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Research Article

Demand Response Design for Healthy Operation of Transformers in Heavy-Load and High-Temperature Conditions

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Abstract: The healthy operation of high-power transformers plays a crucial role in the reliability of power systems. Given the thermal model of transformers under heavy-load and high-temperature conditions, the hot spot temperature exceeding the maximum allowable value may result in oil dissolution and cascading. This paper uses a thermal model of transformers to analyze the hot spot temperature load level under predicted ambient temperature, which may cross the healthy conditions. Then, an Incentive-Based Demand Response (IBDR) and a thermal model of transformers are used to determine optimal load curtailment. On the other hand, as the paper uses the demand response (DR) for security reasons, the risk of load participation in IBDR programs should be minimized. Hence, a Response Fatigue Index (RFI) is employed to maintain the comfort level of demands participated in DR. Also, the feasible solution area for multi-objective optimization is determined, given costs and RFI, using the sequential solution of a single-objective problem with cost reduction as the objective and RFI as the constraint with different levels of maximum acceptable RFI. The developed model was applied to a real substation in Iran as a test case. The results show that DR can enhance the reliability and life expectancy of the transformer while keeping the comfort level of loads as high as possible.

Keywords: Demand response, hot spot temperature, response fatigue index, transformer thermal model.

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NOMENCLATURE

Subscripts

$Cntrl$	Controllable loads
$Crit$	Critical demand
$Degr$	Transformer degradation
$dissat$	Dissatisfaction
$WODR$	Without DR
$Rated$	Rated load
amb	Ambient

Indices

i	Controllable loads
T (T)	Time

Variables and parameters

$Cost^{cap}$	Transformer capital cost
C^d	Transformer degradation cost
Inc	Incentive paid to the load for curtailment
L^T	Transformers' useful life
P	Power
DRF	Demand response fatigue
s	Binary variable of the demand participated in DR
U	Utility function
v	Load insistence parameter
V	Customer's displeasure value
θ	Temperature
θ_o	The increase in top oil temperature compared to the ambient temperature

θ_{fl}	The increase in top oil temperature compared to the ambient temperature at the nominal load
θ_u	The maximum temperature rise of top oil at load K
θ_i	The initial value of temperature rise of top oil at t = 0
θ_{amb}	Ambient temperature
T_o	Time constant of transformer oil at rated load
P_{fl}	Total loss at rated load
C	Heat capacity of the transformer
n	Oil exponent
K	Loading ratio
R	The ratio of load losses to no-load losses at rated load

1. Introduction

1.1. Problem Statement

Power transformers are often the most expensive components in a power distribution system. Their lifetime depends on the conditions of the paper insulation, which deteriorates due to heat loss, and the loss depends on the load speed of the transformer. In unexpected situations, overloads occur in healthy transformers of substations. The acceptable overloads defined by standards [1, 2] are at the expense of the transformer's life. In a heavily used system, contingencies with the overload time are severe, resulting in significant wear and tear of the transformers. Therefore, it is necessary to reduce the overload of transformers to extend their life.

Also, slight Load Factor (LF) and redundancy requirements impair the efficiency of transformers. In fact, transformers are generally designed and operated with a 40-60% nominal load to maintain system reliability at a desired level [3]. Almost one-quarter of distribution system equipment in the United States is operated for only 440 hours at peak loads [4]. Also, as the load increases, it is necessary to upgrade the transformers. The conventional method of system amplification for growing loads has high capital costs [5]. Therefore, applications tend to increase the LF of existing equipment [3]. Based on [6], it can be said that a distribution transformer loses 12-15% due to aging and overload. Therefore, it is necessary to check the basic and essential factors affecting the load, lifetime, and operation of transformers with new methods of monitoring the state of transformers so that by using them, we can use the capacity of network equipment in the best possible way.

1.2. Literature Review

A solution based on fuzzy logic is proposed in [6] to increase the life of distribution transformers. This solution tries to provide a good prediction for transformer loading. Some factors, such as reverse power currents, increase in ambient temperature, and voltage distortion, increase the temperature of the transformer coils, thereby impairing the transformer's performance.

