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A Genetic Algorithm Based Multi Objective Service Restoration in Distribution Systems

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Abstract: Problem statement: A Genetic Algorithm (GA) used here to find exact or approximate solutions to optimization and search problems. Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology such as inheritance, mutation, selection and crossover. **Approach:** GA is a method for search and optimization based on the process of natural selection and evolution. In this approach, several modifications are done for effective implementation of GA to solve the Electric Power Service Restoration Problem. **Results:** The problem statement includes all the objectives and constraints required for a practical supply restoration scheme. GA is used here to obtain the better result compared with other methods. GA starts with number of solutions to a problem, encoded as a string of status of sectionalizing and tie switches. **Conclusion**: The status of the switch ‘1’ and ‘0’ has been considered as ‘close’ and ‘open’ condition of the switch. The string that encodes each string is ‘chromosome’ and the set of solutions are termed as population. Obtained results are good and this technique is recommended here for future study.

Key words: Genetic algorithm, Electric Power Distribution Systems (EPDS), Electric Diesel Generator (EDG), Optimistic Time (OT), Pessimistic Time (PT), Maximum Time (MT), Standard Deviation (SD), current transformer

INTRODUCTION

Service Restoration Process Using Critical Path Method: The service restoration process involves several actions based on certain conditions before the start of each restoration activity. The main processes in restoring the supply to the radial feeder can be classified in two types: restoration of supply under power failure and restoration of supply after occurrence of fault. The first process involves the start of EDGs and closure of switches and breakers at the distribution network. The second process requires isolation or disconnection of the faulty load and then reconnection of the feeders within the minimum time.

The critical path method (Sarabian and Lee, 2010) helps in exact estimation of restoration time at each and every stage of the above mentioned processes or activities. At each stage of the restoration process or restoration activity, three estimation of duration are considered namely OT, PT and MT.

The OT is taken as the actual operating time based on the repeated testing conditions. The PT is taken as less than the optimistic time to account for additional loading effects and switching transients under abnormal conditions. The MT is taken as more than the OT to account for the probability of failure due to ageing, poor maintenance and defects in manufacturing of the accessories of the power plant. Experience of field engineers in optimal operation of power systems shows that these durations of activities follows the beta distribution of probability. Then the Expected Time (ET) for an activity can be approximately expressed as:

$$ET = (OT + 4 * MT + PT)/ 6 \tag{1a}$$

$$\sigma = (OT - PT)/6 \tag{1b}$$

where, σ is Standard Deviation (SD) in seconds. If the breaker or relay is a fast electronically controlled device and its operating time is in terms of milliseconds, then OT, PT and MT can be treated as almost equal. For these very fast operating switches the ET of operation is given by:

$$\text{Total Restoration Time (TRT)} = \sum_{i}^{n} ET_i \tag{1c}$$

where, i=1,2,3….n.(n is the total no: of activities.)

TRT1 in operation of the various relays in the part of system under fault (Alfred, 2010).

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TRT = TRT1 (ET1) + TRT2 (ET2)

TRT1 (ET1)	TRT2 (ET2)
3.5000	55.0
+3.5500	+62.5
+3.9800	70.0

TRT for the restoration of power supply to distribution network will be sum total of total restoration time of isolating the faulty circuit and the starting of EDG:

TRT= TRT1 + TRT2 = 270.83 + 24.6167 sec = 295.58 sec

The standard deviation of whole activity is given by:

$$\sigma_t = (\Sigma\, \sigma^2)^{1/2} \quad (1d)$$

The longest path will draw more attention to the substation operator or the distribution engineer, which needs more time to receive the power supply from the distribution substation and hence it is considered a critical path.

MATERIALS AND METHODS

Genetic algorithm is implemented as a computer simulation in which a population of abstract representations (called chromosomes) of candidate solutions (called individuals) to an optimization problem evolves towards better solutions. Traditionally solutions are represented in binary as strings of 0s and 1s, but other encodings are also possible. The evolution starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the population (based on their fitness) and modified (recombined and possibly mutated) to form a new population. The new population is then used in the next iteration of the algorithm. Commonly, the algorithm terminates due to maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population. If the algorithm has terminated due to maximum number of generations, a satisfactory solution may or may not have been reached.

