IMPACT OF TIME OF USE TARIFF ON DISTRIBUTION TRANSFORMER LIFETIME

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ABSTRACT

This paper examines the implementation of time of use tariff (TOU) which is one of the demand response programs in distribution networks. The lifetime of distribution transformer as one of the most important and most expensive equipment in the distribution network has always been significant. In this paper, the lifetime of the transformer as an indicator for evaluating the effectiveness of TOU is selected and the lifetime of a 250 KVA transformer is calculated, at first, based on transformer initial load curve, then using improved load curve by TOU program. Simulation results show that the implementation of this program reduces transformer hot spot temperature and aging accelerating factor and improves transformer lifetime.

INTRODUCTION

Electric power utilities are facing with increasing demand of electricity, leading to high investment costs for new plants or development of transmission and distribution networks. In distribution networks, generally to have a balance between generation and consumption, developing of the supply side has been considered and less attention has been taken to demand management [1]. Demand side management or demand response refers to activities carried out by utilities to impact on customer electricity consumption and make appropriate changes in customer load curve.

Demand response programs are divided into two categories: Incentive-based and time-based programs. Incentive-based programs include direct load control (DLC), Interruptible/Curtailable (I/C) service, demand bidding (DB), emergency demand response program (EDRP), capacity market program (CAP) and ancillary service (A/S). Time-based programs include time of use (TOU), real time pricing (RTP) and critical peak pricing (CPP).

In general, customers react to demand response in two ways; they interrupt a part of their consumption or transfer it from peak period to off-peak period.

This paper examines the implementation of time of use tariff (TOU) in a distribution network in Rasht city. And the lifetime of the transformer as an indicator for evaluating the effectiveness of TOU is selected.

The implementation of TOU program makes customers reduce their consumption in peak hours and transfer it to off peak hours [3].

Transformer lifetime which is expressed by the insulation aging is related to its loading [4].

TIME OF USE TARIFF PROGRAM

In time of use tariff program, different tariffs are considered for electricity consumption at different times of day, days of the week or seasons of the year based on energy cost in each period. To perform TOU program, at least three time periods are considered, so the price of the energy is high at peak period, moderate at off-peak period and low at valley period.

ECONOMIC MODEL OF DEMAND RESPONSE

Elasticity

Elasticity is defined as demand sensitivity respect to energy price [5].

$$E = \frac{\rho_0}{d_0} \cdot \frac{\partial d}{\partial \rho} \qquad (1)$$

Where:
E = Elasticity
d =the demand value (KWh)
ρ =Electricity price (Rials/KWh)
ρ_0= Initial electricity price (Rials/KWh)
d_0=Initial demand value (KWh)

According to equation 1, self elasticity (E_{ii}) and cross elasticity (E_{ij}) will be written as:

$$E(i,j) = \frac{\rho_0(j)}{d_0(i)} \cdot \frac{\partial d(i)}{\partial \rho(j)} \qquad (2)$$

$$E(i,j) \le 0 \;\; if \;\; i = j$$

$$E(i,j) \ge 0 \;\; if \;\; i \ne j$$

With the variation of the energy price in different time periods, the reaction of customers is different.

Single period modelling

Some loads such as illuminating loads are not able to be transferred from a period to another period and can only be on or off. Such response to price changes is called single period model. These types of loads are sensitive just in a single period and this sensitivity is called self elasticity, which always has a negative value. We suppose that:

$d(i)$ = Customer demand in i-th hour (KWh)

$\rho(i)$ = Electricity price in i-th hour (Rials/KW)

$B(d(i))$ = Customer's income in i-th hour (Rials)

$E(i,i)$ = Self elasticity

And also suppose that the customer changes its demand from $d_0(i)$ to $d(i)$.

$$\Delta d(i) = d(i) - d_0(i) \quad (3)$$

So, the customer's benefit for i-th period is as follows:

$$S(d(i)) = B(d(i)) - (d(i).\rho(i)) \quad Rials \quad (4)$$

To maximize the customer's benefit, $\frac{\partial S}{\partial d(i)}$ should be equal to zero. So:

$$\frac{\partial S}{\partial d(i)} = \frac{\partial B(d(i))}{\partial d(i)} - \rho(i) = 0 \quad (5)$$

$$\frac{\partial B(d(i))}{\partial d(i)} = \rho(i) \quad (6)$$

The customer's benefit function is a quadratic function [6].

$$B(d(i)) = B_0(i) + \rho_0(i)[d(i) - d_0(i)]\left\{1 + \frac{d(i) - d_0(i)}{2E(i,i).d_0(i)}\right\} \quad (7)$$

Where:

$B_0(i)$ = Benefit when the demand is at nominal value

$\rho_0(i)$ = Energy price when the demand is at nominal value

Considering the last two equations:

$$\rho(i) = \rho_0(i)\left\{1 + \frac{d(i) - d_0(i)}{E(i,i).d_0(i)}\right\} \quad (8)$$

So, the customer's consumption will be as follow:

$$d(i) = d_0(i)\left\{1 + \frac{E(i,i)[\rho(i) - \rho_0(i)]}{\rho_0(i)}\right\} \quad (9)$$

Multi period modelling

Some loads are able to move from peak hours to other periods. Such response to price changes is called multi period model. This sensitivity is called cross elasticity.

$$E(i,j) = \frac{\rho_0(j)}{d_0(j)}.\frac{\partial d(i)}{\partial \rho(j)} \qquad i \neq j \quad (10)$$

We suppose that $\frac{\partial d(i)}{\partial \rho(j)}$ is constant for $i, j = 1,2,\ldots,24$. So the demand response to price changes is defined as a linear function [7].

$$d(i) = d_0(i) + \sum_{\substack{i=1 \\ i \neq j}}^{24} E(i,j).\frac{d_0(i)}{\rho_0(j)}.[\rho(j) - \rho_0(j)] \quad (11)$$

$$i = 1,2,\ldots,24$$

In this equation, a 24 hour period is considered. By combining equations 8 and 9, final equation is obtained as follows:

$$d(i) = d_0(i)\left\{1 + E(i,j)\frac{[\rho(i) - \rho_0(i)]}{\rho_0(i)} + \sum_{\substack{j=1 \\ i \neq j}}^{24} E(i,j).\frac{[\rho(j) - \rho_0(j)]}{\rho_0(j)}\right\} \quad (12)$$

$$i = 1,2,\ldots,24$$

Above equation shows customer's consumption in a 24 hours period to achieve maximum benefit.

In Iran, to execute TOU program, the amount of customer's consumption at peak period is multiplied by 300 rials and added to customer's bill and the consumption value at valley period is multiplied by 150 rials and deducted from the bill.

TRANSFORMER LIFETIME

To predict the lifetime of a distribution transformer, the IEEE standard C57.91 can be used [8]. The transformer lifetime is expressed by its insulation aging, which is a function of temperature, moisture and oxygen. In modern transformer constructions, the probability of increasing the percentage of oxygen and moister is low, so the only parameter affecting the transformer lifetime is temperature. Since the temperature distribution of the transformer is non-uniform, so generally, the hottest spot temperature of the transformer is considered for studding the insulation aging.

Transformer temperature is related to active loading and ambient temperature, so it's necessary to reduce the highest peaks. Experimental evidence indicates that the relation of insulation deterioration to time and temperature has the following form:

$$Per\ unit\ \ life = AEXP^{[\frac{B}{\theta_H + 273}]} \quad (13)$$

Where,

θ_H : The winding hottest spot temperature

A,B : are constants

Experimental results show that temperature is the principal variable affecting thermal life, also the degree to which the rate of aging is accelerated beyond normal for temperature above a reference temperature of $110\,^oC$ and is reduced below normal for temperature below $110\,^oC$ as shown in figure.1.

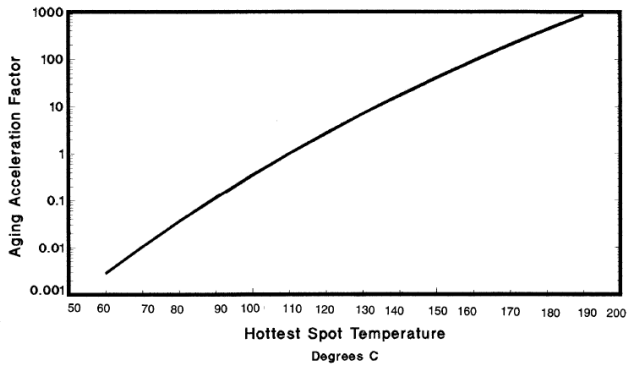

Fig.1: Aging acceleration factor

This curve should be used for both distribution and power transformers, because both are manufactured using the same cellulose conductor insulation. The equation for the curve is as follows:

$$Per\ unit\ \ life = 9.8*10^{-18} EXP^{[\frac{1500}{\theta_H+273}]} \quad (14)$$