A solution to increase transformers' life is the Demand Response (DR) [7], which is used by changing the load in smart networks and shows the best performance when the load reaches its maximum. With this method, the efficiency of the transformer increases, and it also saves money in terms of amplifiers. Therefore, the idea of the DR method to extend transformers' life is implemented in the worst conditions by applying maximum heat to the transformer windings before the temperature of the transformer windings rises too high. However, this method is unsuitable for oil temperature and the effects on the transformer. On the other hand, it does not provide a solution for the transformer's life. Smart meters use DR methods to prevent customers' excessive energy demand and reduce the effect of the load on the transformer. These methods provide their management programs based on the clustered data of the smart meters [8].

This method does not provide an idea for changes in ambient temperature, excessive effects caused by overloading, and failure rates. In [9], the researchers conducted various studies of the DR method on the transformer's life, one of which was the hot spot, which was considered a desirable method. However, they did not provide an optimal type of DR. Furthermore, this method fails to track the rise in the failure rate. In fact, the failure rate is important in the reliability assessment of power systems, and a fixed value is currently considered for it. Therefore, this investigation gave acceptable results, but it did not positively affect the accuracy of the failure rate because it did not consider the heterogeneity in the component population. In [10], a risk-based model was investigated, in which the risk caused by different measurements was evaluated to obtain the failure rate in the population. So, 12 power transformers were applied, and the failure rate obtained showed the maintenance performance. These transformers usually had a higher failure rate over a longer period.

Online monitoring, as well as the continuous removal of damage from oil, was used in [11] to increase the transformer's life and efficiency in charging electric vehicles. Transformers, including both medium-pressure and low-pressure ones, have been analyzed by many researchers [12]. In [13], the authors proposed a model to improve the use of transformers by keeping the HST under certain limits using DR.

In [14], the numerical health index of a transformer was calculated based on six components, including insulation resistance, the amount of water, tan δ, and dissolved gases. These components were combined using a neural network. The results revealed that these six components accurately showed the health status of the transformer. This study did not consider the transformer failure rate index, which is the main reason for replacing the transformer. The authors in [15] presented the health index of the studied 69-kV transformers with the help of gas measurements in oil, oil analysis, and aldehyde analysis in oil. Finally, due to the existing uncertainties, the fuzzy method was used for evaluation, and the calculated index was also fuzzy. In [16], a health index method was provided for transformers using equipment life criteria, equipment loading pattern during its lifetime, periodic service and repairs, internal errors occurring in the equipment history, substation location, transformer manufacturer, winding insulation test, the amount of water in the oil, insulating strength, analysis of gases in the oil, the resistance of the coils, and the power factor of the coil.

In [17], indicators such as insulation resistance, inspection and routine testing of power transformers, thermographic analyses, oil quality, analysis of undissolved gases in the oil, periodic testing and inspection of tap changer, tan δ, excitation current, coil resistance, and partial failure were used to determine the remaining life or relative health of the transformer. In [18], a method was provided for calculating the specific failure rate for each transformer based on its failure history, reliability measurements, undissolved gases, and furfuraldehyde. This study was conducted on 30 transformers, and the new index was compared with previous indices and asset management methods. In [19], a method was presented for ranking equipment based on the need for preventive maintenance. This rating took the initial condition of the equipment (after the previous overhaul), operating conditions, and environmental conditions during its operation into account.

The researchers in [20] evaluated the effect of lifetime, environmental conditions, and preventive and corrective repairs on the failure rate of transformers with the help of transformer failure and repair history information. Also, Ref. [21] used past information on the failure rate of transformers to evaluate their reliability for the current conditions. However, the transformer conditions were not considered. In summary, Table 1 provides a good comparison between some references and the research reported in this article.

1.3. Innovation and Research Contributions

So far, no research has studied the effect of DR on reducing the unreliability arising from transformers at unexpected times in the case of overload. Two important points considered in this article to accurately evaluate the failure rate include:

Table 1: The comparison of references

Ref. No.	Oil impurity	Thermal model	Loading	Demand response
[8,9]	-	-	-	✓
[10]	-	-	✓	-
[11]	✓	-	✓	-
[12]	✓	-	✓	-
[13]	-	-	-	✓
[14]	✓	-	-	-
[15]	✓	-	-	-
[16]	✓	-	✓	-
[17]	✓	-	-	-
[18]	✓	-	-	-
[19]	-	-	✓	-
[20]	-	✓	✓	-
[21]	-	✓	✓	-
Proposed	-	✓	✓	✓

1- The effect of loading on failure rate

2- The effect of special operating conditions

In this situation, the temperature of the hot spot exceeds the permissible limit and negatively affects the failure rate of the transformer. These two cases are clearly the main research contributions compared to other studies, as they have not been considered in any of the references.

