Load Profile Based Determination of Distribution Feeder Configuration by Dynamic Programming

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Abstract-- **This paper presents a new method to determine feeder reconfiguration scheme considering variable load profile. The objective function consists of system losses, reliability costs and also switching costs. In order to achieve an optimal solution the proposed method compares these costs dynamically and determines when and how it is reasonable to have a switching operation. The proposed method divides a year into several equal time periods, then using particle swarm optimization (PSO), optimal candidate configurations for each period are obtained. System losses and customer interruption cost of each configuration during each period is also calculated. Then, considering switching cost from a configuration to another one, dynamic programming algorithm (DPA) is used to determine the annual reconfiguration scheme. Several test systems were used to validate the proposed method. The obtained results denote that to have an optimum solution it is necessary to compare operation costs dynamically.**

Index Terms-- **Distribution feeder reconfiguration, dynamic programming, load profile, loss reduction, reliability.**

I. INTRODUCTION

Most of interruptions in power system are due to distribution networks failures. Energy loss is another important problem in distribution system operation. To improve system reliability and efficiency it is necessary to improve distribution network operation.

Generally distribution systems are designed ring and operated radial. To have an efficient and reliable system, distribution feeder configuration could be varied via switching operation.

Marilyn Beck presented the idea of reconfiguration for the first time in 1975 [1]. Civanlar proposed an early method on feeder reconfiguration in [2]. The method was to find a normally open (N.O.) switch based on the maximum voltage difference, close it and search to find the appropriate normally closed (N.C.) switch in the loop to open. Optimal configuration obtained by this method was highly dependent on the initial configuration. In [3] Shirmohammadi presented a method that closes all N.O. switches at first, then opens suitable switches gradually in the ring network to achieve a radial network with minimum loss.

As there are many candidate switches in a distribution system, reconfiguration optimization is a non-linear and complicated problem. Several intelligent algorithms like genetic algorithm, particle swarm optimization (PSO),

simulated annealing, ant colony optimization and heuristic algorithms were used to solve this problem [4]-[7]. In [8] distribution network is considered as a graph which has a tree structure and graph theory is used for reconfiguration of networks. In this method starting with a feasible configuration, using graph theory all tree based configurations are obtained and comparing cost of each configuration, optimal solution is achieved. In most of studies the main objective is loss reduction. In [9] Brown solved feeder reconfiguration problem to improve system reliability. In [10] a reconfiguration methodology is presented that aims to achieve the minimum power loss and increment load balance factor of radial distribution networks with distributed generators.

In most of presented reconfiguration methods, fixed load and parameters were used for one snap shot optimization [1]-[10]. But in [11] Chen presents a method to determine optimal switching criterion for each four season and compute switching cost to find cost benefit result from switching operation. Moreover, in [12] Yin presents a multiobjective operation optimization problem considering time-varying effects and switching costs. The proposed method divides annual feeder load curve into multiperiods of load levels and determine the optimal configuration at each load level [12].

System configuration in each time interval of a year is not independent from configuration of other intervals. Therefore in this paper a novel method is presented to determine feeder reconfiguration scheme of a network considering continual changes of variables such as load curves and line failure rates. To achieve an optimal solution, the costs of system loss, customer interruption and switching are compared dynamically to determine optimal feeder reconfiguration scheduling over a year. Results show that it is necessary to consider configuration of previous and latter periods to achieve the optimal switching operation scheme.

II. PROBLEM FORMULATION

Dynamic reconfiguration optimization is a multiobjective problem. As it can be seen in (1), the objective function is to minimize total cost of energy loss, customer interruption and switching costs over a year.

$$\text{Minimize } f(x) = CLOSS + CCI + CSW \qquad (1)$$

Where $f(x)$ denotes the total operation cost for a distribution system. Moreover, $CLOSS$ and CCI represent the loss costs and customer interruption costs, respectively and CSW denotes total annual cost of switching operation.

