An Accurate Evaluation of Consumption Pattern in Reconfiguration of Electrical Energy Distribution Systems

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***Abstract*—Electrical energy consumption pattern has always been important for power distribution companies, because load variations and method of electricity consumption affect energy losses amount. For this, distribution companies frequently encourage the network users to correct their energy consumption behavior by suggesting some incentives. Reconfiguration of distribution systems for a specific load pattern is an effective way to reduce the losses. Hence, some papers have considered load variations in distribution system reconfiguration (DSR) to show importance of consumption pattern for reconfiguration decisions. However, most of specialized studies have been ignored load changes in their reconfiguration models because of a significant increase in computational burden and processing time. On the other hand, neglecting the consumption pattern causes the energy losses is calculated inaccurately. Therefore, this paper intends to evaluate effect of load pattern on reconfiguration plans in order to find out importance of considering load variations in energy losses minimization via DSR. The analysis has been conducted on well-known distribution systems by AMPL (a classic optimization tool).**

***Index Terms*—Consumption pattern, distribution networks, DSR, energy losses.**

I. INTRODUCTION

One of essential power network components [1]–[6] that has important role in delivering electricity to energy consumers [7], [8] is distribution system. However, part of the electrical energy is converted to useless heat during the power delivery because of distribution lines resistance. Ohmic (active) power losses [9] affect the operational costs and voltage profile of the distribution system. Hence, active losses reduction is important for distribution network operators [10].

Distribution system reconfiguration (DSR) is an effective method to reduce the energy losses. In this way, system topology is changed by opening and closing sectional and tie line switches, respectively, as network radiality and connectivity have not been lost [11]. Although losses minimization is important in DSR [12], other objectives such as power quality, network adequacy [13]–[15], system stability [16], reliability indices [17], [18], lines loading [19], [20], line maintenance costs [21], supply capacity expansion, load balancing, distributed generation (DG) costs [22], and power restoration [23] can be optimized along with losses.

After publication of Merlin and Back's paper in 1975, much research has been done on the field of DSR with the aim of active power losses minimization. Some of these research works have employed different power flow methods for solving the problem such as DC [24], AC [25], Newton [26], OPF [27], radial [28], simplified [29], and linearized [30]–[32] load flow techniques. Some of them have proposed new strategies for the problem formulation such as loss change estimation [33], network partitioning and division [34], [35], and Benders decomposition [36]. Also, some others have presented various models for DSR based on linear [37], non-linear [38], integer [39], [40], and binary [41] programming.

However, load variations have not been considered in all of these studies. Regarding importance of consumption pattern in losses calculations, some specialized literature included the power demand changes in DSR for precisely computation of the energy losses and some of them considered load changes for determination of real optimal reconfiguration plans. It is obvious that considering actual variable power demand rather than a fixed load amount lead to a correctly calculation of power losses in static reconfigurations (distribution system topology is determined in the beginning of operation period) and affect reconfiguration plans in dynamic studies (network configuration is changed during operation period according to load levels).

The important question is that is considering load variations changes the reconfiguration plans in a static DSR as some research works claim or it just increases computational burden and time without any specific gains? In order to answer this question, in [42], load pattern was considered in reconfiguration problem with the aim of loss minimization. In this approach, the load curve was divided into four levels and the load level of each bus was estimated by an artificial neural network (ANN). For each load level, a different reconfiguration plan was proposed by ANN. The results show that configuration of distribution system will be changed depending on load demand level in multi-stage (dynamic) frameworks.

However, it was not shown that would be the reconfiguration plan changed by considering whole load profile in static applications? Moreover, the performance of the proposed algorithm is degraded by selecting an inappropriate training set for ANN.

In order to resolve this problem, a clustering technique was employed to determine the best training set in [43]. Although this procedure could enhance the performance of ANN, clustering the loads based on their values without considering their locations can decrease the precision of the solution method. Also, no answer was found in [43] for the question asked by current research.

In [44], distribution losses cost and capacitor investment were minimized by simultaneous network reconfiguration and optimal allocation of shunt capacitors considering the daily load curve. In order to decrease the processing time of the proposed heuristic algorithm, actual demand was approximated by four load levels. However, this approximation has significantly decreased the precision of losses cost calculations. This fact can affect the optimal place and number of capacitor banks and therefore changes the proposed switching scenarios because of imprecisely comparison of losses cost with capacitor investment.