1.4. Research Purposes

This paper proposes the direct effects of DR on the transformer using the transformer's thermal model to determine the accurate time of load curtailment. The dynamic thermal model is developed based on existing standards. Online condition evaluation is then done using the loading and ambient temperature data, and the reliability cost is analyzed for optimal determination of load curtailment considering load response fatigue and demand dissatisfaction to keep load motivation for participation in DRPs.

The contributions of this paper can be itemized as follows:

- Employing a thermal model in studying transformer operation considering DR
- Proposing a new method for monitoring transformer status and load response
- Reducing the DR risk using the Response Fatigue Index (RFI)
- Using sequential single-objective optimization with different RFI to find the Pareto front of the solution

2. Developed Modelling

In the developed model, the direct effects of DR on the transformer's loading level must be considered. The mathematical model consists of an optimization problem to model transformer operation incorporating DR. Then, a thermal model of the transformer is developed based on available standards. Finally, the transformer's degradation cost due to unhealthy conditions (i.e., heavy load or high ambient temperature) is expressed using a short-term virtual model for the failure rate of transformers, which is a function of thermal conditions.

2.1. Optimization Problem

The objective functions are the transformer degradation cost, incentives paid to responsive loads, and the cost of dissatisfaction for DRs, as expressed in (1) [24]:

$$OF = \sum_{t=1}^{T}\left\{Cost_t^{Degr} + Inct_t(\Delta P_t^{DR}) + V_t\right\} \tag{1}$$

where the first term expresses the transformer's degradation cost caused by the high-temperature operation, which is given in (2) [14].

$$Cost_t^{Degr} = (\xi_t^{Degr})C^d \,, \forall t \tag{2}$$

where $Cost_t^{Degr}$ is the degradation cost due to operation in unhealthy conditions. The term ξ_t^{Degr} is the loss of life, which is explained in the next section. C^d is the transformer's wear-out cost and can be calculated by (3) [25].

$$C^d = Cost^{inv}/L^T \tag{3}$$

where $Cost^{inv}$ is the investment cost of the transformer, and L^T is the useful lifetime of the transformer. Also,

$Inct_t(\Delta P_t^{DR})$ represents the incentive paid to the loads participating in an incentive-based program. Lastly, V_t represents the load dissatisfaction due to shifting from the desired consumption time modeled by (4). Note that the term in parenthesis represents ΔP_t^{DR} [24].

$$V_t = \sum_i v_i^{DR} \left(P_{i.t}^{WODR} - P_{i.t}^{DR}\right) \quad (4)$$

where $v_i^{DR} > 0$ is defined as the load's inelasticity parameter [14]. The higher amounts of v_i^{DR} indicate that the consumer insists on consuming load i at the initial time. Equation (5) gives demand response fatigue (DRF) based on [25].

$$DRF = \sum_\omega \pi_\omega \left(\frac{\sum_i v_i^{DR} \tau_i^{dissat}}{T \sum_i v_i^{DR}}\right) \times 100\% \quad (5)$$

where τ_i^{dissat} is the duration of the customer dissatisfaction due to the shifting of appliance i from the most convenient time, T_i^{ini} in a DRP. Equation (6) limits DRF to the given amount of DRF^{max} [25].

$$DRF \le DRF^{max} \quad (6)$$

2.2. Thermal Model

According to the IEEE standard [26], the temperature rise of oil over the ambient temperature can be expressed by (7):

$$T_o \frac{d\theta_o}{dt} = -\theta_o + \theta_u, \theta_o(0) = \theta_i \quad (7)$$

By solving this equation, we get (8) [14]:

$$\theta_o = (\theta_u - \theta_i)(1 - e^{-(t/T_o)}) + \theta_i \quad (8)$$

where θ_u is the maximum top oil temperature at load factor K, which is determined by (9) and (10) [27].

$$\theta_u = \theta_{fl} \left(\frac{K^2 \times R + 1}{R+1}\right)^n \quad (9)$$

$$K = \frac{I}{I_{rated}} \quad (10)$$

and T_o is the time constant of transformer oil at a rated load as shown by (11) [27].