Energy loss varies with time. To calculate cost of energy loss over a time interval based on variable load curves it is

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necessary to use a load flow solution and compute loss for each hour. So that the cost of energy loss can be expressed as

$$CLOSS = C_{energy} * \sum_{d=1}^{ND} \sum_{t=1}^{24} \sum_{l=1}^{NL} R_l * I_l^2 \qquad (2)$$

Where *CLOSS* is the cost of energy loss, moreover C_{energy} represents the energy cost (\$/kWh), *ND* is the number of days in the time interval, while *NL* is the number of lines of system. R_l and I_l are line resistance and line current, respectively.

Operation records show a high correlation between line failure rates and line loading [12]. Seasonal outage data are used to obtain line failure rates. In this study, each line failure rate is obtained based on loading of the corresponding line.

On the other hand, interruption cost of residential, commercial and industrial customers are different and vary with time. To compute cost of customer interruption over a period, (3) is used as

$$CCI = \sum_{d=1}^{ND} \sum_{t=1}^{24} \sum_{i=1}^{NL} \lambda_i(d) l_i \left(\sum_{j=1}^{Nload} C_j(d) L_j(d) \right) \qquad (3)$$

Where $\lambda_i(d)$ is outage rate on day d and l_i is length of line *i*. Moreover *Nload* is the number of customers that are interrupted by failure in line *i*. $L_j(d)$ represents peak load of customer *j* on day *d*, and $C_j(d)$ is the interruption cost (\$/kW) of load *j*. Note that interruption cost of residential, commercial and industrial customers are different.

It is necessary to determine which customers are interrupted by failure in line *i* for each new configuration. To do so, graph theory is used in this paper.

Costs of maintenance, switching operation, switch surge and switch lifetime are considered to determine each switching cost [12]. It is assumed that switching operation cost is a certain percentage of a feeder sectionalizer's installation cost. The annual cost of switching can be calculated by (4).

$$CSW = \sum_{s=1}^{NT-1} CSW_{s,x:y} \qquad (4)$$

$$CSW_{s,x:y} = SW \times NS_{x:y} \qquad (5)$$

Where, CSW represents switching cost from configuration x in s[th] period to configuration y in s+1th period. Moreover $NS_{x:y}$ is the number of switch status changes from period number *s* to period number *s+1*, SW is cost of one switching. NT represents the number of time intervals over a year.

The voltage magnitude at each bus and current magnitude at each branch are two constraints of this problem, and are expressed as follows.

$$V_{min} \leq V_i \leq V_{max} \qquad (6)$$

$$-I_{max} \leq I_i \leq I_{max} \qquad (7)$$

Where V_{min}, V_{max} and I_{max} are the allowable minimum voltage, maximum voltage and maximum current magnitudes, respectively. Moreover, in each generation the network configuration should be radial. In this study graph theory is used to check if a configuration is tree or not.

III. DYNAMIC PROGRAMMING ALGORITHM

Dynamic Programming Algorithm (DPA) has many advantages for solving a problem that the chief advantage of DPA is reduction in dimensionality of a problem. Assume a year is divided into *n* periods and the optimal configuration of a network should be determined over each of those periods. If there are *m* feasible states (*m* feasible configurations for a network), each state (configuration) could be an answer over each period, so there will be about (m)[n] paths for a year. Note that in this study a feasible state is a configuration in which the network is rural and all loads are supplied. As it can be seen it is a large scale problem, so DPA is used to solute this problem (Fig. 1).

As there are several candidate states for each period with different loss and customer interruption costs, DPA should balance the benefits in system reliability and loss against the costs of switching and determine optimum reconfiguration scheme for a year. In this paper the DPA is set up to run forward in time from the initial period to the final period. In each stage the algorithm determine the path with minimum cost to arrive at each state of a period and other non-optimal paths are removed. So in the next stage, for the next time period the path with minimum cost of each state is determined based on costs calculated in the previous period. The recursive algorithm to calculate the minimum cost is as

$$F_{cost}(K,I) = \min[P_{cost}(K,I) + S_{cost}(K-1,L:K,I) + F_{cost}(K-1,L)]$$
$$(8)$$

Where $F_{cost}(K,I)$ is the least total cost to arrive at state (K, I) and $P_{cost}(K,I)$ is operation costs (loss and interruption costs) for state (K,I). Moreover $S_{cost}(K-1,L:K,I)$ is transition (switching) cost from state (K-1, L) to state (K, I) [13]. State (k, I) is the I_{th} configuration in period K.