The steps involved in GA are Initialization, Selection, Reproduction and Termination (Deb Kalyanmoy, 2004).

Programming methodologies: The disturbances in the distribution system are classified into two main categories: phase to phase fault, called a short circuit fault and a phase to earth fault called an earth fault. These disturbances were further classified as either temporary or permanent faults. The restoration time under faulty conditions need the calculation of fault current. Here symmetrical and unsymmetrical faults considered. The fault current can be easily calculated (Alfred, 2010) by forming the bus impedance matrix, considering the faults with and without impedance. The fault current at the faulted bus "k" is given by:

$$I_k = V_{ko}/(Z_{kk}+Z_f) \quad (2a)$$

where, Z_f is impedance of the fault and its value will be zero for the bolted faults. Z_{kk} is the k^{th} row and k^{th} column impedance element of Z_{bus}. V_{ko} is the prefault voltage at the bus K. The sequence network interconnection has to be done for unsymmetrical faults. Based on the total equivalent sequence impedances the positive, negative and zero sequence currents and then the fault currents can be calculated. For example, for the commonly occurring line to ground fault the positive sequence current is given by:

$$I_{a1} = V_{k0}/(Z_{akk1}+Z_{akk2}+Z_{akk0}) \quad (2b)$$

where, Z_{akk1}, Z_{akk2}, Z_{akk0} are positive, negative and zero sequence impedances of the "a"phase, "k"th row and "k"th column element of bus impedance matrix.

Then the fault current in the phase "a" is given by:

$$I_{af} = 3I_{a1} \quad (2c)$$

Operating time calculation of relays: The relay in power system network senses the fault and actuates the circuit breaker to isolate faculty circuit from the healthier one. These protective devices are connected via Current Transformer (CT). The current in the secondary winding of the current transformer is given by:

$$I_s = I_f / (\text{CT Ratio}) \quad (2d)$$

$$PSM = I_s / (OLS * PS) \quad (2e)$$

Where:

- I_f = Fault current
- PSM = Plug setting multiplier
- OLS = Overload setting for operation of transformer circuit breaker
- PS = Plug setting of relay

Table 1: Multiplication factor of circuit breakers

Multiplication factor	Type of circuit breaker
1.0	8-cycle or slow breaker
1.1	5 cycle breaker
1.2	3 cycle breaker
1.4	2 cycle breaker

The time corresponding to the operating current or PSM has been evaluated from the time current characteristics of the relay. The momentary rated r.m.s current of the circuit breaker I given by:

$$I_{mom} = MF * (E/X_d^{ll}) \quad (2f)$$

Where:
X_d^{ll} = Subtransient reactance of the generator
E = Rated phase operating voltage of the generator
MF = Multiplication factor

The MF for different types of circuit breaker (Manjunath and Mohan, 2007; Mohan and Manjunath, 2004) is given in Table 1. In this analysis the breaker is assumed to be a five cycle one.

Approach for solving EPSR using GA: In the past, considerable efforts have been devoted to the subject of service restoration in EPDS. The approaches are based on the application of various optimization methods to determine the optimal restoration plan of the EPDS. The shortcoming of these methods is that, the nature of the problem is so complex and due to the burdening of performance variants and due to practical difficulties, the desired optimal solution cannot be obtained in the minimum possible time. The increased computational time with large size distribution systems limits the efficient use of these approaches in service restoration procedures of DAS. The theory behind GA is taken from (Mahi and Izabatene, 2011).

Initial population generation: An ‘n’ feeder EPDS remains radial if at least ${}^{n}P_2$ number of branches are kept in ‘OFF’ status. To ensure this the faulted bus number is searched in bus data and corresponding branches where the faulted bus is found is switched ‘OFF’. Now randomly ‘n_1’ number of branches is switched ‘OFF’. Where $n_1 = {}^{n}P_2$-no. of branches switched off due to fault. Rest of the branches is kept ‘ON’ to restore maximum possible number of loads in the EPDS (Kothari, 2004).

