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Evaluating the effects of demand response programs on life expectancy of distribution transformers

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Abstract. This paper presents a new method to investigate the effects of demand response programs on the life expectancy of distribution transformers. The proposed method is applied to a realistic distribution network, and the outcomes have been assessed using different models of demand response programs and varying tariff levels. The results indicate that applying demand response programs can extend the life of distribution transformers, which leads to significant economic benefits, despite the variations among different scenarios. The same results indicate a significant life extension in the lifespan, ranging from about 9 to 33 years. Moreover, this life extension results in a substantial economic benefit, ranging from 624.91$ to 821.669$ per year. However, the amount of economic benefit considerably depends on the model of the demand response program and the level of tariffs. Besides, the economic analysis from both the utility and customer perspectives aims to determine the optimal demand response model. To this end, an economic index is presented and the best solution is determined by using an Analytic Hierarchy Process (AHP) so that it can satisfy both utilities and customers. Findings indicate that the total annual benefits of the utility and customers are increased by 762.64$ and 73.85$, respectively.

1. Introduction

Recently, due to economic and reliability issues, asset management plays a vital role in power systems. Asset physical life management is one of the most critical areas of asset management [1]. Considering that the number of equipment in distribution networks exceeds generation and transmission networks, the life management in distribution networks is more important than the others. Distribution transformers are one of the most expensive and essential equipment of a distribution network. Therefore, their life management can improve the network reliability and bring a considerable economic benefit.

Transformers' life is a function of time, temperature, humidity, and oxygen content. The temperature directly corresponds to transformer loading and is often considered as the only controllable factor in transformer life management by network operators [2]. Transformers' Loss Of Life (LOL) increases as the loading rate increases [3]. Therefore, transformers' loading management can extend their service life. Several studies have proposed various solutions to manage the power passing through transformers and improve their service life.

Online monitoring is one of these solutions that

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can keep the transformers' loading below the Dynamic Thermal Rating (DTR).

Integrating the resources of Distributed Generation (DG) into distribution networks is another effective way to manage the load on transformers and improve their lifespan [4–10]. Agah and Abyaneh assessed the impact of DGs owned by customers on the transformers' LOL rate reduction [8]. The results indicate a considerable reduction in the LOL rate. However, the reduction saturates at high levels of DGs penetration.

Charging of Electric Vehicles (EVs) can add a significant load to the transformers, especially at peak hours. Therefore, charging time planning for EVs can reduce the transformer loading and improve their lifespan [11–17].

Demand Response Programs (DRPs) represent another effective way to manage the load side [18–23]. In [24], based on DRPs implementation, the lifespan of distribution transformers was optimized by categorizing household electrical appliances into five groups and transferring their working time to other times. In [25], a similar study was conducted considering Heating Ventilation and Air Conditioning (HVAC) as a responsive load. Humayun et al. extended the service life of high-power and high-capacity transformers by maintaining the Hottest Spot Temperature (HST) level below a threshold using an optimal DRP [26]. In this study, the LOL rate of transformers was not evaluated. In [27], an optimization model based on an event-based DRP was utilized to improve the life of power transformers, not distribution transformers, considering their congestion. In [18], the objective was to optimize the lifespan of distribution transformers by identifying the most effective model of DRPs. To achieve this, a cost-benefit objective function was used to determine the optimal levels of incentive and penalty tariffs. However, this study did not evaluate the effects of multiple models of DRPs on the transformers' life or compare their effectiveness. Additionally, the impact of different tariff structures on the life extension of transformers was not assessed.

Based on this literature review, it is evident that there has been significant focus on enhancing the lifespan of distribution transformers through the integration of DG resources and effective planning for EVs. However, the effects of DRPs on the life extension of transformers are the subjects of few studies. Furthermore, these studies have primarily focused on the behavior of residential loads, whereas in real distribution networks, there are also office buildings and commercial loads, or a combination of them, in addition to residential loads. Moreover, categorizing them in several groups is quite complicated and cannot be suitable for DRPs analysis. The overall load profile is more accurate, practical, and realistic for DRPs analysis. Thus, this paper thoroughly investigates the impacts of different DRP models on the life extension of distribution transformers considering the overall load profile of different types of consumers: residential, office building, and commercial. Further, for each model of DRP, several levels of tariffs are assumed and their effects on the LOL rate reduction are determined. Besides, the economic analysis of the obtained benefits, including the benefits of the distribution transformers' life extension, the energy loss reduction, and the energy sales under various scenarios, is carried out to assess different models of DRPs' performance. To do so, an economic index is presented and the models are prioritized using Multi-Attribute Decision Making (MADM) method. By choosing the first priority as the best solution, all the stakeholders of DRPs will be satisfied. Also, an investigation into a realistic distribution network of Sirjan city center, Iran, is conducted for eight typical days, taking into account different seasons as well as weekdays and weekends. The contributions of the paper can be summarized as follows:

- Evaluating the effects of different DRP models and their varying tariffs on the LOL rate reduction of distribution transformers;
- Prioritizing various DRP models based on the MADM method to determine the best solution to improve the transformers' LOL rate as well as other economic factors.

The remainder of the paper is organized in five sections: In Section 2, different models of DRP are briefly explained. Thermal modeling of the distribution transformer and its LOL rate calculation are given in Section 3. In Section 4, problem formulation is proposed to assess the LOL rate of distribution transformers in the presence of DRPs. Simulation results are presented in Section 5. Finally, Section 6 presents concluding remarks.

2. Modeling of DRPs

DRPs can be classified as follows:

- Linear model;
- Non-linear models.

2.1. Linear edmand response model

Price elasticity is defined as the variation of demand with respect to the price of energy as follows [22,28]:

$$E(i,j) = \frac{\partial l(i)}{\partial \rho(j)}.\frac{\rho_0(j)}{l_0(i)} \qquad n = 1, ..., 24. \tag{1}$$

Besides, customer's benefit function, S, can be presented as:

$$S = B(i) - l(i).\rho(i). \tag{2}$$

Total incentive payments due to the reduced customer consumption at the ith hour, $P(\Delta l(i))$, can be expressed as follows:

$$\Delta l(i) = l(i) - l_0(i), \tag{3}$$

$$P(\Delta l(i)) = A(i).(l_0(i) - l(i)). \tag{4}$$

Also, the total penalty payment for violating the customer's contracted amounts at the ith hour is presented as follows:

$$Pen(\Delta l(i)) = Pen(i)[IC(i) - \{l_0(i) - l(i)\}]. \tag{5}$$

Considering Eqs. (4) and (5), Eq. (2) can be rewritten as:

$$S = B(l(i)) - l(i).\rho(i) + P(\Delta l(i)) - Pen(\Delta l(i)). \tag{6}$$

To maximize the customer's consumption, the derivative of its benefit concerning its demand should be equal to zero.

$$\frac{\partial S}{\partial l(i)} = \frac{\partial B(l(i))}{\partial l(i)} - \rho(i) + \frac{\partial P}{\partial l(i)} - \frac{\partial Pen}{\partial l(i)} = 0, \tag{7}$$

$$\frac{\partial B(l(i))}{\partial l(i)} = \rho(i) + A(i) + Pen(i). \tag{8}$$

Taylor expansion of $B(i)$ for linear modeling is stated as follows [29]:

$$B(i) \cong B_0(i) + \rho_0(i).(l(i) - l_0(i)). \left\{1 + \frac{l(i) - l_0(i)}{2E(i,i).l_0(i)}\right\}. \tag{9}$$