IV. EFFECTIVE CONFIGURATIONS DETERMINATION

By above descriptions there will be many feasible states for each period of DPA that should be limited. To do so, adopting a PSO algorithm optimal feeder configuration is obtained for multi periods (e.g. all 365 days) over a year disregarding switching cost, as have been done in traditional studies [1]-[10]. So several optimal configuration are obtained that can be used to determine effective configurations of each period in DPA.
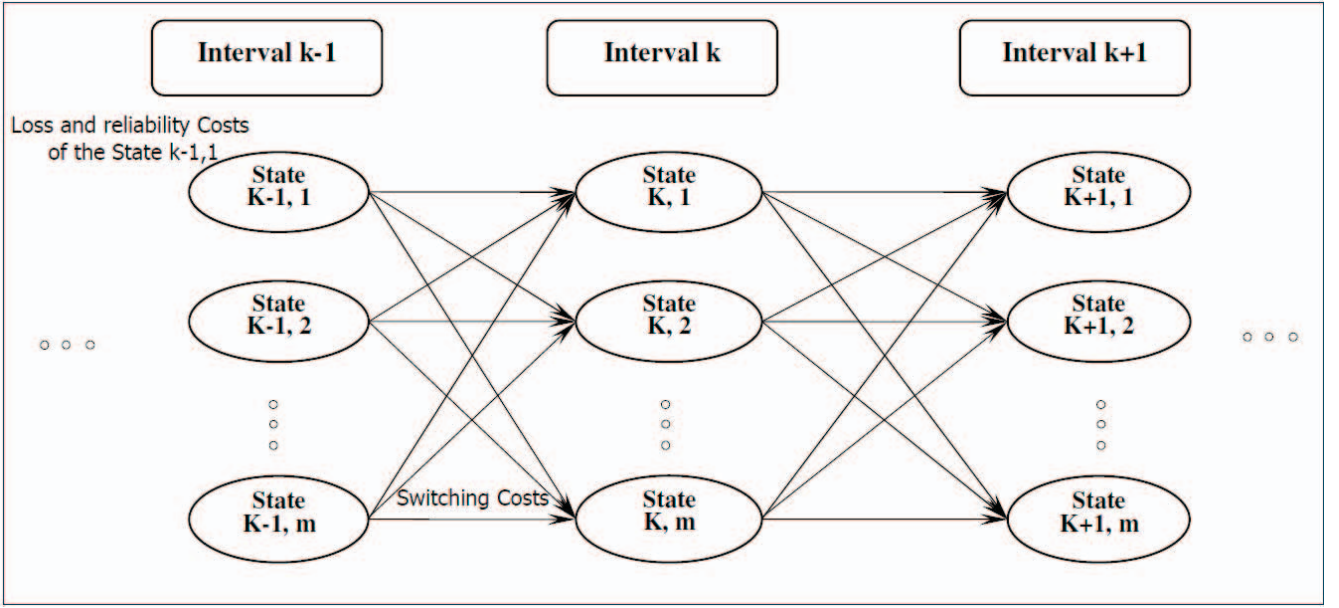
Fig. 1. Forward Dynamic Programming Algorithm for a network with *m* effective configuration

After determining configuration of all periods, it could be seen that some switches are always closed over a year. In other words, just some switches help distribution network reinforcements to have an optimal configuration. Therefore, appropriate switches for switching can be determined to develop effective feasible configurations.

V. SOLUTION PROCESS AND DISCUSSION

The proposed method to determine annual feeder reconfiguration consists of two main stages. The presented method is as follows:

First Stage: Effective configurations determination

Step 1) Divide a year into 365 daily periods. Note that if the periods are selected shorter the execution time will be longer. On the other hand, if the periods are selected longer it may result in suboptimal solution.

Step 2) Achieve the optimal feeder configuration for all daily periods independently using PSO algorithm, disregarding switching cost.

Step 3) Develop a matrix that contains all obtained optimal feeder configurations in step 2 and find the active switches that participate in switching operation.

Step 4) Determine the effective feasible configurations based on the active switches.

