Q21= 0.090	Q21= 0.075
	Q24= 0.150	Q24= 0.000	Q24= 0.000	Q24= 0.000	Q24= 0.015	Q24= 0.015
	Q25= 0.090	Q25= 0.030	Q25= 0.000	Q25= 0.000	Q25= 0.015	Q25= 0.015
	Q50= 0.120	Q50= 0.000	Q50= 0.000	Q50= 0.000	Q50= 0.030	Q50= 0.000
total capacitor [pu]	**Qt = 1.005**	**Qt = 0.900**	**Qt = 0.930**	**Qt = 0.765**	**Qt = 0.840**	**Qt = 0.825**
minimum voltage [pu]	1.029	1.016	1.013	0.998	1.003	1.005
maximum voltage [pu]	1.055	1.056	1.059	1.050	1.050	1.050
maximum THD_v [%]	**8.486**	**6.370**	**4.720**	**4.899**	**4.883**	**4.982**
losses [kW]	282.93	246.43	250.37	257.46	249.31	248.18
capacitor cost [$/year]	1,978.20	1,692.00	2,206.80	1,458.30	1,788.75	1,817.55
total cost [$ / year]	159,853.14	139,199.94	141,913.26	145,120.98	140,903.73	140,302.8
benefits [$ / year]		**20, 653.6**	**17,939.88**	**14,732.16**	**18,949.41**	**19,550.34**

*) Simulation results before any optimization and capacitor placement [25].

**) Simulation results after MSS [11], MSS-LV [12], fuzzy set [14], and genetic [15] optimizations (capacitors were removed before optimization).

TABLE IV
NONLINEAR LOAD DATA FOR THE IEEE 123-BUS SYSTEM

nonlinear bus	nonlinear load type (Table A1)	kW	kVAR
6	six-pulse variable frequency drive	15	10
7	six-pulse 3	15	10
10	six-pulse 2	24	3
19	six-pulse 2	24	3
26	six-pulse 2	15	10
30	six-pulse 1	24	3
33	six-pulse 3	24	3
42	six-pulse 3	15	10
49	six-pulse variable frequency drive	60	45
52	six-pulse 1	24	3
64	six-pulse 1	24	3
71	six-pulse variable frequency drive	15	10
73	six-pulse 3	24	3
87	six-pulse 2	60	45
89	six-pulse 1	24	3
92	six-pulse 1	24	3
94	six-pulse variable frequency drive	15	10
95	six-pulse 1	24	3
106	six-pulse variable frequency drive	15	10
113	six-pulse 2	24	3

TABLE V
SIMULATION RESULTS OF GENETIC ALGORITHM [15] AND THE PROPOSED GA–FL APPROACH FOR THE 123-BUS, DISTORTED IEEE DISTRIBUTION SYSTEM

optimization method	before optimization	GA optimization	GA-FL optimization
capacitor bank locations [kW]	Q83 = 200	Q26 = 150	Q42 = 300
	Q88= 50	Q42= 300	Q52= 300
		Q72= 150	Q72= 300
		Q76= 300	Q105 = 150
total capacitor [kW]	**Qt = 350**	**Qt = 900**	**Qt = 1050**
minimum voltage [pu]	0.874	0.904	0.915
maximum voltage [pu]	0.980	0.980	0.980
maximum THD_v [%]	**8.0319**	**3.1018**	**2.7603**
losses [kW]	94.96	82.021	81.28
capacitor cost [$/year]	125	360	390
total cost [$ / year]	53,114.5	46,127.72	45,744.24
benefits [$ / year]		**6,986.8**	**7,370.3**

VII. ANALYSIS AND CONVERGENCE CRITERION

tion network of Fig. 11 [26]. To introduce harmonic distortion, 20 nonlinear loads (Table IV) with different harmonic spectra (Table VI) are included. These loads are modeled as harmonic current sources and the coupling between harmonics is not considered. The high penetration of these nonlinear loads causes a maximum THD_v of 8.03% (column 2, Table V).

The results of the proposed GA–FL approach show a 5.5% increase in total annual benefits compared with those generated by the GA method (last row of Table V) while the maximum THD_v is significantly limited to 2.76%.

The generations of the GA–FL algorithm are continued until all chromosomes of the population become equal or the maximum number of generations is achieved. The initial conditions for (4) (i.e., the initial capacitor values) do not usually reside inside the permissible solution region. In this paper, a GA–FL approach is used to minimize the objective function while directing the constraints toward the permissible region.

To select the parent population at each generation, a fuzzy expert system (Fig. 7) is used to compute the fitness function of each chromosome considering the uncertainty of decision making based on the objective function and constraints. As a
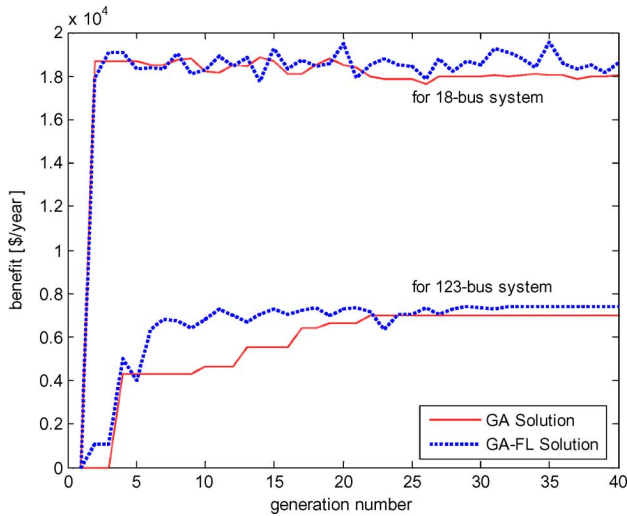
Fig. 10. Solution progress of the proposed GA–FL and the GA methods for the 18-bus (Table III) and 123-bus, distorted IEEE distribution systems (Table V).