Using Eq. (9), Eq. (8) can be expressed as follows:

$$\rho(i) + A(i) + Pen(i) = \rho_0(i). \left\{1 + \frac{l(i) - l_0(i)}{E(i,i).l_0(i)}\right\}. \tag{10}$$

Finally, by simplifying Eq. (10), the linear model of the DRP for a single period is calculated as follows [22,28]:

$$l(i) = l_0(i). \left\{1 + E(i,i). \frac{\rho(i) - \rho_0(i) + A(i) + Pen(i)}{\rho_0(i)}\right\}. \tag{11}$$

Furthermore, the linear model of the DRP for a multi-period objective is derived as follows [22,28]:

$$l(i) = l_0(i). \left\{1 + \sum_{j=1}^{24} E(i,j). \frac{\rho(j) - \rho_0(j) + A(j) + Pen(j)}{\rho_0(j)}\right\}. \tag{12}$$

2.2. Non-linear demand ersponse models

Various nonlinear models of $B(m)$ can be found in [29]. Similar to what has been done in Section 2.1, the multi-period nonlinear models of the DRP can be obtained by Eq. (13) as shown in Box I (see Ref. [29] for more details): Various models of DRP presented in this section are used to evaluate the life expectancy of distribution transformers under various scenarios.

3. Thermal and LOL modeling of distribution transformers

3.1. Thermal modeling of distribution transformers

For thermal modeling of transformers, the thermal model proposed in [30] is usually used. The calculation procedure presented in [30] is as follows:

1) Calculate the ultimate hottest-spot temperature rise along with ultimate top-oil temperature rise based on the transformer's load level at each time interval using Eqs. (14) and (15), respectively:

$$\Delta\Theta_{H,U} = \Delta\Theta_{H,R} \times K^{2m}, \tag{14}$$

$$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,R} \times \left(\frac{K^2 R + 1}{R + 1}\right)^n. \tag{15}$$

2) At each time interval, by using the ultimate top-oil temperature rise resulting from Eq. (15) and the ambient temperature, calculate the increase in the top-oil temperature by solving a differential equation as follows:

$$\tau_{TO} \frac{d\Theta_{TO}}{dt} = (\Delta\Theta_{TO,U} + \Theta_A) - \Theta_{TO}. \tag{16}$$

$$\begin{cases} l(i) = l_0(i). \prod_{j=1}^{24} \left(\frac{E(i,j).(\mathrm{A}(j)+Pen(j)+\rho(j)+\rho_0(j))+\rho(j)+\mathrm{A}(j)+Pen(j)}{\rho_0(j).(E(i,j)+1)}\right)^{E(i,j)} \Rightarrow Power \\ l(i) = l_0(i).exp\left(\sum_{j=1}^{24} \frac{E(i,j).(A(j)+Pen(j)+\rho(j)-\rho_0(j))}{\rho_0(j)}\right) \Rightarrow Exponential \\ l(i) = l_0(i). \left\{1 + \sum_{j=1}^{24} E(i,j). \ln\left(\frac{\rho(j)+A(j)+Pen(j)}{\rho_0(j)}\right)\right\} \Rightarrow Logarithmic \end{cases} \tag{13}$$

Box I

3) At each time interval, obtain the increase in HST rise by solving a differential equation as:

$$\tau_H \frac{d\Delta\Theta_H}{dt} = (\Delta\Theta_{H,U} - \Delta\Theta_H). \tag{17}$$

4) Finally, calculate the HST using Eq. (18) as follows:

$$\Theta_H = \Theta_{TO} + \Delta\Theta_H. \tag{18}$$

3.2. LOL modeling of distribution transformers

The aging acceleration factor (F_{AA}) is introduced by the ANSI/IEEE Standard C.57.91 [2] in order to calculate the LOL rate of the oil-immersed transformers and it can be calculated as follows:

$$F_{AA} = exp\left[\left(\frac{15000}{383}\right) - \left(\frac{15000}{\Theta_H + 273}\right)\right]. \tag{19}$$

Also, by calculating the LOL rate at each time interval (Δt_r), the equivalent LOL rate of the transformers over the whole period (F_{EQA}) can be calculated as follows [2]:

$$F_{EQA} = \frac{\sum_{r=1}^{N} F_{AA,r}\Delta t_r}{\sum_{r=1}^{N} \Delta t_r}. \tag{20}$$

It should be noted that the load level of distribution transformers is time-varying during their service life, and it is not suitable for aging analysis [8]. The recorded data on transformer's load level was categorized into eight typical days based on seasons, weekdays, and weekends. This helped to remove the time dependency of the data. Thus, the annual LOL rate of the distribution transformer can be calculated based on the LOL rate of these typical days.

4. Problem formulation

From Eqs. (14)–(20), it can be found that the load level of a distribution transformer is the only controllable parameter to manage its LOL rate. As stated before, DRPs are able to change customer behavior and, accordingly, amount of power flow through the transformer. This can lead to a reduction in the thermal and electrical stresses of the transformer and, consequently, an increment in its life. The life extension of distribution transformers will lead to economic benefits for their owners. For the economic analysis of benefits, we assume that the LOL rate and life of the under-load distribution transformer are F and L, respectively. Additionally, we assume that the installed cost of the transformer and the interest-inflation rate are C and k, respectively. If the implementation of DRPs can reduce the LOL rate by ΔF, the transformer life will increase by ΔL. This life increment from L to $L + \Delta L$ years obtains an economic benefit, B. The achieved benefit includes two components, B_1 and B_2. B_1 and B_2 result from an increase in the book value of a transformer and its later replacement, respectively.

$$B = B_1 + B_2, \tag{21}$$

$$B_1 = \frac{\Delta L}{L}.C = \frac{\Delta F}{F - \Delta F}.C, \tag{22}$$

$$B_2 = C.(1+k)^{L+\Delta L} - C.(1+k)^L$$
$$= C.(1+k)^{\frac{L_0}{F-\Delta F}} - C.(1+k)^{\frac{L_0}{F}}. \tag{23}$$

The present worth of the obtained benefit can be derived as follows:

$$PW = \frac{B_1}{(1+k)^L} + \frac{B_2}{(1+k)^{L+\Delta L}} = \frac{B_1}{(1+k)^{\frac{L_0}{F}}}$$
$$+ \frac{B_2}{(1+k)^{\frac{L_0}{F-\Delta F}}}. \tag{24}$$

Using Eqs. (22) and (23), Eq. (24) can be deduced as follows [31]:

$$PW = C.\left(\frac{\Delta L}{L} \times \frac{1}{(1+k)^L} + 1 - \frac{1}{(1+k)^{\Delta L}}\right)$$
$$= C.\Bigg(\frac{\Delta F}{F - \Delta F} \times \frac{1}{(1+k)^{\frac{L_0}{F}}} + 1$$
$$- \frac{1}{(1+k)^{\frac{L_0 \Delta F}{F(F-\Delta F)}}}\Bigg). \tag{25}$$

The annual worth of the obtained benefit is provided using present to annual factor, P/A factor [32], as follows:

$$AW = PW.\left(\frac{k.(1+k)^{\frac{L_0}{F-\Delta F}}}{(1+k)^{\frac{L_0}{F-\Delta F}} - 1}\right), \tag{26}$$

$$AW = C.K.\Bigg(\frac{\Delta F}{F - \Delta F} \times \frac{(1+k)^{\frac{L_0 \Delta F}{F(F-\Delta F)}}}{(1+k)^{\frac{L_0}{F-\Delta F}} - 1}$$
$$+ \frac{(1+k)^{\frac{L_0}{F-\Delta F}}}{(1+k)^{\frac{L_0}{F-\Delta F}} - 1} - \frac{(1+k)^{\frac{L_0}{F}}}{(1+k)^{\frac{L_0}{F-\Delta F}} - 1}\Bigg). \tag{27}$$

Furthermore, application of DRPs can provide other economic benefits due to decrease in energy losses.