Step 5) If the number of feasible configurations that were obtained from step 4 is enormous, use data mining technique to decrease the number of feasible configurations

Second Stage: Dynamic Programming Algorithm

Step 6) Divide a year into multiperiods and calculate loss and customer interruption for all effective configurations (that are obtained from step 5) during each periods.

Step 7) Calculate switching costs between configurations.

Step 8) Run DPA to determine annual reconfiguration scheme.

A. PSO algorithm

Population based optimization algorithms, such as PSO and GA often can find optimal solutions for reconfiguration problem. PSO is adopted in this paper to find the optimal configuration of each period independently. The method that is used for this purpose is like [5]. The objective function is to minimize total cost of energy loss and customer interruption for each interval

$$\text{Minimize } C(x) = CLOSS + CCI \tag{9}$$

Where $C(x)$ denotes the total operation cost for a distribution system in each period.

More details of PSO algorithm can be found in [5].

B. Data mining technique

In real large distribution networks, number of active switches and consequently number of feasible configurations feed to the DPA will be so high that handling of these feasible configurations may be impossible for DPA. Our experience shows that if there are 1000 candidate configurations for 52 weekly periods, the execution time for running DPA will be about 8 hours. Therefore, if the number of feasible configurations that were obtained from step 4 is enormous, data mining technique will be used for solving the problem for reduction in number of possible configurations. A technique of data mining called APRIORI is used here for reduction in number of possible configurations. The main application of the algorithm is in analyzing of market baskets [14]. Based on items bought by customers, the algorithm finds some association rules. Each rule is something like this:

$X \Longrightarrow Y$: {confidence, support}
Where, X and Y are two set of items.

Confidence shows the probability of being X and Y in a bought basket together. And support shows that if X is in a basket, with which probability Y is also in that basket. More details of APRIORI algorithm can be found in [14].

Assume that each network configuration is a bought basket and each normally opened switch is an item in the basket. So based on the configurations matrix that has been developed in step 3, APRIORI algorithm determines many rules about the relationship between switches.

For example assume a rule is obtained as follow:

lhs	rhs	support	confidence
{switch38} => {switch19}		0.1153846	1.0000

Support 0.1153 means that switch 19 and 38 have been opened in 11.53% of configurations. Confidence 1.00 means that if switch 38 was opened in a configuration, switch 19 have been opened in that configuration with the probability of 1.00 (surely). In this problem, rules with confidence of 1.00 are used to limit the number of effective configurations. For example the mentioned rule is applied as: if switch 38 is opened in a configuration, consider the configuration as an effective configuration, just if switch 19 is opened in that configuration too. These rules will be applied to problem insofar as problem dimension becomes proper.

VI. NUMERICAL RESULTS

The proposed method was tested on several test systems. Simulation results of a 33-bus distribution system are presented here. The test system has been used in many reconfiguration studies and is shown in Fig. 2. Operation records of a feeder in Iran have been used as a pattern for residential, commercial and industrial annual load curve.
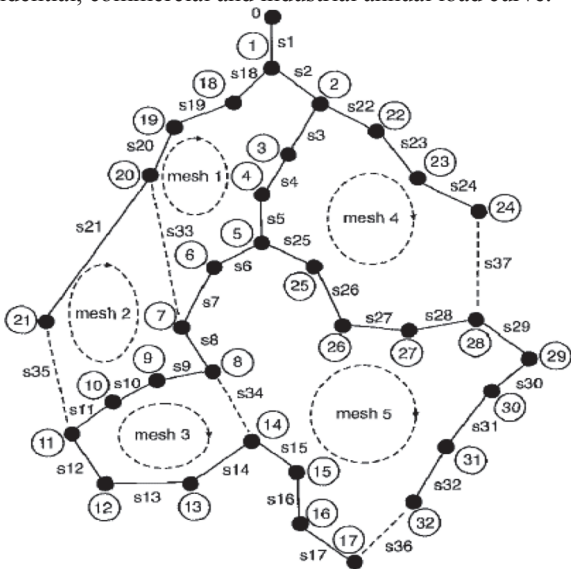

