Evaluating the Effects of Demand Response Programs on Life Expectancy of Distribution Transformers

Hamed Dehghani¹, Behrooz Vahidi²*

¹²Department of Electrical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran 1591634311, Iran

¹First author, Hafez Ave, Tehran, Iran, Mobile: +98 9127401123, Email: Hamed.Dehghani@aut.ac.ir

²Corresponding author; Second author, Hafez Ave, Tehran, Iran, Phone: +98 21 64543330, Mobile: +98 9126179646, Email: vahidi@aut.ac.ir

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 has been applied on a realistic distribution network, and the results are evaluated under various models of the demand response program and different levels of tariffs. According to the results, distribution transformers’ life extension under various scenarios of applying demand response programs, in spite of differences among them, brings a great economic benefit. The results show a significant life extension in the interval of about 9 to 33 years. Also, this life extension brings a considerable benefit between 624.91$ to 821.669$, per year. However, the amount of obtained benefit considerably depends on the model of the demand response program and the level of tariffs. Besides, an economic analysis from both utility’s and customer’s perspectives is carried out in order to determine the optimal demand response model. To do this, an economic index is presented, and the best solution is determined by an Analytical Hierarchy Process so that it can satisfy both utilities and customers. As revealed by the results, the total annual benefits of the utility and customers are increased by 762.64$ and 73.85$, respectively.

Keywords: Distribution transformers, Demand response programs, Loss of Life rate, Economic
benefits, Analytical Hierarchy Process

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$l_0(t)$ ($kWh$)</td>
<td>Initial load in $t^{th}$ hour</td>
</tr>
<tr>
<td>$l(t)$ ($kWh$)</td>
<td>Final load in $t^{th}$ hour</td>
</tr>
<tr>
<td>$E$</td>
<td>Customers price elasticity matrix</td>
</tr>
<tr>
<td>$B$</td>
<td>Customers income</td>
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<tr>
<td>$S$</td>
<td>Customers benefit</td>
</tr>
<tr>
<td>$P(\Delta l)$</td>
<td>Total incentive payments due to a reduction in customers’ consumption</td>
</tr>
<tr>
<td>$i, j$</td>
<td>Hour</td>
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<tr>
<td>$IC$</td>
<td>Contract level</td>
</tr>
<tr>
<td>$A(t)$ ($$/kWh$)</td>
<td>Incentive tariff in $t^{th}$ hour</td>
</tr>
<tr>
<td>$Pen(t)$ ($$/kWh$)</td>
<td>Penalty tariff in $t^{th}$ hour</td>
</tr>
<tr>
<td>$\rho_0(t)$ ($$/kWh$)</td>
<td>Initial electricity price in $t^{th}$ hour</td>
</tr>
<tr>
<td>$\rho(t)$ ($$/kWh$)</td>
<td>Spot electricity price in $t^{th}$ hour</td>
</tr>
<tr>
<td>$P$</td>
<td>Number of demand response program models</td>
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<td>$\alpha$</td>
<td>Weights of decision-makers derived by AHP method</td>
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<tr>
<td>$\Delta \Theta_{TO,U}$ ($^{\circ}$C)</td>
<td>Ultimate top-oil rise over ambient temperature for load $L$</td>
</tr>
<tr>
<td>$\Delta \Theta_{TO,R}$ ($^{\circ}$C)</td>
<td>Top-oil rise over ambient temperature at rated load on the tap position to be studied</td>
</tr>
<tr>
<td>$\Delta \Theta_{H,U}$ ($^{\circ}$C)</td>
<td>Ultimate winding hottest-spot rise over top-oil temperature for load $L$</td>
</tr>
<tr>
<td>$\Delta \Theta_{H,R}$ ($^{\circ}$C)</td>
<td>Winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied</td>
</tr>
<tr>
<td>$K$ (per unit)</td>
<td>Load ratio</td>
</tr>
<tr>
<td>$R$</td>
<td>Ratio of load loss at rated load to no-load loss on the tap position to be studied</td>
</tr>
<tr>
<td>$n$</td>
<td>An empirically derived exponent used to calculate the variation of $\Delta \Theta_{H,U}$ with changes in load</td>
</tr>
<tr>
<td>$m$</td>
<td>An empirically derived exponent used to calculate the variation of with changes in load</td>
</tr>
<tr>
<td>$\Theta_{TO}$ ($^{\circ}$C)</td>
<td>Top-oil temperature</td>
</tr>
<tr>
<td>$\Theta_{A}$ ($^{\circ}$C)</td>
<td>Average ambient temperature during the load cycle to be studied</td>
</tr>
<tr>
<td>$\tau_{TO}$ (h)</td>
<td>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</td>
</tr>
<tr>
<td>$\Delta \Theta_{H}$ ($^{\circ}$C)</td>
<td>Winding hottest-spot rise over top-oil temperature</td>
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<td>$\tau_{H}$ (h)</td>
<td>Winding time constant at hot spot location</td>
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<td>$L_0$ (years)</td>
<td>Transformers design life time</td>
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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 the fact that the number of equipment in distribution networks is more than 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. So, their life management can improve the network’s reliability and bring a considerable benefit.