Moreover, in [45], the power losses and switching costs were minimized through network reconfiguration in presence of DG considering seasonal power demand. Although the simulation results demonstrate a significant decrease in energy losses due to DG usage, the optimal solutions are not true because of ignoring DG investment and operational costs in the problem formulation.

In [46], weekly and seasonal load profiles were considered to maximize the annual investment return via network reconfiguration. The investment return contains cost saving due to loss reduction, the installation cost of communication equipment, and the maintenance cost of remote control switches. The results confirmed that the large amount of investment can be saved through the dynamic reconfiguration of distribution systems by automatic switches. Spite of increase in computation burden and processing time of the proposed model, load variations had to be considered in [46] because of dynamic nature of the problem and optimization of losses cost beside other operational expenses.

Finally, in [47] and [48], energy losses cost was minimized considering the daily load curve using an artificial immune system (AIS). It has been shown that load variations change the reconfiguration plans in static frameworks. If this is true, accuracy of most optimal reconfiguration plans found by previous research are questionable because they have not included the load profile. On the other hand, this change should not happen based on power system engineering knowledge because peak loads (critical situations) usually determine the network operation conditions. Thus, accurate evaluation of consumption pattern effect on reconfiguration decisions is necessary to find out if load variations are effective, consumption pattern has to be considered in static reconfiguration problems even for power losses minimization.

This paper analyzes impact of load profile on distribution network reconfiguration considering different consumption patterns. The behavior of demand variations is modeled using different hourly load profiles as a mixed-integer conic programming (MICLP) problem. The proposed idea is tested on several distribution systems using CPLEX in AMPL.

II. CONSUMPTION PATTERNS

Figures 1 to 4 show different load patterns for a distribution system during an operation period 24 h. In these profiles, vertical axes represent the power demand as a percentage of the system peak load.

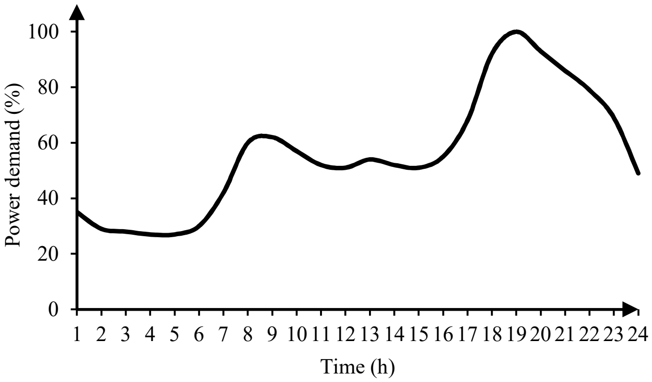

Fig. 1. Load pattern 1.

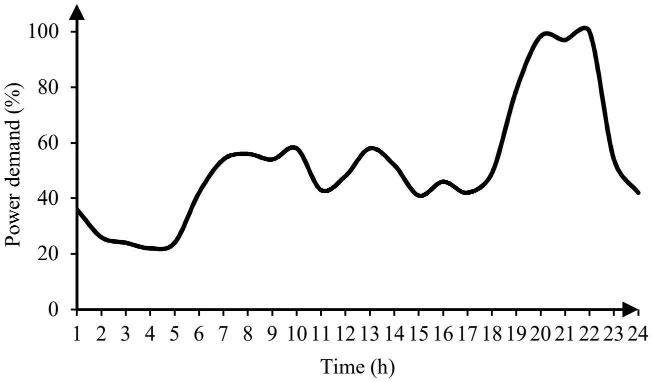

Fig. 2. Load pattern 2.

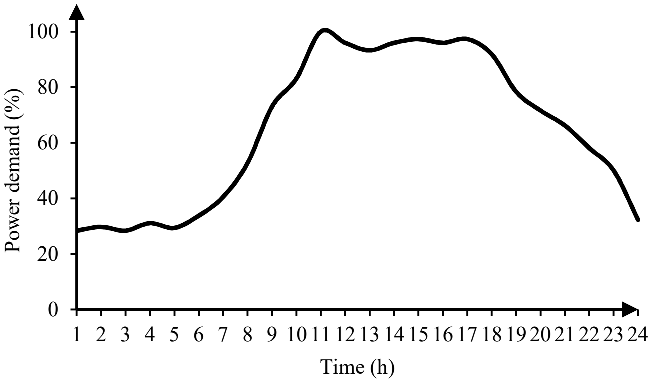

Fig. 3. Load pattern 3.