On the other hand, the application of DRPs incurs expenses such as incentive payments and reduction of energy sales [19,33]. To clarify, the implementation of DRP reduces power consumption during specific intervals of a day, which results in a reduction of energy sold, and therefore, a reduction in utilities' benefits. Conversely, during specific intervals of a day, the power consumption increases, which leads to an increase in the amount of energy sold and, consequently, utility benefit. The benefit provided from energy selling can be quantified as follows:

$$SE=\sum_{t=1}^{24}\rho(t).\,(l(t)-l_0(t))+Pen(t).\,(l(t)-l_0(t))$$
$$-A(t).\,(l(t)-l_0(t))\,,$$
$$\Delta l(t)=l(t)-l_0\rightarrow(t)SE=\sum_{t=1}^{24}\Delta l(t).(\rho(t)$$
$$+Pen(t)-A(t)). \quad (28)$$

The application of one DRP model can increase benefits for some stakeholders while decreasing the benefits for others. Therefore, the optimal model should be selected by the network's regulator to optimize the benefits of all the participants. To this end, stakeholders are classified into two basic groups: Customers and utilities. Besides, the following attributes are taken into account as indices raised from concerns of the stakeholders: the annual benefit of distribution transformers' life extension (ALE), the annual benefit of loss reduction (ALR), and the annual benefit of selling energy (ASE). Then, an annual economic benefit index is provided for each of the utilities and customers considering the mentioned indices. Finally, based on MADM techniques, the optimum model of DRP can be determined so as to maximize the value of the proposed annual benefit index considering the importance degree of the stakeholders. The various models of DRP based on MADM techniques are assessed and prioritized by a three-layer hierarchy, as presented in Figure 1.

According to Figure 1, in the third layer, by conducting each model of DRP on a distribution network, the considered indices are calculated. Then, in the second layer, an economic benefit index is presented for each stakeholder viewpoint as follows:

$$ALE_i=\sum_{j=1}^{NT}(AW_{i,j})\qquad i=1,...,P, \quad (29)$$

where ALE is the annual benefit of the distribution transformers' life extension for each model.

$$ASE_i=\sum_{j=1}^{365}(SE_{i,j})\qquad i=1,...,P, \quad (30)$$

where ASE is the annual benefit of the energy sold for each model.

$$ALR_i=\sum_{j=1}^{365}\left(\sum_{t=1}^{24}(P\_loss(t)_{refrence,j}\right.$$
$$\left.-P\_loss(t)_{i,j}).\rho_j(t)\right)\qquad i=1,...,P, \quad (31)$$

where ALR is the annual benefit of the loss reduction for each model. Next, the total benefits of utilities and customers for each model are proposed by Eqs. (32) and (33) per year, respectively.

$$TBU_i=ALE_i+ASE_i+ALR_i\qquad i=1,...,P, \quad (32)$$

$$TBC_i=ASE_{reference}-ASE_i\qquad i=1,...,P. \quad (33)$$

The decision matrix indicates the performance of each model of DRP for each index and is created as follows:

$$D=\begin{bmatrix}TBU_1 & TBC_1\\ ... & ...\\ ... & ...\\ ... & ...\\ TBU_p & TBC_P\end{bmatrix}. \quad (34)$$

In the first layer, based on Analytic Hierarchy Process (AHP) method [34], the weights of the decision-makers (stakeholders) are determined, α and the final decision matrix (FD) is calculated as follows:

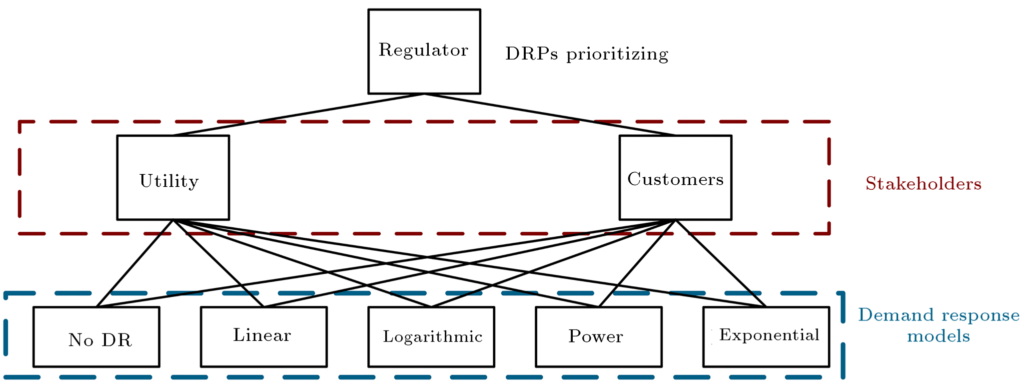


Figure 1. Demand response programs prioritized based on MADM techniques.

$$FD = D \times \alpha. \tag{35}$$

Finally, the regulator sorts the models in terms of FD values and selects the model with the highest FD value as the optimal solution. The economic benefits of all the decision-makers are maximized in terms of their importance. The proposed approach can be carried out in 14 steps as follows:

Step 1. Obtain the load profiles of the three sample transformers for the first typical day;

Step 2. Calculate the daily LOL rate of the sample transformers using Eqs. (14)–(20);

Step 3. Repeat Steps 1 and 2 for the rest of the typical days;

Step 4. Calculate the annual LOL rate of the sample transformers using their obtained daily LOL rates (reference scenario);

Step 5. Select one of the demand response models explained in Section 2;

Step 6. Derive the modified load profiles of the sample transformers for the first typical day after applying the selected demand response model;

Step 7. Calculate the daily LOL rate of the sample transformers considering the modified load profiles using Eqs. (14)–(20);

Step 8. Repeat Steps 6 and 7 for the rest of the typical days;

Step 9. Calculate the annual LOL rate of the sample transformers considering their obtained daily LOL rates after applying the selected demand response model (new scenario);

Step 10. Repeat Steps 6–9 for all DRP models presented in Section 2;

Step 11. Calculate ALE, ASE, and ALR for all the scenarios using Eqs. (29)–(31);

Step 12. Considering the results of Step 11, calculate TBU and TBC for all the scenarios using Eqs. (32) and (33);

Step 13. Based on the results of Step 12, create D and FD matrices using Eqs. (34) and (35);

Step 14. Sort the scenarios (models) according to their calculated FD index in descending order and choose the first one, with the highest amount of FD index, as the optimum solution.

The flowchart of the proposed method to find the best solution is given in Figure 2.

5. Simulation and results

In this section, the proposed method presented in Section 4 is employed on a realistic distribution network of Sirjan city center in Iran, as shown in Figure 3. A 63/20 kV primary substation, bus M, supplies this network via two main 20 kV feeders with an approximate length of 19 km. These feeders supply the Low Voltage (LV) loads including residential, office building, commercial, or a combination of them, through 77 distribution transformers (see Ref. [35] for more details).