$$T_o = \frac{C\theta_{fl}}{P_{fl}} \quad (11)$$

According to the above information, the oil temperature above the trans is obtained from (12) [22,31] :

$$\theta_{top} = (\theta_o + \theta_{amb}) = (\theta_u - \theta_i)\left(1 - e^{-(t/T_o)}\right) + \theta_i + \theta_{amb} \quad (12)$$

For practical use to predict and make an estimation, the above parameters in (12) are discretized using the Euler method as shown in (13) [17]:

$$\frac{d\theta_o[k]}{dt} \approx \frac{\theta_o[k] - \theta_o[k-1]}{\Delta t_1} \quad (13)$$

where Δt is the sampling period. Equation (13) can be written as (14) [23]:

$$\theta_o[k] = \frac{T_o}{T_o + \Delta t}\theta_o[k-1] + \frac{\Delta t \theta_{fl}}{T_o + \Delta t}\left(\frac{\left(\frac{I[k]}{I_{rated}}\right)^2 R + 1}{R+1}\right)^n \quad (14)$$

If the load is close to the nominal load or more precisely, R>1, (15) and (16) can be used [23].

$$\theta_u \rightleftarrows \theta_{fl}\left(\frac{I}{I_{rated}}\right)^{2n} \quad (15)$$

$$\theta_u[k] \rightleftarrows \theta_{fl}\left(\frac{I[k]}{I_{rated}}\right)^{2n} \quad (16)$$

Using the above equations, the following model can be extracted by (17) [23]:

$$\theta_o[k] = \frac{T_o}{T_o + \Delta t}\theta_o[k-1] + \frac{\Delta t \theta_{fl}}{T_o + \Delta t}\left(\frac{I[k]}{I_{rated}}\right)^{2n} = K_1\theta_o[k-1] + K_2 I[k]^{2n} \quad (17)$$

To use the above equation, we must estimate parameters K_1 and K_2 and, subsequently, T_o and θ_{fl}. For this, since K_1 and K_2 seem to be linear, the least squares method can be used (n=1). In fact, state n=1 corresponds to the Oil Forced Air Forced (OFAF) cooling system. According to the definition of θ_o, the top oil temperature can be expressed as (18) [25]:

$$\theta_{top} = \theta_o + \theta_{amb} \quad (18)$$

According to (17) and (18), the top oil temperature can be written as (19) [25]:

$$\theta_{top}[k] = K_2(\theta_{top}[k-1] - \theta_{amb}[k-1]) + K_1 I[k]^{2n} + \theta_{amb}[k] \quad (19)$$

2.2.1. Improved model

Since the model cannot follow the dynamics of the ambient temperature, the relationships must be modified. There are lots of modified models to include dynamic thermal models in the literature, but there are no easy-to-use correction factors, e.g., the effect of the coolers' thermal resistance and top-oil and hot-spot gradients. For example, the authors in [28, 29] have proposed a simple model for the thermal monitoring of Oil-Directed Air Forced (ODAF) transformers. In this paper, (18) replaces (7), and (20) is obtained for dynamic condition consideration [26].

$$T_o \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_{amb} + \theta_u \quad (20)$$

whose parameters are similar to (7). When this equation is solved, it results in (21) [30]:

$$\theta_{top} = (\theta_u + \theta_{amb} - \theta_{top,i})(1 - e^{-(t/T_o)}) + \theta_{top,i} \quad (21)$$

The discrete form of (21) can be expressed as (22) [26] in which R, T_0, and θ_{fl} are defined by (23), (24), and (25), respectively [26]:

$$R = \frac{K_1}{K_3} \quad (23)$$

$$T_0 = \frac{K_2 \Delta t}{1 - K_2} \quad (24)$$

$$\theta_{fl} = \frac{T_0(K_1 + K_3)}{K_2 \Delta t} \quad (25)$$

2.3. Variable Failure Rate Depending on the Temperature

According to the estimated models, the hot-spot temperature can be obtained and used to extract the duration of occurrences of unauthorized temperature in the hot spot during the equipment's lifetime. In this way, a model for the transformer failure rate is presented in this study by (26) [26].