Fig. 11. IEEE 123-bus distribution system [15] with 20 nonlinear loads.

result, new generations have a higher probability of capturing the global solution.

As demonstrated in Fig. 10, the relatively narrow search band of the conventional GA does not allow a large variation of chromosomes between generations and, thus, it is more difficult to escape from local optima. For the 18-bus and 123-bus systems, the solution is trapped at a near global point after the 14th and 22nd iterations, respectively. In the proposed GA–FL approach, there is more variety in the generated parent population as the chromosome evaluation is based on FL. The larger search space (allowing large variations of benefits in consecutive iterations) has resulted in a better near global solution at the 35th and 29th iterations for the 18-bus and 123-bus systems, respectively.

The inclusion of objective function and PQ constraints will automatically eliminate all solutions generating extreme values for voltages and/or currents and prevents fundamental and harmonic parallel resonances.

VIII. CONCLUSION

A GA, in conjunction with fuzzy logic (GA–FL), is proposed for the discrete optimization problem of fixed shunt capacitor placement and sizing in the presence of voltage and current harmonics. Power losses, energy losses, and the cost of fixed capacitors are used as the objective function. The PQ limits of IEEE-519 standard, maximum, and minimum of bus rms voltages and the allowed number of capacitor banks at each bus are considered as constraints. The main contributions of the proposed GA–FL approach are:

- PQ and cost index of the power system are improved simultaneously by optimal capacitor placement;
- a fuzzy expert system is used to improve the evolution process of GA (selecting the most suitable capacitor locations and sizes) by defining fitness (suitability) functions for each chromosome (computed from membership values of suitability of THD_v, suitability of voltage, and "$cost$");
- the uncertainty of decision making based on the objective function and suitability of constraints is considered in
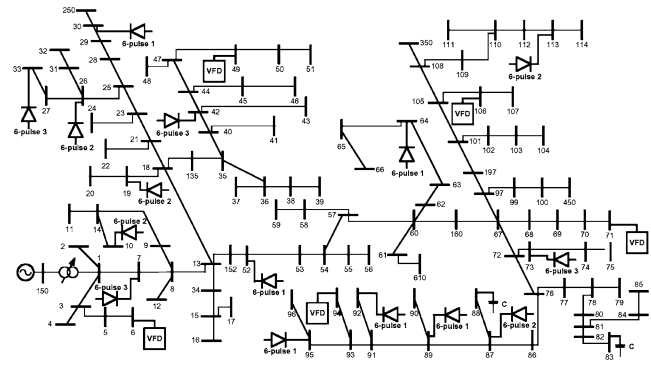
TABLE VI
HARMONIC SPECTRA OF NONLINEAR LOADS

order	nonlinear load							
	six-pulse1		six-pulse2		six-pulse3		six-pulse VFD	
	mag [%]	ph [deg]	mag [%]	ph [deg]	mag [%]	ph [deg]	mag [%]	ph [deg]
1	100	0	100	0	100	0	100	0
5	20	0	19.1	0	20	0	23.52	111
7	14.3	0	13.1	0	14.3	0	6.08	109
11	9.1	0	7.2	0	9.1	0	4.57	-158
13	7.7	0	5.6	0	0	0	4.2	-178
17	5.9	0	3.3	0	0	0	1.8	-94
19	5.3	0	2.4	0	0	0	1.37	-92
23	4.3	0	1.2	0	0	0	0.75	-70
25	4	0	0.8	0	0	0	0.56	-70
29	3.4	0	0.2	0	0	0	0.49	-20
31	3.2	0	0.2	0	0	0	0.54	7
35	2.8	0	0.4	0	0	0	0	0
37	2.7	0	0.5	0	0	0	0	0

the fitness function, hence, the probability of capturing a global solution is higher than the previously proposed GA method [15];
- the dependency of the GA–FL solution on the initial conditions is weak and can escape local optima and converge to the near global solution. This is not true for other proposed algorithms (e.g., MSS, LV, MSS–LV, and fuzzy);
- compared with GA [15], the proposed method utilizes a wider search space and avoids numerical problems by computing fitness functions based on fuzzy approximate reasoning;
- the inclusion of PQ constraints in the proposed fuzzy fitness functions prevents the occurrence of harmonic parallel resonance. As a result, harmonic resonances are shifted to other nondisturbing frequencies by relocating and resizing capacitor banks;
- simulation results for the 18-bus and 123-bus IEEE distorted networks are presented. Compared with previous methods, the proposed GA–FL approach generates better results (e.g., greater annual benefits within the permissible region of constraints).

APPENDIX

Fig. 11 illustrates the 123-bus system [26], [27] simulated in Section VI, and Table VI shows the harmonic spectra of nonlinear loads that are included to inject harmonics.

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