In order to quantify the efficiency of the proposed method in improving the life of distribution transformers, the transformers T_1, T_2, and T_3 are selected as samples. These samples are selected in terms of best representing the transformers serving various types of customers. T_1, T_2, and T_3 are residential, office building, and commercial transformers supplying several household customers, an office building, and several commercial customers, respectively. Furthermore, their rated voltage is 20/0.4 kV and their rated powers are 25 kVA, 160 kVA, and 315 kVA, respectively. Their cooling system is of ONAN type and its thermal characteristics are tabulated in Table 1 based on the manufacturer's data.

As mentioned before, to assess the life extension of distribution transformers over a year, the analyses are carried out for eight typical days. The realistic load profiles of three types of customers in the typical days are shown in Figure 4.

First, the LOL rate of the sample transformers is investigated under reference scenario (before implementation of DRPs). Figure 5 depicts the daily evolution of LOL rate for the residential transformer under reference scenario for typical summer and winter weekdays.

As can be seen from Figure 5, during the typical weekdays of summer and winter, the LOL rate of the residential transformer varies considerably. Indeed, the value of the LOL rate is negligible during the first hours of the days. During the daytime interval, the LOL rate rises sharply after which it approximately remains steady for two or three hours at the end of the days. Throughout the nighttime, it again rises and reaches its peak at hour 22 and then, falls until the end of the nighttime. Attention should be given to the fact that during a wide range of the summer weekdays, from hour 12:00 to hour 24:00, the LOL rate of the residential transformer exceeds the design rate of 1 by a significant amount (it reaches peak value, 26.53, at hour 22:00). On the contrary, during the winter

Table 1. Thermal parameters of the sample transformers [8].

τ_H	τ_{TO}	R	n	m	$\Delta\Theta_{H,R}$	$\Delta\Theta_{TO,R}$
0.1 hr	3.2 hr	5	0.8	1.6	25°C	55°C

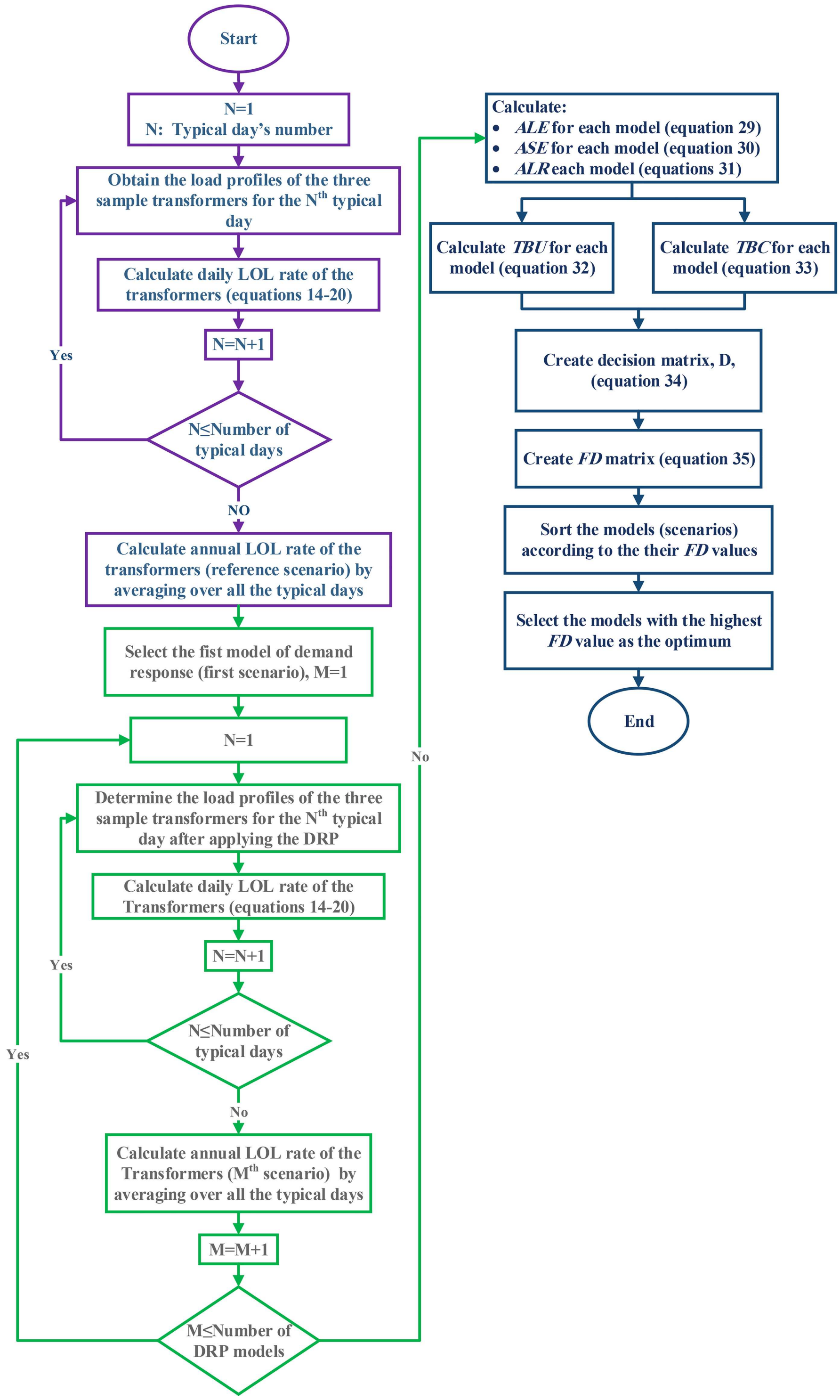


Figure 2. Flowchart of the proposed method to find the best solution.

weekday, due to the moderate load level of customers, the LOL rate remains well below the design rate at all times. The given results relate to the residential transformer, although almost similar LOL rate trends can be seen for office building and commercial ones.

The daily LOL rates are deduced by averaging the LOL over the typical days to make a better comparison. Furthermore, the analyses are conducted for all the sample transformers through all the typical days over the year. The daily LOL rates of the sample transformers under reference scenario for all the typical days are tabulated in Table 2. Based on the seasonal LOL rates, the annual average is formed and presented in the last column of the table.