$$\lambda_t = \left(1 + \frac{DU}{DU_{max}}\right)\lambda_{ini} \quad (26)$$

2.4. Degradation Cost

The term ξ_t^{Degr} in (2) represents the degradation coefficient, which is related to the transformer's failure rate as (27) [18]:

$$\xi_t^{Degr} = \eta + (1-\eta)(\frac{\lambda_{ini}}{\lambda_t}) \quad (27)$$

According to (27) and (2), the value of a transformer falls to η times its annualized cost as the failure rate equals zero. On the other hand, it decreases with the growth of λ_t. Using the results of the previous parts, an algorithm can be obtained for the optimal loading of the transformer. The lost lifetime index (LOL) is one of the important indices in evaluating the results of such modeling, which is defined according to (28) [32].

$$LOL\% = \sum_{i=1}^{T} \frac{F_{AA,i}}{NIL} \times 100 \quad (28)$$

where F_{AA} is the definition called the aging intensity factor and is defined as (29), and θ_H is the temperature of the trans hot spot. Also, NIL is the transformer's normal insulation lifetime provided by its manufacturer [32].

$$F_{AA} = exp\left(\left[\frac{NIL}{383}\right] - \left[\frac{NIL}{\theta_H+273}\right]\right) \quad (29)$$

We assume that the load curve and ambient temperature are known. The goal is to find the maximum coefficient that, if multiplied by the load curve, the oil temperature and the temperature of the hot spots, as well as the amount of lost life of the transformer, do not exceed the permissible limits.

Using the results, we can propose an algorithm to calculate the productivity, which is specified in Fig. 1. The algorithm should determine the maximum delivered peak load (maximum load factor) of the transformer according to the limitations. It should also calculate the temperature of the oil above the transformer, the temperature of the hot spots, and the amount of lost life of the transformer hour by hour. The inputs of this algorithm are as follows:

1- Load and temperature curves and thermal limitations and the maximum allowable life that is lost

2- The coefficients of the model obtained from the loading data in the previous days

The output is as follows:

1- Displaying the maximum load factor (F) and the maximum load that can be delivered by the transformer;

2- Calculating oil temperature and temperature of hot

$$\theta_{top} = \frac{T_o}{T_o+\Delta t}\theta_{top}[k-1] + \frac{\Delta t}{T_o+\Delta t}\theta_{amb}[k] + \frac{\Delta t\theta_{fl}R}{(T_o+\Delta t)(R+1)}\left(\frac{I[k]}{I_{rated}}\right)^2 + \frac{\Delta t\rightleftarrows\theta_{fl}}{(T_o+\Delta t)(R+1)} = K_1 I[k]^2 + (1-K_2)\,\theta_{amb}[k] + K_2\theta_{top}[k-1] + K_3 \quad (22)$$

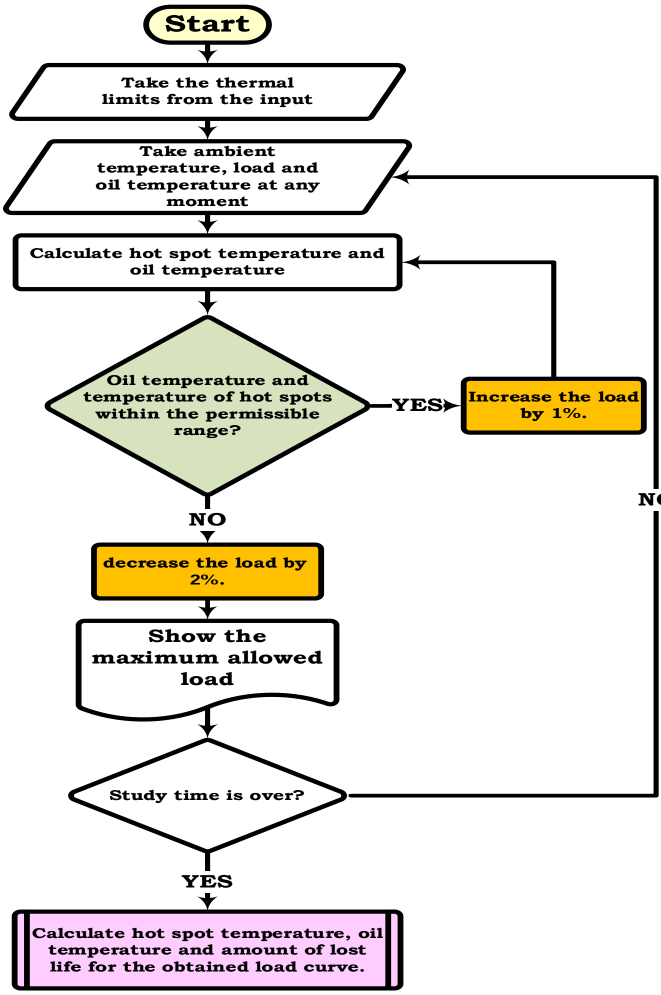

Fig. 1: Prediction flowchart of the maximum transferable load of the transformer.