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

On-line monitoring is one of these solutions which can keep the transformers’ load below the dynamic thermal rating (DTR).

Integration of distributed generation resources (DGs) to distribution networks is another effective way of the transformers load management and life improvement [4-10]. Agah et al. have assessed the effects of the DGs owned by the customers on the transformers’ LOL rate reduction [8]. The results show a considerable reduction in the LOL rate. However, the reduction saturates at high levels of DGs penetration.
Electric vehicles charging (EVs) can add a significant load to the transformers, especially in peak hours. So, EVs’ charging time planning can reduce the transformers’ loading and improve their life [11-17].

Demand response programs (DRPs) are the other effective ways of load side management [18-23]. In [24], based on DRPs implementation, the life of distribution transformers has been optimized by categorizing household electrical appliances into five groups and transferring their working time to other times. In [25], a similar study has been done considering heating ventilation and air conditioning (HVAC) as a responsive load. Humayun et al. have extended high-power and high-capacity transformers’ service life by maintaining the hottest spot temperature (HST) level below a threshold using an optimal DRP [26]. In this study, the LOL rate of transformers is not evaluated. In [27], an optimization model based on an event-based demand response program has been presented to improve the life of power transformers, not distribution transformers, considering their congestion. In [18], the life of distribution transformers has been optimized by finding the best model of DRPs based on a cost-benefit objective function and determining the optimum amounts of the incentive and penalty tariffs. However, the effects of several models of DRPs on the transformers' life and their superiority are not evaluated. Also, the effects of the tariffs of the various models on the transformers life are not assessed.

From this literature review it can be found that a great deal of attention has been received on improving the life of distribution transformers based on DGs integration and EVs planning. However, the effects of DRPs on the life of transformers are the subjects of few researches. Furthermore, in these studies only the behavior of residential loads has been considered, whereas in real distribution networks, in addition to the residential loads there are office buildings and
commercial loads or a combination of them. Moreover, categorizing them in several groups is quite complicated and can’t be suitable for demand response programs analysis. Overall load profile is more accurate, practical, and realistic for DRPs analysis. So, in this paper, we have investigated in detail the impacts of different models of DRP on the distribution transformers’ life extension considering 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, an 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 performed to assess the 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 selecting choosing the first priority as the best solution, all the stakeholders of DRPs will be satisfied. Also, the investigations are performed on a realistic distribution network of Sirjan city-center in Iran for eight typical days, according to seasons and to weekdays and weekends. The contributions of the paper can be summarized as follows:

- Evaluating the effects of different models of DRPs along with their various amounts of tariffs on the LOL rate reduction of distribution transformers
- Prioritizing various models of DRP based on MADM method to find 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 II, different models of DRP are briefly explained. Thermal modeling of the distribution transformer and its LOL rate calculation are given in Section III. In Section IV, problem formulation is proposed to assess distribution transformers LOL rate in the presence of DRPs. Simulation results are presented in
Section V. Finally, Section VI presents concluding remarks.