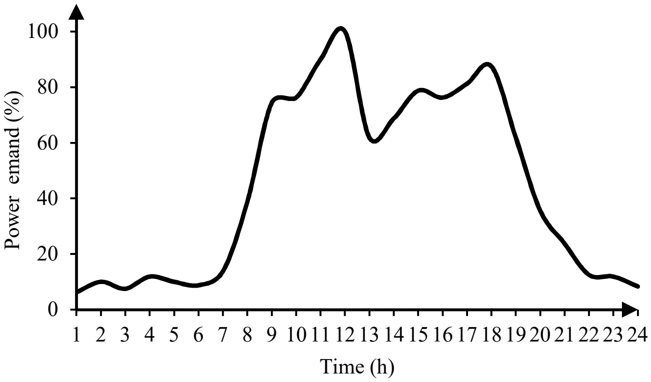

Fig. 4. Load pattern 4.

In order to prevent high computational burden and processing time in static reconfiguration, usually power consumption of distribution system is considered to be a fix for whole operation period. On the other hand, the power losses cannot be calculated correctly if load demand is considered to be fixed. This is an important challenge for distribution system operators because considering load profile in DSR calculations increases computational time and ignoring it decreases computational accuracy. On the other hand Refs [47] and [48] show that load profile and variations affect reconfiguration plans and have to be considered in DSR. Accordingly, in present paper, the effect of consumption patterns are evaluated on DSR problem using load patterns 1 to 4.

III. RECONFIGURATION PROBLEM CONSIDERING LOAD PATTERN

The DSR problem, aiming minimization of energy losses cost (C_{Loss}) including load profile can be formulated by (1) to (9).

$$Min\ C_{Loss} = \int_{t=1}^{t=24} C_L(t) \sum_{ij\in\Omega^l} R_{ij} \left|I_{ij}(t)\right|^2 dt \tag{1}$$

subject to:

$$P_i^S(t) + \sum_{ki\in\Omega^l} P_{ki}(t) - \sum_{ij\in\Omega^l} P_{ij}(t) - \sum_{ij\in\Omega^l} R_{ij}\left|I_{ij}(t)\right|^2 = P_i^D(t) \tag{2}$$

$$Q_i^S(t) + \sum_{ki\in\Omega^l} Q_{ki}(t) - \sum_{ij\in\Omega^l} Q_{ij}(t) - \sum_{ij\in\Omega^l} X_{ij}\left|I_{ij}(t)\right|^2 = Q_i^D(t) \tag{3}$$

$$\begin{aligned}&\left|V_i(t)\right|^2 - \left|V_j(t)\right|^2 = 2\left[R_{ij}P_{ij}(t) + X_{ij}Q_{ij}(t)\right] \\ &+\left(R_{ij}{}^2 + X_{ij}{}^2\right)\left|I_{ij}(t)\right|^2 + b_{ij}(t) \qquad \forall i,j\in\Omega^b\end{aligned} \tag{4}$$

$$\left|V_j(t)\right|^2 \left|I_{ij}(t)\right|^2 = P_{ij}{}^2(t) + Q_{ij}{}^2(t) \qquad \forall j\in\Omega^b, ij\in\Omega^l \tag{5}$$

$$\sum_{ij\in\Omega^l} y_{ij} = \left|\Omega^b\right| - 1 \tag{6}$$

$$V_{\min}^2 \le \left|V_i(t)\right|^2 \le V_{\max}^2 \qquad \forall i\in\Omega^b \tag{7}$$

$$0 \le \left|I_{ij}(t)\right|^2 \le \left(I_{ij}^{\max}\right)^2 y_{ij} \qquad \forall ij\in\Omega^l \tag{8}$$

$$\left|b_{ij}(t)\right| \le \left(V_{\max}^2 - V_{\min}^2\right)\left(1 - y_{ij}\right) \quad \forall ij\in\Omega^l \tag{9}$$