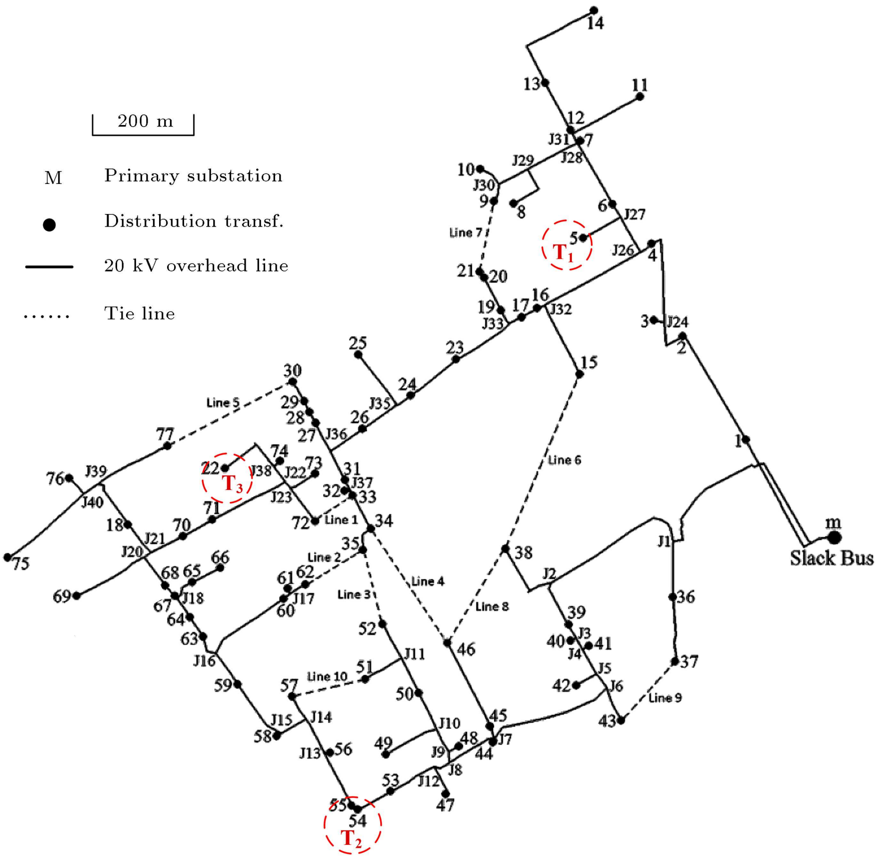


Figure 3. Realistic distribution network of Sirjan city center in Iran.

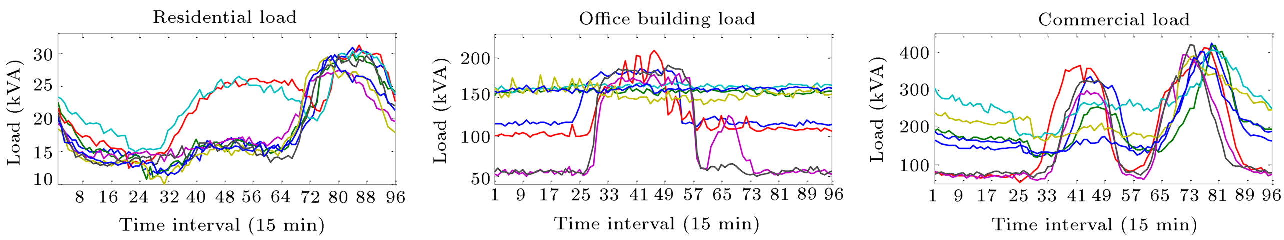


Figure 4. Realistic load profiles of three types of customers for the typical days [18].

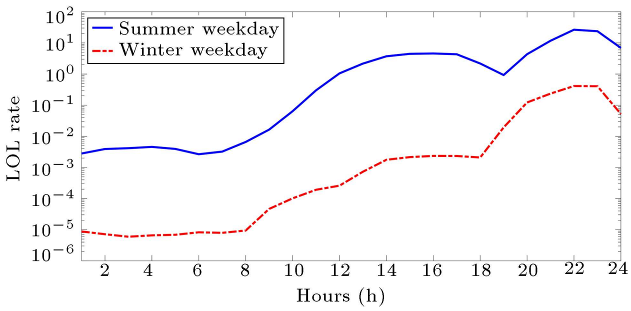


Figure 5. Daily evolution of LOL rate for the residential transformer before implementation of DRPs (reference scenario).

Table 2 shows that the transformers' LOL rate fluctuates extremely throughout different seasons. Additionally, the LOL rates during summer are higher compared to other seasons and also higher than the annual averages, as a result of the higher ambient temperature and increased electricity consumption by cooling systems. It is implied that most of the annual LOL rates occur in the summer. Therefore, planning with the aim of the highest LOL reduction in the summer may lead to the highest life extension for distribution transformers.

Furthermore, during the spring and summer seasons, the number of people who are present at home or work on weekends is lower compared to weekdays, which may lead to a reduction in electricity consumption. As shown in Table 2, the seasonal LOL rates are lower on weekends during those seasons compared to weekdays.

From the last column of Table 2, it can be seen that the annual LOL rate for the commercial transformer is less than 1, which indicates longer life

Table 2. The LOL rate of the sample transformers under reference scenario for all the typical days.

Transformer	Spring		Summer		Autumn		Winter		Annual
	WD[a]	WE[b]	WD	WE	WD	WE	WD	WE	
Residential	0.339	0.279	4.044	3.058	0.128	0.120	0.052	0.050	**1.092**
Office building	0.524	0.374	4.212	3.223	0.304	0.237	0.190	0.171	**1.247**
Commercial	0.288	0.230	2.571	2.300	0.130	0.119	0.060	0.054	**0.753**

[a]WD: Weekday; [b]WE Weekend.

Table 3. Self-elasticity and cross-elasticity of loads.

	Load type	Valley	Off-peak	Peak
Valley	Residential	–0.1	0.01	0.012
	Office building /commercial	–0.07	0.006	0.0072
Off-peak	Residential	0.01	–0.1	0.016
	Office building /commercial	0.006	–0.07	0.0096
Peak	Residential	0.012	0.016	–0.1
	Office building /commercial	0.0072	0.0096	–0.07

expectancy for the transformer than its design life (20.55 years). On the contrary, the annual LOL rate for the residential and office building transformers is larger than 1, implying shorter life expectancy for them than their design life. In other words, the residential and office building transformers with 1.092 and 1.247 annual LOL rates lose 1.73 and 4.07 years of their design life under the reference scenario, respectively. As a result, in terms of distribution transformers' life extension planning, the residential and office building transformers have a higher priority than the commercial one.

To evaluate the impacts of DRPs on the LOL rate of the sample transformers, the loads fed from transformers T_1, T_2, and T_3, marked in Figure 3, are supposed to be responsive loads. Self-elasticity and cross-elasticity of the loads are presented in Table 3 [19,36]. Also, the price of energy for all the typical days is taken from Iran Grid Management Company (IGMC) [37].

Then, different models of DRP explained in Section 2 are applied on the responsive loads and consequently, their consumption behavior is changed, leading to some variations in the LOL rate of the sample transformers. The daily evolution of the LOL rate for the residential transformer under these scenarios for typical summer and winter weekdays is depicted in Figure 6. According to the figure, during a wide range of the days, there is a significant reduction in the LOL rate, especially during peak hours.

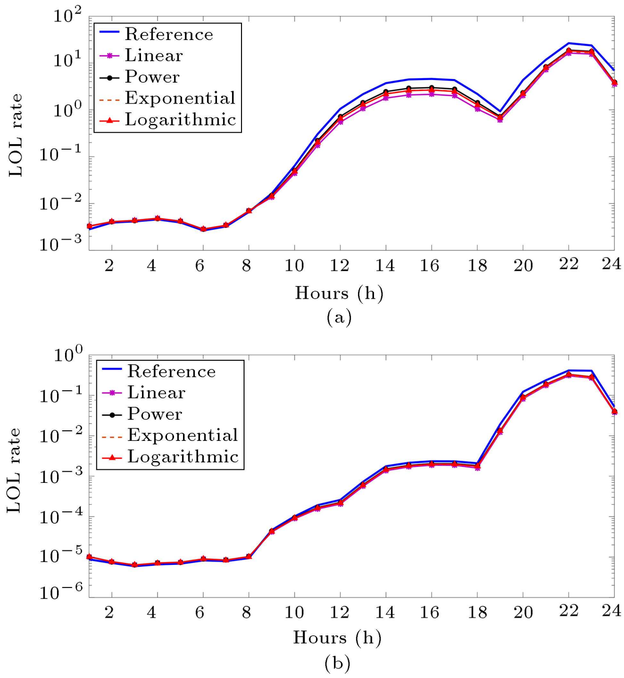


Figure 6. Daily evolution of the LOL rate for the residential transformer under various scenarios: (a) Summer weekday and (b) winter weekday).