spots and the amount of the lost life of the transformer according to the obtained load factor;

For a better understanding of the issue, Fig. 1 displays the flowchart of the algorithm for predicting the maximum load that can be delivered by the transformer.

3. Numerical Studies

The numerical studies consist of two main parts: testing the prediction model to prove the proposed thermal model and conducting case studies for DR analysis and optimal solution area for two objective functions.

3.1. Prediction of Top Oil Temperature

There are several models for predicting the temperature of transformers, which can be used according to the coefficients given by the transformer manufacturer and the information that is measured. However, most of these models require measurements that are not usually done, or the information is unavailable. As a result, they cannot be used in practice. Variables that are typically measured are ambient temperature, transformer top oil temperature, and load. In this section, using these data, we obtained a model for predicting the oil temperature in the next moments. Then, using the model obtained, we predicted the temperature of the hot spots for the next moments. To evaluate the model, we used the load and temperature data of a 180-MVA, 230/63-kV transformer with OFAF cooling made by Toshiba located in Ghorkhane Station between July and March 2013. The capital cost of this transformer was considered 8 M$, and the parameter η was considered 0.5 while λ_{ini} was considered 1.

These data are manually recorded hour by hour in offices. The data was transferred to MATLAB software, and these data were processed. An example of data for 1000 hours of loading in the time interval from July 26 to March 4 is shown in Fig. 2.

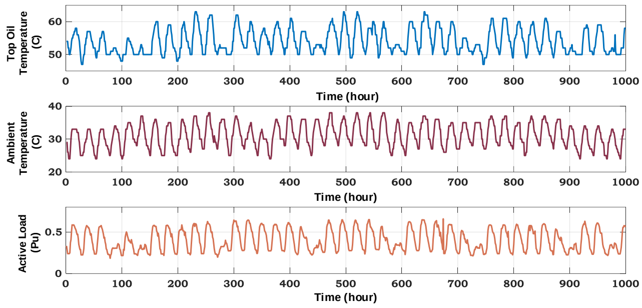

Fig. 2: Data for 1000 hours of loading in the time interval.

The simulation results and the measured values with the improved model are shown in Fig. 3. It can be seen that, in this case, the model could respond to the variation of ambient temperature and load. The error values of RMSE=1.36, and the maximum error is Max Error = 3.5˚C.

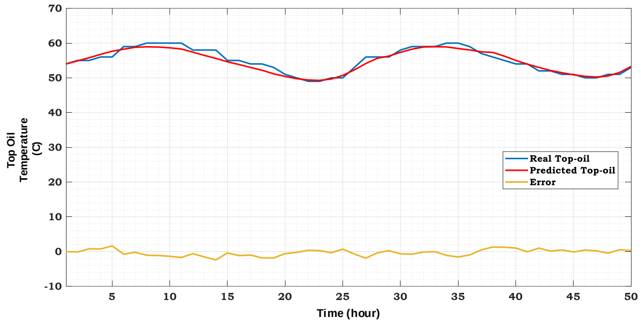

Fig. 3: Prediction with the improved model.

As can be seen in Fig. 3, the transformer thermal modeling method used in this paper was able to predict the temperature of the transformer oil well. In Fig. 3, the predicted temperature from the proposed thermal model is shown in red color. It can also be seen that the blue lines, which are the actual temperature of the transformer oil, have a slight difference from the red lines, and as the yellow lines show, this difference is a value of zero. Finally, all these comparisons express the accuracy and efficiency of the thermal model proposed for the transformer in this article.