Where, Ω^l and Ω^b are set of distribution lines and buses, respectively. $C_L(t)$ is cost per unit of energy losses at time t. $P_{ij}(t)$ and $Q_{ij}(t)$ are active and reactive power flows of line ij at time t, respectively. R_{ij} is resistance and X_{ij} is the reactance of line ij. $P_i^S(t)$, $Q_i^S(t)$, $P_i^D(t)$, and $Q_i^D(t)$ are active and reactive powers of substation and demand on bus i at time t, respectively. $\left|I_{ij}(t)\right|$ and I_{ij}^{max} are the current magnitudes of line ij at time t and its maximum value. $\left|V_i(t)\right|$, V_{max}, and V_{min} are the voltage magnitude of bus i at time t and its maximum and minimum amounts, respectively. $b_{ij}(t)$ is a variable for representing the Kirchhoff's voltage law (KVL) in the loop formed by line ij at time t. Also, y_{ij} is a binary variable for the switch status of line ij (0 for open and 1 for closed switches).

Equations (2) and (3) express nodal active and reactive power balances at time t (Kirchhoff's current law, KCL). Equation (4) describes the net summation of voltage drops of all lines in a planar loop, which has to be equal to zero (KVL) at each time. In this equation, $b_{ij}(t)$ will be zero, when the switch of line ij is closed at time t (KVL must be established) and will be a real number for open switches (KVL is not necessary). Also, (5) shows the relationship between line power flow and its active and reactive components. Equation (6) indicates the radiality constraint. Accordingly, the total number of lines under operation (total number of closed switches) has to be equal to the total number of buses minus one (according to graph theory). Constraints (7) and (8) represent voltage and current limits, respectively. (9) makes sure that the value of $b_{ij}(t)$ will be zero, if the switch of line ij is closed (y_{ij}=1) and a real number between $V^2_{max}–V^2_{min}$ and $V^2_{min}–V^2_{max}$ when the corresponding line is disconnected (y_{ij}=0). In order to convert the above-mentioned non-linear programming model to a convex mixed-integer non-linear optimization problem that can be solved by linear commercial solvers and classic optimization tools, (1)–(9) are modified as follows.

$$Min\ C_{Loss} = \sum_{h=1}^{24} C_L(h) \sum_{ij\in\Omega^l} R_{ij} I_{ij}^{sqr}(h) \tag{10}$$

subject to (6) and:

$$P_i^S(h) + \sum_{ki\in\Omega^l} P_{ki}(h) - \sum_{ij\in\Omega^l} P_{ij}(h) - \sum_{ij\in\Omega^l} R_{ij} I_{ij}^{sqr}(h) = P_i^D(h) \tag{11}$$

$$Q_i^S(h) + \sum_{ki\in\Omega^l} Q_{ki}(h) - \sum_{ij\in\Omega^l} Q_{ij}(h) - \sum_{ij\in\Omega^l} X_{ij} I_{ij}^{sqr}(h) = Q_i^D(h) \tag{12}$$

$$\begin{aligned}&V_i^{sqr}(h) - V_j^{sqr}(h) = 2\left[R_{ij}P_{ij}(h) + X_{ij}Q_{ij}(h)\right] + \\ &\left(R_{ij}{}^2 + X_{ij}{}^2\right) I_{ij}^{sqr}(h) + b_{ij}(h) \quad \forall i,j\in\Omega^b, h = 1,...,24\end{aligned} \tag{13}$$

$$V_j^{sqr}(h) I_{ij}^{sqr}(h) \ge P_{ij}{}^2(h) + Q_{ij}{}^2(h) \tag{14}$$

$$V_{\min}^2 \le V_i^{sqr}(h) \le V_{\max}^2 \qquad \forall i\in\Omega^b, h = 1,...,24 \tag{15}$$

$$0 \le I_{ij}^{sqr}(h) \le \left(I_{ij}^{\max}\right)^2 y_{ij} \qquad \forall ij\in\Omega^l, h = 1,...,24 \tag{16}$$

$$\left|b_{ij}(h)\right| \le \left(V_{\max}^2 - V_{\min}^2\right)\left(1 - y_{ij}\right) \quad \forall ij\in\Omega^l, \forall h = 1,...,24 \tag{17}$$

Where, $I_{ij}^{sqr}(h)$ and $V_i^{sqr}(h)$ are square of branch current and bus voltage magnitudes in hour h, respectively.

IV. SIMULATION RESULTS

In order to accurate evaluation of consumption pattern role in distribution network reconfiguration, the proposed model was tested on 33-bus [28] and 84-bus [49] distribution systems for the load profiles shown in Figs 1 to 4 using CPLEX in AMPL.