Reproduction or selection operator: (1) Identify good solutions in a population, (2) Make multiple copies of good solutions, (3) Eliminate bad solutions from the population so that multiple copies of good solutions can be placed in the population.

There exists a number of ways to achieve the above tasks, but the method applied here is the tournament selection operator. In the tournament selection, tournaments are played between two solutions and the better solution is chosen and placed in the mating pool. Two other solutions are picked again and another slot in the mating pool is filled with the better solution if carried out systematically, each solution can be made to participate in exactly two tournaments. The best solution in a population will win both times there by making two copies of it in the new population using a similar arguments, the worst solution will lose in both tournaments and will be eliminated from the population.

Crossover operator: A crossover operator is applied next to the strings of the mating pool. Here two chromosomes are taken together and a random probability is generated if its less than the specified probability of cross over then only the cross over operation will take place. Now a number is generated between zero and size of the chromosome string. The bit strings of two selected chromosomes are swapped from the random number generated to the last bit of the chromosome. Hence the cross over operator recombines together good substrings from two good strings to hopefully form a better substring.

Checking of constraints: Now all the chromosomes are arranged in ascending order according to their fitness function value computed after mutation. Starting from the first chromosome having the minimum value of fitness function is tested for constraints checking. The first chromosome which satisfies all the constraints is chosen as the solution. If none of the chromosomes satisfies all the constraints then the whole process is repeated for one more generation. The solution to the multi-objective service restoration optimization problem should meet the following requirements:

- The Power Loss in the reconfigured PDN should be as less as possible
- Radial Structure of the PDN should be retained
- The switch operations should be as less as possible in order to minimize the interruption of power supply
- The Power supply should be restored to as much load as possible in the minimum time and the load

shedding should be according to the highest priority order consideration of the loads

- The Restoration time should be minimal

The multi-objective function for solving the Electric Power Service Restoration Problem is formulated as follows:

$$\text{Minimize } F = w_1f_1+w_2f_2+w_3f_3+w_4f_4+w_5f_5 \quad (2g)$$

where, $w_1 = w_2 = w_3 = w_4 = w_5 = 0.2$

Subject to the following constraints:

- Constraint on bus voltages: $|V_k|_{min} \le |V_k| \le |V_k|_{max}$
- Constraint on Real Power Transmission Loss: $P_{LL} \le P_{LLmax}$
- Constraint on Radial structure of the PDN: PDN must be Radial

Where:

$$f_1 = LostP_{Load} / TP_{Load}, f_2 = P_{LL} / PP_{Load},$$

$$f_3 = \frac{\sum_{j=1}^{nbch}(SW_j - SWB_j)^2}{SW_{max}}$$

$$f_4 = (V_{min} - V_k) / V_{max}, \text{if } V_k < V_{min},$$
$$= (V_k - V_{max}) / V_{max}, \text{if } V_k < V_{max},$$
$$k = 1,2,...n_{bus}, \; f_5 = 1 - (SMLP / nload \times nload + 1) / 2)$$

Where:

V_k = Voltage at the k^{th} bus
$LOSTP_{LOAD}$ = Loss of Real Power Demand due to change of network configuration in each iteration
TP_{LOAD} = Total Real Power Demand of the pre fault PDN
PP_{LOAD} = Present total real power demand on each iteration
P_{LL} = Total Real Power Transmission Loss in each iteration
P_{LLmax} = Maximum allowable PLL
nbch = Total number of branches
SW_{OP} = Number of switching operations
SW_j = Status of the switch j after the reconfiguration
SWB_j = Status of the switch j before the reconfiguration
SW_{max} = Sum of total number of sectionalizing and tie switches
N_{bus} = Total number of buses
SMLP = Sum of Priority order of the loads in the post fault PDN
n_{load} = Total number of connected loads in the post fault power distribution network
w_i = Positive weights for the i^{th} objective of the objective function 'F': $\sum_i^n w_i = 1$