FIG. 2. 33-bus distribution network with assigned nodes and switches
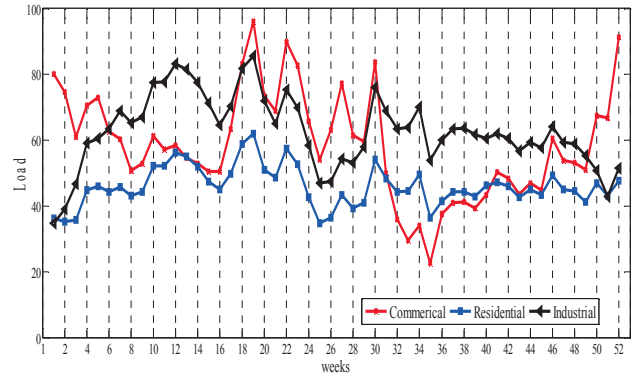

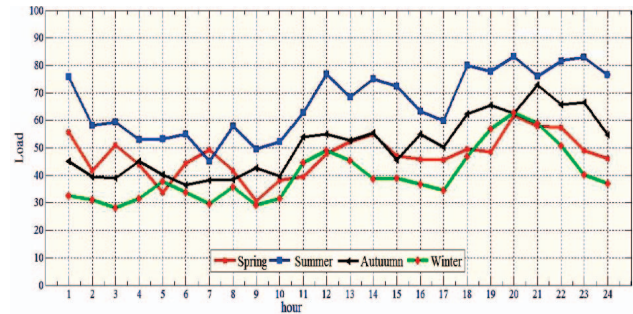FIG. 3. Annual average peak load for commercial, residential and industrial consumers

FIG. 4. Average daily load profiles for a typical residential customer during four seasons of a year.

Fig. 3 shows average peak load for commercial, residential and industrial consumers. Moreover, Fig. 4 shows average daily load profiles for a typical residential customer during four seasons of a year. Most of parameter, such as energy, customer interruption and switching cost are borrowed from [12]. The cost of electricity is assumed $6.5625 cents per kWh, the average customer interruption cost for one hour is assumed $0.482, $9.085, and $8.552 per kW for residential, industrial, and commercial customers, respectively. Furthermore, the cost of one switching is assumed $50.75 which is one-eightieth of a new switch installation cost.

At the first step a year is divided into 365 days, then using PSO algorithm, disregarding switching cost, the optimal feeder configurations for all days are obtained. Nine different optimal configurations were obtained that the optimal configuration for all of days was one of these nine configurations. Table I shows these nine configurations. Note that each configuration is shown by its normally open switches.

TABLE I
OPTIMAL CONFIGURATIONS DISREGARDING SWITCHING COST

Configuration	Opened switches	Configuration	Opened switches
1	7-9-13-36-37	6	7-9-14-27-36
2	7-9-14-28-36	7	7-9-14-28-37
3	7-9-14-32-37	8	7-9-13-28-36
4	7-9-14-36-37	9	7-9-14-27-34
5	7-9-13-32-37		

TABLE II
FEASIBLE CONFIGURATIONS (STATES OF DP ALGORITHM)

	Normally opened switches status				
1	7-9-13-27-37	9	7-9-14-27-37	17	7-9-27-34-37
2	7-9-13-28-37	10	7-9-14-28-37	18	7-9-28-34-37
3	7-9-13-27-32	11	7-9-14-27-32	19	7-9-27-32-34
4	7-9-13-28-32	12	7-9-14-28-32	20	7-9-28-32-34
5	7-9-13-32-37	13	7-9-14-32-37	21	7-9-32-34-37
6	7-9-13-27-36	14	7-9-14-27-36	22	7-9-27-34-36
7	7-9-13-28-36	15	7-9-14-28-36	23	7-9-28-34-36
8	7-9-13-36-37	16	7-9-14-36-37	24	7-9-34-36-37

TABLE III
FEEDER RECONFIGURATION SCHEDULING USING DPA

Weeks	Opened switches	Interruption cost($)	Loss Cost ($)
1-4	7-9-14-28-36	4966.44	3456.19
5-10	7-9-14-36-37	20345.24	13411.64
11	7-9-14-28-36	6602.904	4559.693
12-14	7-9-14-36-37	22042.95	14187.14
15-29	7-9-14-28-36	70218.07	46444.73
30-52	7-9-14-32-37	20948.21	30915.65