The per unit energy losses costs of [47] were chosen according to Table I. The same load levels used in [47] were selected for load patterns 2 to 4 as Tables III to V. Also, load levels of Fig. 1 are according to Table II.

The peak load of each bus should be multiplied by the hourly demand percentage to obtain load levels of the corresponding bus in each hour. The results of the proposed idea, such as network topology (open switches) and daily cost of energy losses ($) are listed in Tables VI to XI for both test systems. According to [47], it is assumed that 60%, 25%, and 15% of the consumers have load patterns 2 to 4, respectively.

TABLE I
COSTS PER UNIT OF ENERGY LOSSES ($/KWH)

Hour	Cost	Hour	Cost	Hour	Cost
1	0.065	9	0.11	17	0.13
2	0.065	10	0.11	18	0.13
3	0.065	11	0.11	19	0.15
4	0.065	12	0.11	20	0.15
5	0.065	13	0.11	21	0.15
6	0.065	14	0.11	22	0.065
7	0.11	15	0.13	23	0.065
8	0.11	16	0.13	24	0.065

TABLE II
DATA OF LOAD PATTERN 1

Hour	Demand Percentage (%)	Hour	Demand Percentage (%)
1	35	13	54
2	29	14	52
3	28	15	51
4	27	16	55
5	27	17	68
6	30	18	92
7	42	19	100
8	60	20	93
9	62	21	86
10	57	22	79
11	52	23	69
12	51	24	49

TABLE III
DATA OF LOAD PATTERN 2

Hour	Demand Percentage (%)	Hour	Demand Percentage (%)
1	36	13	58
2	26	14	52
3	24	15	41
4	22	16	46
5	24	17	42
6	42	18	49
7	54	19	79
8	56	20	98.4
9	54	21	97
10	58	22	100
11	43	23	54
12	48	24	42

TABLE IV
DATA OF LOAD PATTERN 3

Hour	Demand Percentage (%)	Hour	Demand Percentage (%)
1	28.38	13	93.24
2	29.73	14	95.95
3	28.38	15	97.3
4	31.08	16	95.95
5	29.38	17	97.3
6	33.78	18	91.89
7	40.54	19	78.38
8	52.7	20	71.62
9	72.97	21	66.22
10	83.11	22	58.11
11	100	23	50
12	95.95	24	32.29

TABLE V
DATA OF LOAD PATTERN 4

Hour	Demand Percentage (%)	Hour	Demand Percentage (%)
1	6.25	13	61.88
2	10	14	68.75
3	7.5	15	78.75
4	11.88	16	76.25
5	10	17	81.25
6	8.75	18	87.5
7	13.75	19	61.88
8	38.75	20	35.63
9	74.38	21	23.75
10	76.25	22	12.5
11	90	23	11.88
12	100	24	8.32

TABLE VI
RECONFIGURATION RESULTS OF 33-BUS TEST SYSTEM FOR FIXED LOAD

Model	Reconfiguration	Topology	Cost of Energy Losses ($)
Proposed	Before	33,34,35,36,37	493.5
	After	7,9,14,32,37	339.8
[47]	Before	33,34,35,36,37	493.5
	After	7,9,14,32,37	339.8
[48]	Before	33,34,35,36,37	493.5
	After	7,9,14,32,37	339.8

TABLE VII
RECONFIGURATION RESULTS OF 84-BUS TEST SYSTEM FOR FIXED LOAD

Model	Reconfiguration	Topology	Cost of Energy Losses ($)
Proposed	Before	84,85,86,87.88.89,90, 91,92,93,94,95,96	1295.45
	After	7,13,34,39,42,55,62, 72,83,86,89,90,92	1144.15
[47]	Before	84,85,86,87.88.89,90, 91,92,93,94,95,96	1295.45
	After	7,13,34,39,42,55,62, 72,83,86,89,90,92	1144.15
[48]	Before	84,85,86,87.88.89,90, 91,92,93,94,95,96	1295.45
	After	7,13,34,39,42,55,62, 72,83,86,89,90,92	1144.15

TABLE VIII
RECONFIGURATION RESULTS OF 33-BUS TEST SYSTEM FOR A COMBINATION OF LOAD PATTERNS 2 TO 3

Model	Reconfiguration	Topology	Cost of Energy Losses ($)
Proposed	Before	33,34,35,36,37	175.6
	After	7,9,14,32,37	123.1
[47]	Before	33,34,35,36,37	175.6
	After	7,9,14,28,32	128.8
[48]	Before	33,34,35,36,37	175.6
	After	7,9,14,28,32	128.8