3.2. Case Studies

The hypothetical loading profile and ambient temperature for the horizon of 760 hours for the current problem were considered as depicted in Fig. 4. Two case studies are presented in this section to show the effect of DR on the transformer operation as follows:

- Case1: Operation without DR
- Case2: Operation with DR

3.2.1. Case1

Fig. 5 depicts the predicted oil temperature, while the horizontal line is the limit of allowable temperature. As can be seen in this figure, the permissible temperature of transformer oil during the 760-hour period under investigation was higher than the threshold of 90°C in most of the hours, which is shown by the black horizontal line in Fig. 5. The reason for this issue is that the transformer is not used optimally, and the transformer loading is considered in the first case when the DR program has not yet been implemented.Also, as the results of Table 2 show, the cost of transformer failure is 0.0143 million dollars, which is obtained because the transformer is operated in suboptimal conditions. Therefore, if it is possible to optimize the operating conditions by using DR programs, this cost can be reduced. In the next case, the effect of the DR program has been examined.

3.2.2. Case 2

The result of changes in the objective function in terms of the maximum value of the acceptable load response fatigue constraint is drawn in Fig. 6. From Fig. 6, it can be concluded that if the maximum response fatigue index exceeds about 5.5, no improvement in the cost objective is achieved. Hence, the Pareto solution area for the problem is the area in the depicted rectangle. As the cost function is the main objective, the maximum optimal value for RFI^{max} = 5.5 is selected in this case study. In this case, 0.18 $/MWh is considered the incentive for 20% of loads participated in DRP. The results of Case 2 are presented in Table 3. As can be seen in Table 3, the degradation cost of the transformer decreased to 0.0090 million dollars. The reason for this reduction was the implementation of the DR program, which optimized transformer loading. Of course, this work was done by paying a 0.000414-dollar incentive to the subscribers participating in the DR program and paying a 0.000054 dissatisfaction fee to the subscribers who did not participate in the plan. The total

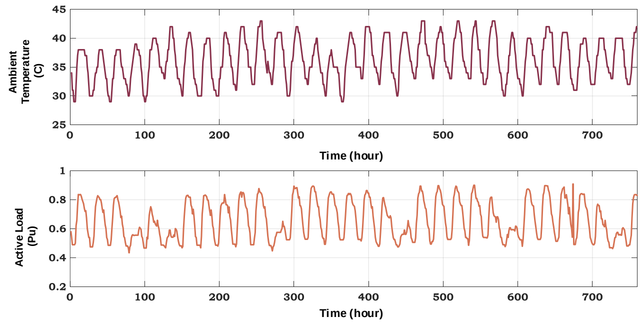

Fig .4: Hypothetical loading profile and ambient temperature for the horizon of 760 hours.

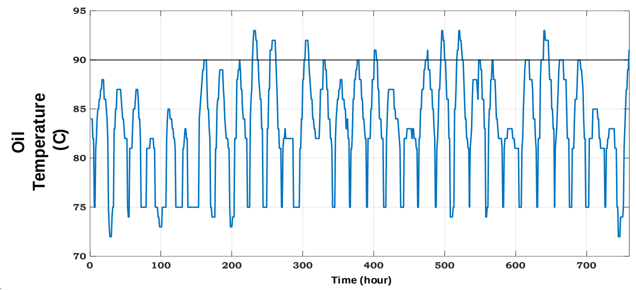

Fig. 5: Oil temperature by prediction for Case1.

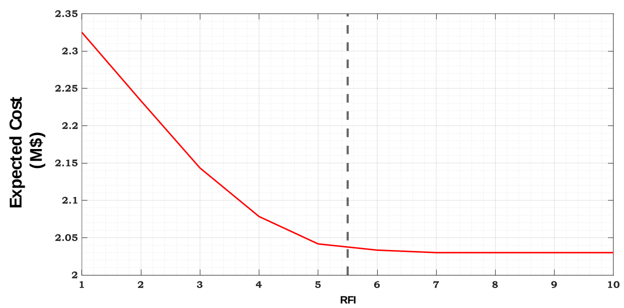

Fig. 6: The cost objective function value relative to the maximum value of the load response fatigue constraint.

Table 2: The costs for Case 1(M$).

Degradation cost of transformers	0.0143
Incentive paid to responsive load	0
Dissatisfaction cost	0
Total cost	**0.0143**

Table 3: The costs for Case 2 (M$).