TABLE IV
OPTIMAL CONFIGURATION, DISREGARDING SWITCHING COST

Weeks	Opened switches	Weeks	Opened switches
1	7-9-14-28-36	28-29	7-9-14-28-36
2	7-9-14-36-37	30	7-9-14-32-37
3-4	7-9-14-28-36	31	7-9-14-28-36
5-7	7-9-14-32-37	32-33	7-9-14-32-37
8	7-9-14-28-36	34-35	7-9-14-28-36
9	7-9-14-32-37	36-38	7-9-14-32-37
10	7-9-14-36-37	39-40	7-9-14-28-36
11	7-9-14-28-36	41	7-9-14-32-37
12	7-9-14-32-37	42	7-9-14-17-28
13	7-9-14-36-37	43	7-9-14-28-36
14-15	7-9-14-32-37	44-45	7-9-14-32-37
16-19	7-9-14-28-36	46	7-9-14-28-36
20	7-9-14-32-37	47-48	7-9-14-32-37
21-23	7-9-14-28-36	49	7-9-14-36-37
24	7-9-14-32-37	50	7-9-14-28-32
25	7-9-14-28-36	51	7-9-14-28-36
26	7-9-14-32-37	52	7-9-14-32-37
27	7-9-14-36-37		

TABLE V
DIFFERENT CONFIGURATION METHODS COMPARISON

Configuration method	Loss Costs & Interruption Costs	Switching Costs	Total Costs
Base configuration	395,520	No Sw.	395,520
One reconfiguration from base configuration	260,090	No Sw.	260,090
Multiple reconfigurations without considering the switching cost	257,520	2892.75	260,412.75
Multiple reconfigurations by Dynamic Programming	258,100	304.5	258,404.5

The active switches that participate in switching operation are as below:

S7, S9, S10, S11, S13, S14, S15, S17, S28, S32, S34, S36, S37.

Each feasible configuration of these switches which does not violate technical constraints can be used as one of feasible configurations of DPA for finding annual feeder scheduling. Based on different combination of these active switches 24 feasible configurations are obtained that are shown in Table II.

After derivation of feasible configuration from active switches, in next stage a year is divided into 52 weeks. Therefore there will be 24 candidate states for each period. Loss and customer interruption costs for each of the 24 states during all 52 weekly periods are computed. In addition, a matrix with size of 24×24 is developed that each array of that ($C_{i,j}$) is the switching cost between configuration i to j using (5).

After the cost of each state and transition costs between states are determined, using DPA, optimal annual feeder scheduling will be obtained. The simulation results are shown in Table III.

If feeder configurations of 52 weeks being determined without considering the switching cost in feeder scheduling, the result will be as Table IV.

Comparison between results of different reconfiguration scheme is shown in Table V. For the configuration shown in fig. 4, the annual total cost is $395,520. If only one reconfiguration for a whole year is assumed, switches number 7-9-14-28-36 will become normally open switches, and neglecting the switching cost (Table IV), the annual cost will reduce to $260,090. As it can be seen multiple reconfigurations without considering the switching cost results total cost of $260,412.75, which denotes that the switching operation is inappropriate, and reduction in loss and reliability costs may not result in reduction of the total costs. After executing the procedure proposed in section V, an annual operation cost of $258,404.5 is achievable that is less than other solutions. Comparing the obtained results from third and fourth rows of this table denotes that it is necessary to compare operation costs consists of system loss, switching costs and reliability costs dynamically to achieve the optimum solution.

VII. CONCLUSION

In a deregulated power market distribution companies have to provide electricity with an acceptable reliability and efficiency to satisfy the customers. This paper presented a novel method for reconfiguration that considers variable load profile. The proposed method compares costs of system loss, costumer interruption and switching costs dynamically to find the optimal reconfiguration scheme with the minimum cost. To solve the problem, several effective configurations were determined for the network and using DPA optimal feeder reconfiguration scheduling over a year was obtained. Simulation results illustrate that to have an optimal switching operation it is necessary to analyze benefit of reliability and loss against the costs of switching. In addition, it can be seen

from the results that configurations of the network during a time period is not independent from other periods.

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