TABLE IX
RECONFIGURATION RESULTS OF 84-BUS TEST SYSTEM FOR A COMBINATION OF LOAD PATTERNS 2 TO 3

Model	Reconfiguration	Topology	Cost of Energy Losses ($)
Proposed	Before	84,85,86,87.88.89,90, 91,92,93,94,95,96	470.1
	After	7,13,34,39,42,55,62, 72,83,86,89,90,92	417.6
[47]	Before	84,85,86,87.88.89,90, 91,92,93,94,95,96	470.1
	After	7,34,39,63,72,83,84, 86,88,89,90,92,95	418.2
[48]	Before	84,85,86,87.88.89, 90, 91,92,93,94,95,96	470.1
	After	7,34,39,63,72,83,84, 86,88,89,90,92,95	418.2

TABLE X
RECONFIGURATION RESULTS OF 33-BUS TEST SYSTEM FOR DIFFERENT LOAD PROFILES

Load Pattern	Topology	Cost of Energy Losses ($)
1	7,9,14,32,37	137.9
2	7,9,14,32,37	117.2
3	7,9,14,32,37	190.3
4	7,9,14,32,37	118.7

TABLE XI
RECONFIGURATION RESULTS OF 84-BUS TEST SYSTEM FOR DIFFERENT LOAD PROFILES

Load Pattern	Topology	Cost of Energy Losses ($)
1	7,13,34,39,42,55,62,72,83,86,89,90,92	467.12
2	7,13,34,39,42,55,62,72,83,86,89,90,92	397.13
3	7,13,34,39,42,55,62,72,83,86,89,90,92	642.80
4	7,13,34,39,42,55,62,72,83,86,89,90,92	401.73

From Tables VI and VII it can be seen that the proposed approach and models presented in [47] and [48] suggest the same optimal topologies for a fix load amount and reduce the cost of energy losses efficiently after reconfiguration, in which the peak load has been considered as fixed demand during whole operation period.

Moreover, Tables VIII and IX indicate that the proposed model can find the more optimal topologies and less losses costs than those of [47] and [48] when different load patterns are considered instead of a fixed load amount. Comparing results of Tables VIII and IX with those of Tables VI and VII, respectively, explain that considering consumption patterns in reconfiguration of distribution systems reduce the cost of energy losses significantly but it cannot change the network topologies (reconfiguration plans). Even though the models of [47] and [48] could find different reconfiguration plans from the fixed load situation, their proposed topologies are not accurate and are not as optimal as topologies found by the proposed model. Therefore it can be said that considering load pattern should not change the reconfiguration plans even if each hour has the different cost of energy losses, because the proposed topologies have to meet the maximum peak load of all consumers even this maximum happen in just one hour. The results of Tables X and XI confirm this important fact because same reconfiguration plans are proposed for all consumption patterns. By the way, these tables describe the important role of power demand variations and load pattern in energy losses calculations.

Solving the DSR problem for fixed load is adequate if the goal is just finding the best configuration with the minimum power or energy losses or lowest energy losses cost. Whereas the aim is to optimize energy losses or its cost compared to other operational or investment expenses, load profile and consumption pattern have to be considered.

V. CONCLUSION

Consumption pattern and load profile are important factors in energy losses reduction. For this, electric power distribution companies suggest some discounts or incentives to electricity customers for changing their consumption manner. This issue has been attention by distribution network operators. Distribution system reconfiguration (DSR) is an efficient way for power loss reduction and if load profile is considered, its effectiveness may be increased. Recently, some research works have tried to show this important issue in distribution network reconfiguration. However, considering load variations in network reconfiguration increases computational burden and processing time in real applications. Therefore, the present paper evaluated the consumers' behavior and load profile impact on distribution network reconfiguration problem. The results analysis shows that load profile and consumption manner affect the cost of energy losses significantly but are not able to change the network topology. Therefore, if the network reconfiguration is going to be done with the aim of power losses minimization or its cost, it is easier that DSR is solved for the peak load level ignoring consumption pattern. However, if the DSR is going to be solved for minimization of other costs besides losses, the load profile has to be included in the problem formulation because power losses amount affects the results and may change reconfiguration topologies.

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