Also, Figure 7 shows the daily LOL rate of the sample transformers under these scenarios for typical summer and winter weekdays.

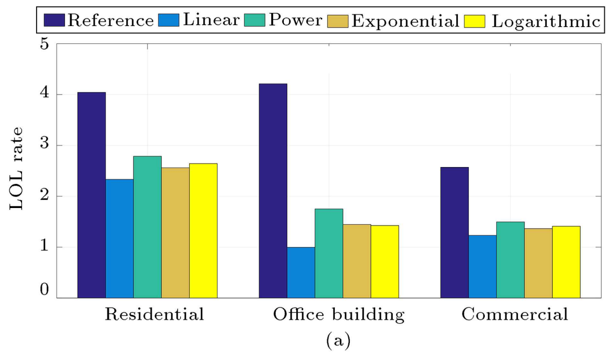
As revealed by Figure 7(a) and (b), the implementation of DRPs significantly reduces the daily LOL rate of the transformers. Besides, the linear model

Table 4. Annual LOL rate of the sample transformers under various scenarios.

	Scenarios				
Transformer	**Reference**	**Linear**	**Power**	**Exponential**	**Logarithmic**
Residential	1.092	0.617	0.742	0.677	0.704
Office building	1.247	0.516	0.691	0.617	0.619
Commercial	0.753	0.342	0.424	0.382	0.399

Table 5. Sample transformers' life extension under various scenarios (years).

	Scenarios			
Transformer	**Linear**	**Power**	**Exponential**	**Logarithmic**
Residential	14.49	8.88	11.54	10.37
Office building	23.35	13.26	16.83	16.72
Commercial	32.80	21.18	26.50	24.21



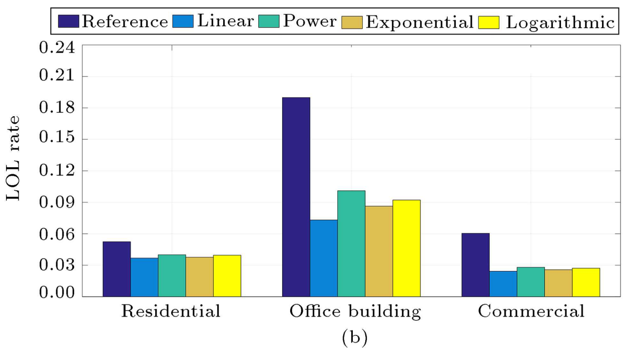


Figure 7. Daily LOL rate of the sample transformers under various scenarios: (a) Summer weekday and (b) winter weekday).

enjoys the best performance in terms of LOL reduction among all the models, especially on summer weekday. The sample transformers are assessed in the remaining typical days under various scenarios, and the annual LOL rate of the sample transformers is presented in Table 4.

According to the results shown in Table 4, applying DRPs can reduce the annual LOL rate of the sample transformers by 58.62%. Further, as stated before, the results imply that the DRPs model plays a vital role in reducing the LOL rate of distribution

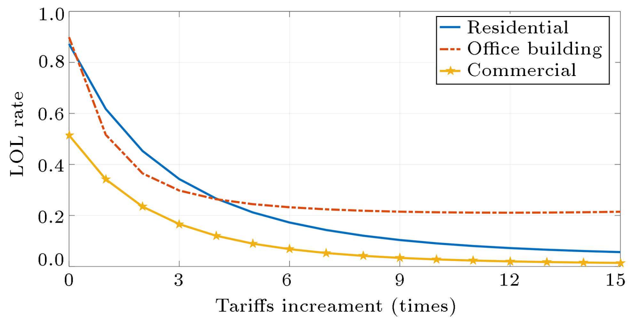


Figure 8. Annual LOL rate of the sample transformers under the linear DRP model scenario.

transformers. Among the models, the linear and power have the best and worst performances in the LOL rate reduction, respectively. Besides, the performance of the logarithmic model is between exponential and power models. Thus, from the viewpoint of LOL rate reduction, the linear and exponential models may receive a higher priority than the others.

Distribution transformers' life extension in the presence of a DRP can be calculated as follows:

$$\Delta L = L_0.\left(\frac{\Delta F}{F.\Delta F}\right). \tag{36}$$

Table 5 shows the sample transformers' life extension under the presented scenarios, compared to the reference scenario.

According to the different models of DRP expressed in Section 2, the tariffs are the only factors that can be specified by the regulator. It is implied that the incentive and penalty tariffs can have significant effects on the life extension of transformers. To analyze the effects of these factors on the life expectancy of distribution transformers, the amount of the tariffs is increased and the annual LOL rates of the sample transformers are quantified, as shown in Figures 8–11.

Table 6. Prices of the sample distribution transformers.

	Residential	Office building	Commercial
Average price ($)	640	4096	8064

Table 7. Annual economic benefit of the distribution transformers' life extension under the various scenarios (Dollars).

	Scenarios			
Transformer	**Linear**	**Power**	**Exponential**	**Logarithmic**
Residential	32.394	23.308	27.908	25.996
Office building	314.050	223.724	259.373	258.406
Commercial	475.225	377.259	427.153	406.451
Total	821.669	624.291	714.434	690.853

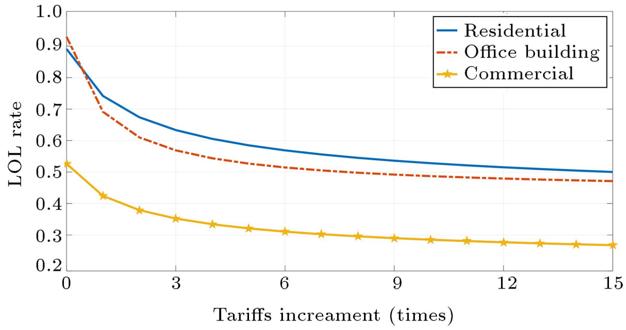


Figure 9. Annual LOL rate of the sample transformers under the power DRP model scenario.

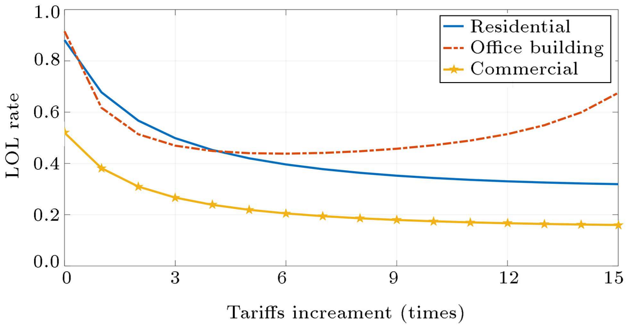


Figure 10. Annual LOL rate of the sample transformers under the exponential DRP model scenario.