RESULTS AND DISCUSSION

Algorithm of the new hybrid multi-objective quick service restoration technique for EPDS:

Step 1: Read the Bus Data, LPRO's, Real and Reactive Power Demand, Shunt Capacitor Bank Ratings Fig. 1-3. Read the Line Data, the number of feeders and the bus number at which substation/source is connected and Read the convergence tolerance (Moon *et al*., 1999)
Step 2: Obtain the Connectivity of the pre-fault PDN using New Network Connectivity Method. Form the Matrix of nodes beyond a particular node 'nbe'.
Step 3: Perform the Load Flow Analysis Using Forward Substitution Method. Data for Load Flow Analysis is given in the Table 2.
Step 4: Compute the line flows and also the branch currents in various sections of the feeders.
Step 5: Check whether any fault is occurred? If there is any occurrence of fault, go to the next Step, otherwise go to Step 27.
Step 6: Check whether the fault is symmetrical or unsymmetrical. If the fault is symmetrical, form the Z_{bus} of the distribution network using Harrison *et al*. (2008). If the fault is unsymmetrical, form the positive, negative and zero sequence impedance matrices of the post fault PDN using Harrison *et al*., 2008
Step 7: Set the generation count, Gen = 1.
Step 8: Obtain the Network Connectivity of the post fault PDN using the above algorithm of this study. Form the Matrix of nodes beyond a particular node 'n_{be}'.
Step 9: Select the population size based on the number of branches in the EPDS. Choose the length of the chromosome as same as that of total number of buses in the PDN.
Step 10: Consider the loads in the order of their highest priority using preemptive method.
Step 11: Perform the load flow analysis using forward substitution method and then, calculate the post fault voltages of the PDN.
Step 12: Compute real and reactive power line flows, real and reactive power losses in the PDN.
Step 13: Compute all the objectives of the objective function f_1, f_2, f_3, f_4 and f_5.
Step 14: Compute the objective function 'F' for each Chromosome.

Table 2: 16 Bus 3 feeder line data

Branch no:	From Bus	To Bus	Line length in km	LPRO	End bus load MW	End bus Load MVAR	Qsh in MVAR
1	1	4	1.25	3	2.100	0.92	0.0
2	4	5	2.50	1	1.750	0.87	1.1
3	4	6	0.75	4	1.250	0.65	1.2
4	6	7	2.16	7	1.500	0.80	0.0
5	2	8	1.05	9	1.280	0.76	0.0
6	8	9	1.00	13	1.300	0.78	1.2
7	8	10	0.79	2	1.650	0.78	0.0
8	5	11	1.18	-	-	-	0.6
9	9	11	2.10	8	0.940	0.56	0.0
10	9	12	0.98	11	1.450	0.59	0.0
11	3	13	1.50	5	1.420	0.68	0.0
12	10	14	1.25	-	-	-	3.7
13	13	14	1.50	6	1.450	0.67	0.0
14	13	15	0.98	10	1.956	0.79	1.8
15	15	16	0.89	12	1.080	0.45	1.8
16	7	16	1.58	-	-	-	-

Step 15: Evaluate the fitness of the individual chromosomes in the population under consideration.

Step 16: Rank the fitness function values in the ascending order.

Step 17: Perform selection of the individuals in the population.

Step 18: Perform the crossover between the chromosomes.

Step 19: Perform Mutation of individuals in the population. The steps of GA are referred from Madan and Madan, 2010.

Step 20: Form the new set of objective functions based on the new population.

Step 21: Check whether the constraints are met or whether the number generations reached maximum generation limit or not. If yes go to Step 24, otherwise go to next Step.

Step 22: Convert the new objective function value to binary equivalent and then perform the logical OR operation of this binary equivalent with to the old chromosomes.

Step 23: Update the generation count Gen = Gen + 1 and then go to Step 8.