II. Modeling of Demand Response Programs

Demand response programs can be classified as follows:

- Linear model
- Non-Linear models

A. Linear Demand Response Model

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

\[ E(i, j) = \frac{\partial l(i)}{\partial \rho(j)} \cdot \frac{\rho(j)}{l(i)} \quad n = 1, ..., 24 \]  

(1)

Besides, customer’s benefit function, \( S \), can be presented as:

\[ S = B(i) - l(i) \cdot \rho(i) \]  

(2)

Total incentive payments due to a reduction in customer’s consumption at the \( i \)th hour, \( P(\Delta l(i)) \), can be expressed as follows:

\[ \Delta l(i) = l(i) - l_0(i) \]  

(3)

\[ P(\Delta l(i)) = A(i) \cdot (l_0(i) - l(i)) \]  

(4)

Also, the total penalty payment for violating the customer’s contracted amounts at the \( i \)th hour is as below:

\[ PEN(\Delta l(i)) = Pen(i)[IC(i) - \{l_0(i) - l(i)\}] \]  

(5)

Considering equations (4) and (5), equation (2) can be rewritten as:

\[ S = B(l(i)) - l(i) \cdot \rho(i) + P(\Delta l(i)) - PEN(\Delta l(i)) \]  

(6)
To maximize the customer’s consumption, the derivative of its benefit concerning its demand should be equal to zero.

\[
\frac{\partial S}{\partial l(i)} = \frac{\partial B(l(i))}{\partial l(i)} - \rho(i) + \frac{\partial P}{\partial l(i)} - \frac{\partial PEN}{\partial l(i)} = 0
\]  

(7)

\[
\frac{\partial B(l(i))}{\partial l(i)} = \rho(i) + A(i) + Pen(i)
\]

(8)

Taylor expansion of \(B(i)\) for linear modelling has been stated as follows [29].

\[
B(i) \approx B_0(i) + \rho_0(i).l(i) - l_0(i).[1 + \frac{l(i) - l_0(i)}{2E(i,i)l_0(i)}]
\]

(9)

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

\[
\rho(i) + A(i) + Pen(i) = \rho_0(i).[1 + \frac{l(i) - l_0(i)}{E(i,i)l_0(i)}]
\]

(10)

Finally, by simplifying equation (10), the linear model of demand response program for a single period is calculated as follows [22, 28]:

\[
l(i) = l_0(i).[1 + \frac{\rho(i) - \rho_0(i) + A(i) + Pen(i)}{\rho_0(i)}]
\]

(11)

Furthermore, the linear model of demand response program for multi-period is derived as follows [22, 28]:

\[
l(i) = l_0(i).[1 + \sum_{j=1}^{24} E(i,j)\frac{\rho(j) - \rho_0(j) + A(j) + Pen(j)}{\rho_0(j)}]
\]

(12)

**B. Non-Linear Demand Response Models**

The various non-linear models of \(B(m)\) can be found in [29]. Similar to what has been done in section II.A, the multi-period non-linear models of demand response program can be obtained as follows (see [29] for more details):
The various models of DRP presented in this section will be used to evaluate the life expectancy of distribution transformers under various scenarios.

III. Distribution transformers thermal and LOL modeling

A. Modeling of distribution transformers thermal

For thermal modelling of transformers, the thermal model proposed in [30] is usually used.

The calculation procedure of [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 equations (14) and (15), respectively.

\[ \Delta \Theta_{H,U} = \Delta \Theta_{H,R} \times K^{2m} \]  
(14)

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

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

\[ \tau_{TO} \frac{d \Theta_{TO}}{dt} = (\Delta \Theta_{TO,U} + \Theta_A) - \Theta_{TO} \]  
(16)
3) At each time interval, obtain the increase in HST rise by solving a differential equation as:

\[ \tau_H \frac{d\Delta \Theta_H}{dt} = (\Delta \Theta_{H,U} - \Delta \Theta_H) \]  

(17)

4) Finally, the HST will be calculated by equation (18) as follows:

\[ \Theta_H = \Theta_{TO} + \Delta \Theta_H \]  

(18)

B. Modeling of distribution transformers LOL

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:

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

(19)

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

\[ F_{EQA} = \frac{\sum_{r=1}^{N} F_{AA,r} \Delta t_r}{\sum_{r=1}^{N} \Delta t_r} \]  

(20)

It should be noted that the distribution transformers’ load level is time-varying during their service life, and it is not suitable for aging analysis [8]. Therefore, by categorizing the database of transformer’s load level into eight typical days, according to seasons and to weekdays and weekends, the time dependency of the recorded data was removed. Thus, the annual LOL rate of the distribution transformer can be calculated based on the LOL rate of these typical days.
IV. Problem Formulation