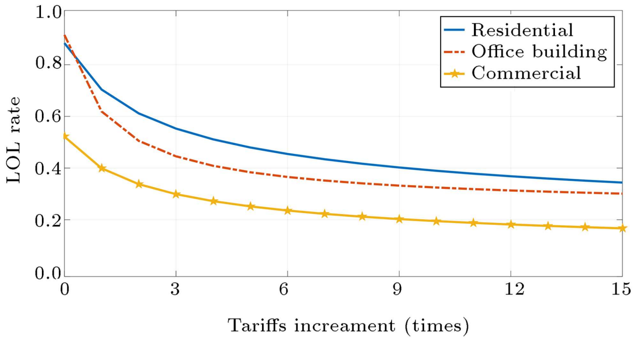


Figure 11. Annual LOL rate of the sample transformers under the logarithmic DRP model scenario.

Figures 8–11 show that the LOL rate of the transformers decreases as the level of the tariffs increases. This behavior seems to be independent of the transformer type and holds true for all DRP models. However, there is an exception to the exponential model at a high level of tariffs in which the LOL rate begins to rise. Figures 8–11 indicate that the reductions obtained by increasing the tariffs from 0 to 5 times are relatively higher than those achieved by increasing them from 10 to 15 times. This suggests that the reductions become saturated at high levels of tariffs. This can be justified by considering the fact that the transformer's LOL is an exponential function of its HST. Furthermore, based on the figures, the linear model shows the best performance in terms of LOL rate reduction compared to other models. By selecting a high value for the tariffs in this model, the LOL rate of the transformers can be reduced to approximately one-tenth of its value in the reference scenario. Another remarkable point is that the variation of the LOL rate in response to the tariff variation in the linear model is greater than the others. It is implied that at the same amount of tariffs, the amount of LOL in the linear model is lower than the others.

By using Eqs. (21) to (27), an economic analysis is carried out to quantify the benefits obtained from extending the service life of the distribution transformers. For this purpose, the average prices of the distribution transformers expressed by Iranian DUs are used. Table 6 shows the average prices for three sample distribution transformers. Also, the annual interest-inflation rate is assumed to be 5%. The annual economic benefits of the sample transformers' life extension under various scenarios are calculated and presented in Table 7.

As can be seen from Table 7, the economic benefits vary in ranges between 23.308$ and 475.225$ per year, depending on the type of transformers and the DRP model. Moreover, the linear DRP is associated with the highest amount of benefits, as it demonstrates

Table 8. Indices under various scenarios per year (Dollars).

Attributes	Scenarios				
	Reference	Linear	Power	Exponential	Logarithmic
ALE	0	**821.67**	624.29	714.43	690.85
ASE	**3828.65**	3754.80	3820.84	3791.21	3801.13
ALR	0	**14.82**	9.62	11.94	11.18
Total Benefit of Utility (TBU)	3828.65	**4591.29**	4454.75	4517.58	4503.17
Total Benefit of Customers (TBC)	0	**73.85**	7.81	37.44	27.52

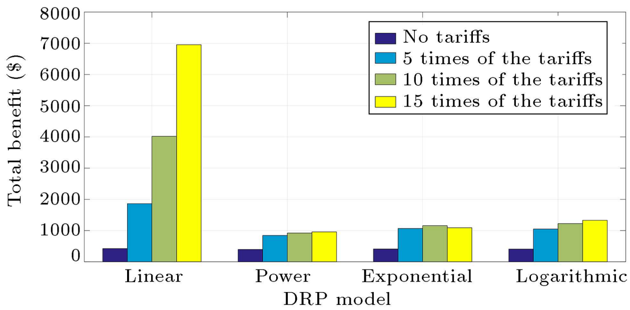


Figure 12. Total economic benefit of the sample transformers' life extension under various scenarios of the tariffs.

the best performance in reducing the annual LOL rates. It is worth noting that the results of Table 7 are determined, assuming that the incentive and penalty tariffs are equal to 0.0008 and 0.0012 kWh/$, respectively. To investigate the effects of the tariffs on the economic benefits of life extension, the total annual economic benefit is calculated under various scenarios, including 0, 5, 10, and 15 times the tariffs, and presented in Figure 12.

From Figure 12, it is clear that the total economic benefit increases as the tariffs of DRPs rise. However, as the tariffs increase, the rate of increase in the economic benefit slows down. Suppose that the coefficient of tariffs changes from 0 to 5 in the power model, the amount of benefit increases by 448.3$ per year. When the coefficient increases from 5 to 10, the resulting economic benefit increases by 76.2$ per year, which represents a slower rate of increase compared to the increase observed when the coefficient increases from 0 to 5. Also, as mentioned before, at high values of the tariffs, the benefit of LOL reduction for the exponential model diminishes.

As demonstrated in Figure 12, it can be concluded that the model of DRP and its tariffs are two critical parameters in estimating the amount of economic benefit caused by distribution transformers' life extension. For instance, when the tariffs are set at 15 times the original value, the annual benefit is limited to $957.3 under the power model. For similar conditions, the annual benefit can reach 6954$ for the linear scenario. This has the potential to contribute to millions of dollars in profits for the entire distribution networks.

As mentioned before, to maximize the benefits of utility and customers based on DRPs, the following indices should be considered: ALE, ASE, and ALR. As the electricity consumption behavior of non-responsive customers does not alter in response to DRPs implementation, the amount of ASE is taken into consideration for responsive customers (the load of the sample transformers). The indices are determined for each scenario and presented in Table 8, considering 0.0008 and 0.0012 kWh/$ for incentive and penalty tariffs, respectively.

From the utility viewpoint, the scenario with the highest amount of TBU is selected as the most appropriate one. In spite of the lowest amount of ASE (Table 8), the linear model will be the best choice in terms of maximizing the total benefit of the utility. This scenario increases the TBU by 19.91% (762.64$) compared to the reference.

From the customers' viewpoint, the best scenario is the one in which ASE is the lowest. In other words, the customers only care about their payments, and the life extension and the energy loss reduction are not essential for them. From the results given in Table 8, the lowest amount of ASE is obtained by the linear model, leading to the highest TBC. Also, the results show that the amount of benefit provided by reducing the loss of energy is insignificant and can be neglected.

In order to select the best scenario by the regulator, the weight of any decision-maker should be indicated. From the viewpoint of the regulator, customer satisfaction is of higher importance than the utility viewpoint [19]. A pair comparison of two DRP stakeholders based on experts' consideration is given in Table 9. In the right column of the table, the weights of decision-makers are added and calculated by AHP method.

Finally, the regulator calculates the priority of the

Table 9. Pair comparisons in the AHP method.

	Customer	**Utility**	**Weight (α)**
Customer	1	2	0.67
Utility	0.5	1	0.33

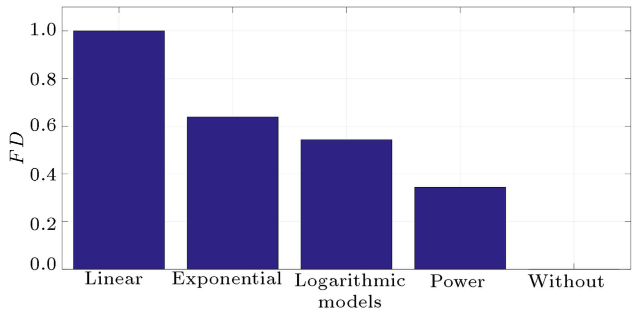


Figure 13. Priority of scenarios (regulator viewpoint).

scenarios by forming the FD matrix and concludes the results by using the AHP method, as shown in Figure 13. As illustrated in the figure, since the linear model provides the best solution for both customers and utilities, the regulator is more likely to select it. Thus, the linear model is given the highest priority, while the other models are considered as secondary options. However, in other case studies, it is probable that the desired solution for the customers and utility be different. If so, the proposed method based on AHP would be very practical for determining the optimum model.