Step 24: Perform the load flow analysis for the new reconfigured post fault PDN. Compute the line losses, power supplied from the substation and also calculate the real and reactive power line losses.

Step 25: Estimate operating time of the all the associated relays/breakers in the post fault PDN.

Step 26: Compute the total restoration time.

Step 27: Print the results.

Step 28: If any further fault analysis is to be carried out for operational planning of EPDS go to Step 1, otherwise go to next Step.

Step 29: Stop.

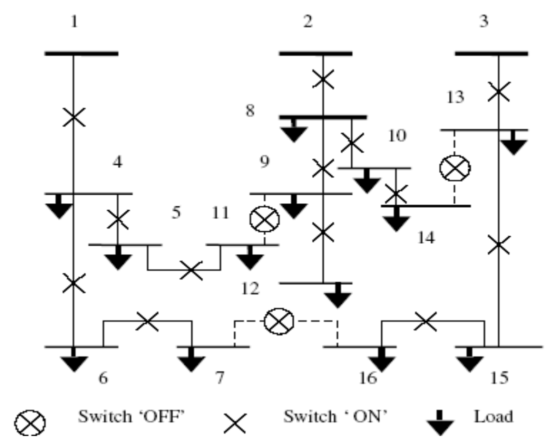

Fig. 1: bus 3 feeder sample network

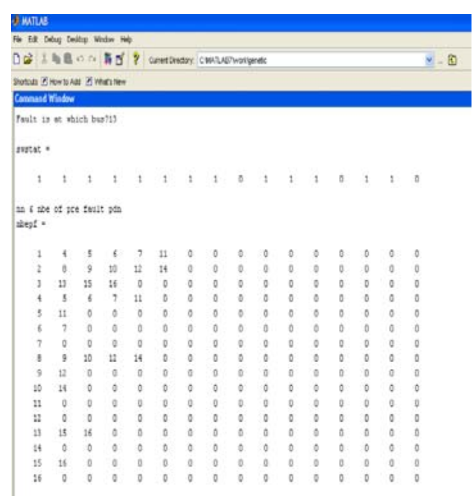

Fig. 2 Result for network connectivity matrix

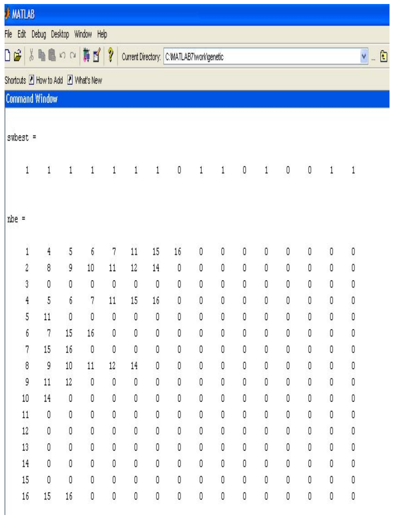

Fig. 3 Result for post fault connectivity matrix

CONCLUSION

Here it has been assumed that a line to ground fault takes place at the bus 13 with a fault impedance of 0.1 p.u. Due to the occurrence of fault, the relay/breaker connected between buses 3 and 13 is operated and hence bus 13 gets isolated from the power supply. Due to operation of the breaker the power supply also gets disconnected to the loads which are connected to the buses 15 and 16. Hence the loads connected to the buses 15 and 16 are in dark state. In order to restore the power supply to the loads which are connected to the buses 15 and 16, the distribution network has to be reconfigured. The search of optimal configuration of PDN has been done using GA. For the 16-Bus EPDS, the GA parameters are selected as follows:

Length of the Chromosome = 16
Population size = 16
Probability of crossover = 0.7
Probability of mutation = 0.7/16 = 0.04375

The optimal configuration of post-fault PDN has been obtained using the GA. The statuses of the switches in optimal configuration of the PDN are given as follows:

SWSTAT= [1 1 1 1 1 1 1 0 1 1 0 1 0 0 1]

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