From equations (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 customers’ 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 bring benefits for their owners. For the economic analysis of the benefits, the LOL rate and life of the under load distribution transformer is assumed to be \( F \) and \( L \), respectively. Also, the installed cost of the transformer and interest-inflation rate are assumed to be \( C \) and \( k \). If DRPs implementation can decrease the LOL rate by \( \Delta F \), the transformer life will increase by \( \Delta L \). 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 \( B_2 \) are resulted from increase in book value of a transformer, and its later replacement, respectively.

\[
B = B_1 + B_2
\]

\[
B_1 = \frac{\Delta L}{L} . C = \frac{\Delta F}{F - \Delta F} . C
\]

\[
B_2 = C.(1+k)^{L+\Delta L} - C.(1+k)^L = C.(1+k)^{L+\Delta F} - C.(1+k)^{L}
\]

The present worth of the resulted benefit can be derived as:

\[
PW = \frac{B_1}{(1+k)^L} + \frac{B_2}{(1+k)^{L+\Delta L}} = \frac{B_1}{(1+k)^L} + \frac{B_2}{(1+k)^{L+\Delta F}}
\]

Using equations (22) and (23), equation (24) can be deduced as follows [31]:

\[
PW = C\left(\frac{\Delta L}{L} \times \frac{1}{(1+k)^L} + 1 - \frac{1}{(1+k)^{\Delta L}}\right) = C\left(\frac{\Delta F}{F - \Delta F} \times \frac{1}{(1+k)^{F-L}} + 1 - \frac{1}{(1+k)^{L}}\right)
\]

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

\[
AW = PW \cdot \left( \frac{k(1+k)^{\frac{\mu}{F-\Delta F}}}{(1+k)^{\frac{\mu}{F-\Delta F}} - 1} \right)
\]

\[
AW = C.K. \left( \frac{\Delta F}{F - \Delta F} \times \left(1 + k\right)^{\frac{l_0}{(F - \Delta F)}} + \left(1 + k\right)^{\frac{l_0}{F - \Delta P}} - 1 \right)
\]

Furthermore, applying DRPs can provide the other economic benefit due to decrease in energy losses.

On the other hand, applying DRPs incur expenses such as incentive payments and reduction of selling of energy \([19, 33]\). To clarify, a DRP implementation reduces the power consumption during specific intervals of a day, which leads to a reduction in selling energy and accordingly utilities’ benefit. Conversely, during specific intervals of a day, the power consumption increases which leads to an increase in selling energy and consequently utilities’ benefit. The provided benefit by selling energy can be quantified as follows:

\[
SE = \sum_{i=1}^{24} \rho(t).\left[l(t) - l_0(t)\right] + Pen(t).\left[l(t) - l_0(t)\right] - A(t).\left(l(t) - l_0(t)\right)
\]

\[
\Delta l(t) = l(t) - l_0(t) \rightarrow SE = \sum_{i=1}^{24} \Delta l(t).\left(\rho(t) + Pen(t) - A(t)\right)
\]

Applying one model of DRPs can increase the benefits of a number of stakeholders, while decrease the benefits for the remainder. Therefore, the optimal model should be selected by the network’s regulator to optimize the benefits of the all the participants. To achieve this goal, 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 proposed annual benefit index considering importance degree of the stakeholders’. Assessing and prioritizing the various models of DRP based on MADM techniques is carried out by a three-layer hierarchy 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’s viewpoint as:

\[
ALE_i = \sum_{j=1}^{NT} (AW_{i,j}) \quad i = 1, \ldots, P
\]

(29)

In which, \( ALE \) is the annual benefit of the distribution transformers’ life extension for each model.

\[
ASE_i = \sum_{j=1}^{365} (SE_{i,j}) \quad i = 1, \ldots, P
\]

(30)

Which, \( ASE \) is the annual benefit of the selling energy for each model.

\[
ALR_i = \sum_{j=1}^{365} \left( \sum_{t=1}^{24} \left( P_{\text{loss}(t)_{\text{reference},j}} - P_{\text{loss}(t)_{i,j}}, \rho_j(t) \right) \right) \quad i = 1, \ldots, P
\]