In another scenario, to evaluate the efficiency of the proposed method, the LOL rates of the sample transformers are calculated based on the DGs penetration method presented by Agah et al. [8] and the results are compared. Their research demonstrates that the Micro Turbine (MT) results in the highest reduction of LOL among DG technologies. Thus, to analyze the performance of these methods, the LOL rate of the sample transformers considering the 30% penetration level of MT technology is calculated and tabulated in Table 10. To make a better comparison, the obtained results for the LOL rates under reference and optimal DRP scenarios are added to the table.

Table 10 demonstrates that the linear DRP model produces the highest annual reduction in LOL rate among the examined scenarios, indicating the effectiveness of the proposed method. As revealed by the results, the proposed method can reduce the annual LOL rate to about 36%, 54.6%, and 47.5% for the residential, office building, and commercial transformers, respectively, compared to those obtained by the MT.

In the end, it is worth mentioning that the proposed method in this study is applied only to three sample transformers as a part of a realistic distribution network. Therefore, given the significant number of transformers installed in distribution networks, the adoption of an appropriate DRP model can lead to the extension of transformers' life expectancy, increased benefits for both utilities and customers, as well as improved network reliability.

6. Conclusion

In this paper, a new method was proposed to quantify the economic benefit of demand response programs in extending distribution transformers' life expectancy. Studies have explored the viability of a realistic distribution network and the results indicate a significant increase in the service life of the analyzed transformers. According to the results, the life of the transformers is extended in the range of 8.88 to 32.8 years. This life extension leads to a considerable economic benefit ranging between 624.91$ and 821.669$ per year. As expected, the model of demand response plays an important role in reducing distribution transformers' Loss Of Life (LOL) rate. The results illustrate that

Table 10. Sample transformers' LOL rate under linear demand response and MT technology scenarios.

Transformer	**Scenario**	**Spring**		**Summer**		**Autumn**		**Winter**		**Annual**
		WD	**WE**	**WD**	**WE**	**WD**	**WE**	**WD**	**WE**	
Residential	Reference	0.339	0.279	4.044	3.058	0.128	0.120	0.052	0.050	1.092
	DG (MT)	0.288	0.241	3.57	2.755	0.112	0.103	0.044	0.043	0.964
	Optimal DRP (Linear)	**0.171**	**0.133**	**2.333**	**1.628**	**0.090**	**0.053**	**0.037**	**0.027**	**0.617**
Office building	Reference	0.524	0.374	4.212	3.223	0.304	0.237	0.190	0.171	1.247
	DG (MT)	0.494	0.354	3.718	3.246	0.264	0.254	0.161	0.172	1.137
	Optimal DRP (Linear)	**0.407**	**0.260**	**0.997**	**2.645**	**0.122**	**0.211**	**0.073**	**0.166**	**0.516**
Commercial	Reference	0.288	0.230	2.571	2.300	0.130	0.119	0.060	0.054	0.753
	DG (MT)	0.242	0.193	2.234	2.010	0.112	0.103	0.050	0.045	0.652
	Optimal DRP (Linear)	**0.103**	**0.060**	**1.232**	**0.994**	**0.059**	**0.054**	**0.024**	**0.022**	**0.342**

the implementation of the linear model leads to the higher amount of LOL reduction than the others. In this case, the life extension of the residential, office building, and commercial transformers was increased by 14.49, 23.35, and 32.8 years, respectively, compared to the reference scenario. It should be mentioned that modeling of the customers' behavior based on one of the four expressed models is challenging. In other words, customer behavior in real areas can be different from the expressed models. Therefore, new modeling of demand response programs based on near-reality behavior of customers and investigating its impact on transformers' life expectancy can be the subject of future studies.

Furthermore, incentive and penalty tariffs of demand response programs can affect the achieved benefits. In general, as the amounts of the tariffs increase, the LOL rates are reduced. However, the high amount of penalty tariffs can cause dissatisfaction for customers and reduce the level of social welfare. In other words, customer dissatisfaction limits the amount of tariffs and, consequently, reduces the amount of LOL rate. Therefore, deriving the optimum amount of the tariffs can be the subject of future research.

In addition, an economic analysis was conducted from the perspectives of both utilities and customers to determine the optimal demand response program model, utilizing a newly developed economic benefit index. The results revealed that the linear demand response program could satisfy both the customers and the utility and provided the highest benefits for them. In this case, the total annual benefits of the utility and customers were increased by 762.64$ and 73.85$, respectively, compared to the reference scenario. Therefore, based on Multi-Attribute Decision Making (MADM) techniques, different models of the demand response program were prioritized by the regulator and the linear model was selected as the optimal solution. This model could not only extend distribution transformers' life expectancy but also increase benefits for both utilities and customers, as well as the network reliability. Also, the results indicate that the proposed method can reduce the annual LOL rate to about 36%, 54.6%, and 47.5% for the residential, office building, and commercial transformers, respectively, compared to those of obtained by the Micro Turbine (MT) technology implementation.

Nomenclature

$l_0(t)$ (kWh)	Initial load at the tth hour
$l(t)$ (kWh)	Final load at the tth hour
E	Customers price elasticity matrix
B	Customers income
S	Customers benefit
$P(\Delta l)$	Total incentive payments due to a reduction in customers' consumption
$i.j$	Hour
IC	Contract level
$A(t)$(\$/kWh)	Incentive tariff at the tth hour
$Pen(t)$(\$/kWh)	Penalty tariff at the tth hour
$\rho_0(t)$(\$/kWh)	Initial electricity price at the tth hour
$\rho(t)$(\$/kWh)	Spot electricity price at the tth hour
P	Number of demand response program models
α	Weights of decision-makers derived by AHP method
$\Delta\Theta_{\mathrm{TO,U}}$ (°C)	Ultimate top-oil rise over ambient temperature for load L
$\Delta\Theta_{\mathrm{TO,R}}$ (°C)	Top-oil rise over ambient temperature at rated load on the tap position to be studied
$\Delta\Theta_{\mathrm{H,U}}$ (°C)	Ultimate winding hottest-spot rise over top-oil temperature for load L
$\Delta\Theta_{H,R}$ (°C)	Winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied
K (per unit)	Load ratio
R	Ratio of load loss at rated load to no-load loss on the tap position to be studied
n	An empirically derived exponent used to calculate the variation of $\Delta\Theta_{H,U}$ with changes in load
m	An empirically derived exponent used to calculate the variation of $\Delta\Theta_{\mathrm{TO,U}}$ with changes in load
Θ_{TO}(°C)	Top-oil temperature
Θ_{A}(°C)	Average ambient temperature during the load cycle to be studied
$\tau_{TO}(h)$	Transformer's oil time constant for any load L and for any specific temperature differential between the ultimate top-oil rise and the initial top-oil rise
$\Delta\Theta_H$ (°C)	Winding hottest-spot rise over top-oil temperature
$\tau_H(h)$	Winding time constant at hot spot location
L_0 (years)	Transformers design life time
N	Number of 15-minute time intervals during a day ($N = 96$)
NT	Number of sample transformers

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