Degradation cost of transformers	0.0090
Incentive paid to responsive load	0.000414
Dissatisfaction cost	0.000054
Total cost	**0.0095**

cost, as seen in Table 3, is $0.0095 million. This cost is significantly lower than that in Case 1 due to the implementation of the DR program. The results in Table 3 versus Table 2 revealed that with very low cost paid as the incentive, a great operation cost reduction can be obtained as degradation cost. Fig. 7 depicts the predicted oil temperature with DR As shown in Fig. 7, unlike Fig. 5, the amount of transformer temperature fluctuations in all 760 hours studied is below the threshold limit of 90°C. This reduction is due to the implementation of optimal operation of the transformer

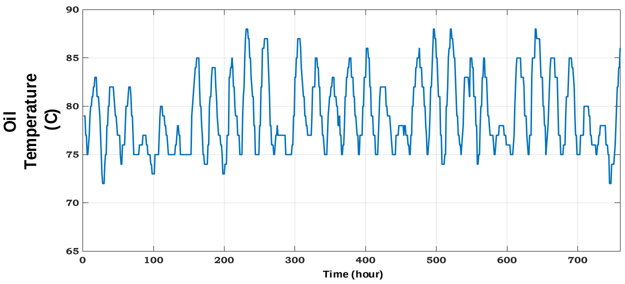

Fig. 7: Oil temperature by prediction for Case 2.

and the management of the transformer load during operation. In order to check the validity of the results of this article, they were qualitatively compared with those of a similar article. The results in that article were examined in two cases, with the DR and without it, as presented in Table 4.

As can be seen, after implementing the DR program with the modeling method proposed in this article, the LOL rate decreased from 0.0102 to 0.0056, which indicates the effectiveness of the DR method and also the accuracy of the RLS thermal model. Also, compared to reference [33], the DR method in this article managed to perform better; that is, it increased the LOL index from 0.00692 to 0.0056.

4. Conclusion

In this paper, the heavy-load and high-temperature conditions for power transformers were alleviated by DR. The standard thermal model for power transformers based on loading level and ambient temperature was used to investigate the effect of DR programs on the hot spot temperature. On the other hand, a temperature-related failure rate was developed to accurately measure the amount of DR effect on transformer healthy operation. To prevent DR application being tedious for loads, the DR fatigue index was also considered an objective function, and the proposed multi-objective optimization was solved by putting RFI as a constraint with different values. Also, as this article showed, by spending 0.0005 million dollars to implement the load response program, the degradation cost of transformers can be reduced by 33.5664%. This reduction shows the capacity of the method proposed in this article for the optimal use and thermal modeling of the transformer. Hence, the Pareto front of the objective functions was obtained. Numerical studies prove that the proposed method can allocate the DR programs for transformer life extension. On the other hand, the implementation of the DR program in transformers has caused the percentage of the transformer's loss of life to decrease significantly so that the LOL percentage decreased from 0.0102 to 0.0056. It means that the lifespan of the transformer was improved and increased by about 45%. Finally, it can be said that the important results obtained in this article are as follows:

- The positive effect of implementing the DR program in reducing transformer failures
- Increasing the lifetime of transformers by implementing DR programs
- Reducing the temperature of transformer oil and less need for periodical repairs due to the implementation of DR programs

Table 4: Comparison of the amount of LOL of the transformer.

	Without DR		
Maximum load can be delivered (pu)	Hot spot temperature (C)	LOL index in [33] (%)	LOL index this paper (%)
1.65	115	0.00726	0.0102
	With DR		
Maximum load can be delivered (pu)	Hot spot temperature (C)	LOL index in [33] (%)	LOL index this paper (%)
1.6	110	0.00692	0.0056

Future researchers are suggested to use the interest rate and the inflation rate to perform economic calculations from a long-term perspective for the economic analysis of the effects of the DR program on the cost of transformer repairs. In addition, this study addressed the effect of consumption time programs for a certain percentage of times, so it is suggested that the percentage of participation be considered as one of the optimization variables in future research. Finally, due to the direct effect of ambient temperature on oil temperature, it is suggested that the design of load response programs be taken into account with regard to ambient temperature changes during the day.

Credit Authorship Contribution Statement

Arash Moghadami: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Resources, Software, Writing - review & editing. **Davood Azizian**: Formal analysis, Funding acquisition, Project administration, Supervision, Validation, Visualization. **Amin Karimi**: Funding acquisition, Writing – original draft, Writing - review & editing.

Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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