(31)

Which, \( ALR \) 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 equations (32) and (33), per year, respectively.

\[
TBU_i = ALE_i + ASE_i + ALR_i \quad i = 1, \ldots, P
\]

(32)

\[
TBC_i = ASE_{\text{reference}} - ASE_i \quad i = 1, \ldots, P
\]

(33)

The decision matrix indicates the performance of each model of DRP for each index, and is created as follows:
In the first layer, based on AHP method [34], the weights of the decision-makers (stakeholders) are determined, $\alpha$, and the final decision matrix ($FD$) is calculated as follows:

$$FD = D \times \alpha$$

(35)

Finally, regulator sorts the models according to their $FD$ values, and selects the model with the highest $FD$ value as the optimal solution. The economic benefits of the all the decision-makers are maximized considering 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 equations (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 II.

**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 equations (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 II.

**Step 11**) Calculate $ALE$, $ASE$, and $ALR$ for all the scenarios using equations (29) - (31).

**Step 12**) Considering the results of step 11, calculate $TBU$ and $TBC$ for all the scenarios using equations (32) and (33).

**Step 13**) Based on the results of step 12, create $D$ and $FD$ matrices using equations (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.

V. Simulation and Results

In this section, the proposed method of section IV is employed on a realistic distribution network of Sirjan city-center in Iran, 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 [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, their rated power is 25 kVA, 160 kVA, and 315 kVA, respectively. Their cooling system is of the ONAN type and their thermal characteristics are tabulated in Table 1, based on the manufacturer’s data.

As mentioned before, to assess the life of distribution transformers over a year, the analyses are carried out in 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, and after that it approximately remains steady for two or three hours at the end of the days. Throughout the nighttime, it again rises and reaches to its peak at hour 22, and then falls until the end of the nighttime. Attention should be taken to the fact that through a wide range of the summer weekday, from hour 12:00 to hour 24:00, the LOL rate of the residential transformer exceeds the design rate, 1, by a significant amount (it reaches peak value, 26.53, at hour 22:00). On the contrary, in the winter 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 the office building and commercial ones.

The daily LOL rates are deduced by averaging the LOL over the typical days, to carry out a
better comparison. Furthermore, the analyses are conducted for all the sample transformers through all the typical days over the year. The daily LOL rate 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 are formed and presented in the last column of the table.

From Table 2 it can be found that the transformers’ LOL rate fluctuates extremely throughout the different seasons. Also, due to higher ambient temperature and electricity energy consumption by cooling systems in the summer, the seasonal LOL rates are higher not only than the other seasons but also than the annual averages. It implies 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, considering the fact that, during the spring and summer seasons, the number of people who presents at home or work on weekends are fewer than weekdays, the electricity consumption may get reduced. So, as revealed by Table 2, the seasonal LOL rates are reduced in weekends of those seasons in comparison with their 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 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 bigger than 1, which means 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 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 II are applied on the responsive loads, and consequently their consumption behavior are changed. This may lead 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.

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, DRPs implementation significantly reduces the daily LOL rate of the transformers. Besides, the linear model has 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 of Table 4, applying DRPs can reduce the annual LOL rate of the sample transformers up to 58.62%. Further, as stated before, the results imply that the DRPs model plays a vital role in reducing the LOL rate of distribution transformers. Among the models, the linear and power have the best and worst performance in the LOL rate reduction, respectively. Besides, the performance of the logarithmic model is between exponential and power models. Thus, from the LOL rate reduction viewpoint, the linear and exponential models
may receive higher priority than the others.

Distribution transformers’ life extension in presence of a DRP can be calculated as:

$$\Delta L = L_0 \left( \frac{\Delta F}{F \cdot \Delta F} \right)$$

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 II, the tariffs are the only factors which can be specified by the regulator. It means that the incentive and penalty tariffs can have significant effects on transformers life extension. 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 rate of the sample transformers are quantified, shown in Figure 8-Figure 11.

From Figure 8-Figure 11 can be found 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 for exponential model at high level of tariffs in which the LOL rate begins to rise. Another point inferred from Figure 8-Figure 11 is that the reductions obtained by going from 0 to 5 times of the tariffs are relatively more than those achieved by going from 10 to 15 times of the tariffs. Indeed, at high level of tariffs, the reductions are saturated. This can be justified by considering the fact that the transformer’s LOL is an exponential function of its HST. Also, as revealed by the figures, from the LOL rate reduction perspective, the linear has the best performance among all the models. By choosing a high amount of the tariffs for this model, the LOL rate of the transformers can reach approximately one-tenth of its amount in the reference scenario. Another remarkable point is that the change of the LOL rate in response to the change of the tariff in linear model is higher than
the others. It means that in the same amount of tariffs, the amount of LOL in linear model is lower than the others.

Using equations (21) to (27), an economic analysis is carried out to quantify the benefits obtained by 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$ to 475.225$ per year, depending on the type of transformers and the model of DRP. Also, the highest amount of benefits is achieved by the linear DRP because it has 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 under various scenarios for 0, 5, 10 and 15 times of the tariffs are calculated and shown in Figure 12.

From Figure 12, it is clear that the total economic benefit increases as the tariffs of DRPs rise. However, the higher amount the tariffs, the slower the increasing rate of the economic benefit. 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 goes from 5 to 10, the created economic benefit rises by 76.2$ per year which is a slower movement compared to the case 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, taking into account the 15 times of the tariffs, the annual benefit is limited to 957.3$ under the power model. For the similar conditions, the annual benefit can reach 6954$ for the linear scenario. This may contribute to millions of dollars 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 just 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’s viewpoint, the scenario with the highest amount of the 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 of 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 regulator’s viewpoint, the satisfaction of the customers has the higher importance than the utility’s opinion [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 which is calculated by AHP method.

Finally, the regulator by forming the $FD$ matrix calculates the priority of the scenarios, and concludes the results by AHP method which is shown in Figure 13. As shown in the figure, due to the fact that the linear model gives the best solution to both the customers and the utility, the regulator definitely shows more tendency to select that. Therefore, the highest priority is for the linear model and the others come next. 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 sample transformers’ LOL rates are calculated based on the DGs penetration method presented by Agah et al. [8], and the results are compared. Their studies show that the micro turbine (MT) has the highest amount of the LOL reductions among DG technologies. So, 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. For better comparison, the obtained results for the LOL rates under reference and optimal DRP scenarios are added to the table.

As shown in Table 10, the linear model of DRP has the highest amount of annual LOL rate reduction among the scenarios, which shows the efficiency 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 of obtained by the MT.
In the end, it is worth to mention that in this study the proposed method is applied only on three sample transformers as a part of a realistic distribution network. Consequently, as a great deal of transformers is installed in the distribution networks, implementation of an appropriate DRP model can not only extend transformers life expectancy but also it increases utilities and customers benefits as well as the network reliability.

VI. Conclusion

In this paper, a new method has been proposed to quantify the economic benefit of demand response programs in extending distribution transformers’ life expectancy. Studies have been conducted on a realistic distribution network, and the results indicate a significant increase in the analyzed transformers’ service life. According to the results, the life of the transformers is extended in the range of 8.88 to 32.8 years. This life extension brings a considerable benefit between 624.91$ to 821.669$, per year. As expected, the model of demand response plays an important role in reducing distribution transformers’ LOL rate. The results illustrate that the implementation of the linear model leads to higher amount of LOL reduction than the others. In this case, the life of the residential, office building and commercial transformers is 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 area can be different from the expressed models. So, the new modelling of demand response programs based on near-reality behavior of customers and investigating its effects 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 decrease.
However, the high amount of penalty tariffs can cause dissatisfaction for customers and reduce the level of social welfare. In other words, customers’ dissatisfaction limits the amount of tariffs and consequently the amount of LOL rate is reduced. So, deriving the optimum amount of the tariffs can be the subject of the future works.

Also, an economic analysis is carried out from utilities and customers viewpoint to determine the optimum model of demand response program considering a new economic benefit index. The results reveal that the linear demand response program can satisfy both the customers and the utility, and provides the highest benefits for them. In this case, the total annual benefits of the utility and customers are increased by 762.64$ and 73.85$, respectively, compared to the reference scenario. Therefore, based on MADM techniques, different models of the demand response program are prioritized by the regulator and the linear model is selected as the optimal solution. This model can not only extend distribution transformers life expectancy but also it increases utilities and customers benefits as well as the network reliability. Also, the results show 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 MT technology implementation.

References


18. Dehghani, H. and Vahidi, B. "Transformers loss of life management in smart distribution


32. LaGrega, M.D., Buckingham, P.L., and Evans, J.C., *Hazardous Waste Management*;


Figures and Tables captions:

Figure 1 Demand response programs prioritizing based on MADM techniques.
Figure 2 Flowchart of the proposed method to find the best solution.
Figure 3 Realistic distribution network of Sirjan city-center in Iran.
Table 1 Thermal parameters of the sample transformers [8].
Figure 4 Realistic load profiles of three types of customers in the typical days [18].
Figure 5 Daily evolution of LOL rate for the residential transformer before implementation of DRPs (reference scenario).
Table 2 The LOL rate of the sample transformers under reference scenario for all the typical days.
Table 3 Self and cross-elasticity of loads.
Figure 6 Daily evolution of the LOL rate for the residential transformer under various scenarios (a. summer weekday b. winter weekday).
Figure 7 Daily LOL rate of the sample transformers under various scenarios (a. summer weekday b. winter weekday).
Table 4 Annual LOL rate of the sample transformers under various scenarios.
Table 5 Sample transformers’ life extension under the various scenarios (years).
Figure 8 Annual LOL rate of the sample transformers under the linear DRP model scenario.
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.
Table 6 Prices of the sample distribution transformers.
Table 7 Annual economic benefit of the distribution transformers life extension under the various scenarios (Dollars).
Figure 12 Total economic benefit of the sample transformers life extension under various scenarios of the tariffs.
Table 8 Indices under various scenarios, per year (Dollars).
Table 9 Pair comparisons in AHP method.
Figure 13 Priority of scenarios (regulator viewpoint).
Table 10 Sample transformers LOL rate under linear demand response and MT technology scenarios.
Figure 1
Start

N=1
N: Typical day's number

Obtain the load profiles of the three sample transformers for the Nth typical day

Calculate daily LOL rate of the transformers (equations 14-20)

N=N+1

N≤Number of typical days

Calculate annual LOL rate of the transformers (reference scenario) by averaging over all the typical days

Select the first model of demand response (first scenario), M=1

N=1

Determine the load profiles of the three sample transformers for the Nth typical day after applying the DRP

Calculate daily LOL rate of the Transformers (equations 14-20)

N=N+1

N≤Number of typical days

Calculate annual LOL rate of the Transformers (Mth scenario) by averaging over all the typical days

M=M+1

M≤Number of DRP models

End

Calculate:
- ALE for each model (equation 29)
- ASE for each model (equation 30)
- ALReach model (equations 31)

Calculate TBU for each model (equation 32)

Calculate TBC for each model (equation 33)

Create decision matrix, D, (equation 34)

Create FD matrix (equation 35)

Sort the models (scenarios) according to their FD values

Select the models with the highest FD value as the optimum

Figure 2
Figure 3

Table 1

<table>
<thead>
<tr>
<th>$\tau_H$</th>
<th>$\tau_{TO}$</th>
<th>R</th>
<th>n</th>
<th>m</th>
<th>$\Delta \theta_{H,R}$</th>
<th>$\Delta \theta_{TO,R}$</th>
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<td>0.1hr</td>
<td>3.2hr</td>
<td>5</td>
<td>0.8</td>
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<td>25$^\circ$C</td>
<td>55$^\circ$C</td>
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Table 2

<table>
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<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
<th>Annual</th>
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<tbody>
<tr>
<td>Residential</td>
<td>0.339</td>
<td>0.279</td>
<td>4.044</td>
<td>3.058</td>
<td>0.128</td>
</tr>
<tr>
<td>Office building</td>
<td>0.524</td>
<td>0.374</td>
<td>4.212</td>
<td>3.223</td>
<td>0.304</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.288</td>
<td>0.230</td>
<td>2.571</td>
<td>2.300</td>
<td>0.130</td>
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</table>

*Weekday **Weekend
Table 3

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<th>Valley</th>
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<td>0.012</td>
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<tr>
<td>Office building / Commercial</td>
<td>-0.07</td>
<td>0.006</td>
<td>0.0072</td>
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<td>Residential</td>
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<td>-0.1</td>
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<tr>
<td>Residential</td>
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<td>Office building / Commercial</td>
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![Figure 6](image-url)
Figure 7

Table 4

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<th>Power</th>
<th>Exponential</th>
<th>Logarithmic</th>
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<tr>
<td>Residential</td>
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<td>0.342</td>
<td>0.424</td>
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### Table 5

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<tr>
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<td>14.49</td>
<td>8.88</td>
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<td>10.37</td>
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<tr>
<td>Office building</td>
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<td>13.26</td>
<td>16.83</td>
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<td>Commercial</td>
<td>32.80</td>
<td>21.18</td>
<td>26.50</td>
<td>24.21</td>
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</table>

**Figure 8**

![Graph showing LOL rate vs. Tariffs Increment (times) for different transformer scenarios.]

**Figure 9**

![Graph showing LOL rate vs. Tariffs Increment (times) for different transformer scenarios.]

---

35
Figure 10

Table 6

<table>
<thead>
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<th>Transformer</th>
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<tr>
<td>Average price ($)</td>
<td>640</td>
<td>4096</td>
<td>8064</td>
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Figure 11

Table 7

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<tr>
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<td>258.406</td>
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<td>Commercial</td>
<td>475.225</td>
<td>377.259</td>
<td>427.153</td>
<td>406.451</td>
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<tr>
<td>Total</td>
<td>821.669</td>
<td>624.291</td>
<td>714.434</td>
<td>690.853</td>
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Table 8

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<tr>
<td>ALE</td>
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<td>ASE</td>
<td>3828.65</td>
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<tr>
<td>ALR</td>
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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

Table 9

<table>
<thead>
<tr>
<th>Customer</th>
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<th>Weight(α)</th>
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<td>Utility</td>
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Table 10

<table>
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<th>Transformer</th>
<th>Scenario</th>
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<td>WD</td>
<td>WE</td>
<td>WD</td>
<td>WE</td>
<td>WD</td>
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<td>0.279</td>
<td>4.044</td>
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<td>0.128</td>
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<td></td>
<td>DG (MT)</td>
<td>0.288</td>
<td>0.241</td>
<td>3.57</td>
<td>2.755</td>
<td>0.112</td>
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<td>Optimal DRP</td>
<td>0.171</td>
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<td>Office building</td>
<td>Reference</td>
<td>0.524</td>
<td>0.374</td>
<td>4.212</td>
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<td>0.304</td>
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<tr>
<td>Commercial</td>
<td>Reference</td>
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<td>2.571</td>
<td>2.300</td>
<td>0.130</td>
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<tr>
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<td>DG (MT)</td>
<td>0.242</td>
<td>0.193</td>
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<td>1.232</td>
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</table>
Biographies

Hamed Dehghani was born in Iran. He received B.S. & M.S degrees in electrical engineering from Tabriz University and Amirkabir University of Technology (Tehran Ploytechinic), in 2011 & 2013. Presently, he is a PhD. student at the department of electrical engineering of Amirkabir University of Technology, Tehran, Iran. His main fields of research are life management, power market, restructuring, and deregulation in power systems.

Behrooz Vahidi was born in Abadan, Iran. He received the B.S. in electrical engineering from Sharif University of Technology, Tehran, Iran in 1980 and M.S. degree in electrical engineering from Amirkabir University of Technology, Tehran, Iran in 1989. He also received his Ph.D. in electrical engineering from UMIST, Manchester, UK in 1997. From 1980 to 1986 he worked in the field of high voltage in industry as chief engineer. From 1989 to present he has been with the department of electrical engineering of Amirkabir University of Technology where he is now a professor. Prof. Vahidi is an IEEE senior member. He is selected by the ministry of higher education of Iran and by IAEEE (Iranian Association of Electrical and Electronics Engineers) as the distinguished researcher of Iran. Prof. Vahidi was Director of Power System Center of Excellence at Amirkabir University of Technology. His main fields of research are high voltage, electrical insulation, power system transient, lightning protection and pulse power technology. He has authored and co-authored more than 500 papers and 20 books and book chapters on high voltage engineering and power system.