The per unit transformer insulation life curve is the basis for calculation of an aging acceleration factor (F_{AA}) for a given load and temperature or for a varying load and temperature profile over a 24hours period. The equation for F_{AA} is as follows:

$$F_{AA} = EXP^{[\frac{1500}{383}-\frac{1500}{\theta_H+273}]} \quad (15)$$

F_{AA} has a value greater than 1 for winding hottest spot temperature above the reference temperature of $110\,^oC$, and less than 1 for temperature below $110\,^oC$. The equivalent life at the reference temperature that will be consumed in a given time period for the given temperature is the following:

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \quad (16)$$

Where,

F_{EQA} : equivalent aging factor for the total time period

n :index of the time interval,

N :total number of time intervals,

F_{AA_n} :aging acceleration factor for the temperature which exists during the time interval Δt_n

Δt_n :time interval, hours

The percent loss of total life is as follows:

$$LOL(\%) = \frac{F_{EQA}.t.100}{Normal\ insulation\ \ life} \quad (17)$$

According to the standard IEEE Std.C57.91, the insulation normal life is 180,000hours or 20.55 years. F_{EQA} gives the life consumption in the respective time period relative to the life consumption at $110\,^oC$. For example, for a time period of one year, F_{EQA} is two, it means that two years of lifetime at $110\,^oC$ were spent during this time. In this model θ_H is calculated as,

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \quad (18)$$

Where θ_A is the ambient temperature, $\Delta\theta_{TO}$ is the rise of the top oil temperature over ambient temperature and $\Delta\theta_H$ is the hottest spot rise over top oil temperature. $\Delta\theta_H$ is calculated as:

$$\Delta\theta_H = (\Delta\theta_{H,U} - \Delta\theta_{H,i})(1 - e^{-\frac{t}{\tau w}}) + \Delta\theta_{H,i} \quad (19)$$

$\Delta\theta_{H,i}$ is the initial temperature rise at the beginning of an interval, t is the duration of an interval in minutes and τ_w is the winding time-constant in minutes. For $\Delta\theta_{TO}$ a similar equation is applied.

$$\Delta\theta_{H,U} = \Delta\theta_{H,R} K_U^{\ 2m} \quad (20)$$

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R} (\frac{K_U^{\ 2} R + 1}{R+1})^n \quad (21)$$

Where, K_U is the ratio of ultimate load to rated load, $\Delta\theta_{H,R}$ is the winding hottest spot temperature rise over oil, $\Delta\theta_{O,R}$ is the top oil temperature rise over ambient at rated load. R is the ratio between no load loss and loss at rated. The factors m and n are between 0.8 and 1, depending on the transformer type.

SIMULATION RESULTS

In this paper, to assess the evaluation of TOU, the daily load curve of a 250 kVA transformer of the distribution network in Rasht city is selected. Three time intervals are defined: from 12pm to 7am as valley period, from 19:30pm to 23:30pm as peak period and 7:30am to 19pm as off-peak period. 300 Rial/Kwh,150 Rial/Kwh and 600 Rial/Kwh are considered as the price in valley, off-peak and peak periods. Approximately 40 percent of customers use multi tariff electricity meters.
Elasticity values are shown in table 1,

Table 1-elasticity values

	Valley period	Off-peak period	Peak period
Valley period	-0.2	0.008	0.006
Off-peak period	0.01	-0.2	0.008
Peak period	0.012	0.016	-0.2

The results of TOU implementation is shown in figure 2, which P0 represents transformer initial load curve with constant rate of electricity and P represents improved load curve by TOU.

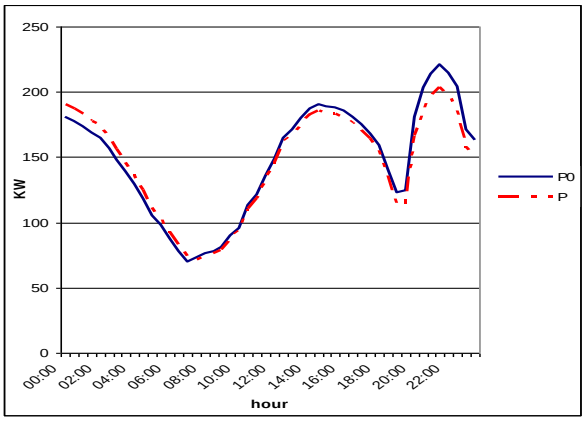

Fig.2: Transformer load curve

Transformer lifetime is calculated in two modes, the first mode uses initial load curve of the transformer and the latter using improved load curve by TOU program.

Transformer parameters taken from IEEE standard C57.91 as follows,

$$\Delta\theta_{H,R} = 28.5$$

$$\Delta\theta_{O,R} = 36$$

$$R = 4.87$$

$$\tau_w = 5$$

$$\tau_{To} = 3.5$$

$$m, n = 1$$

Figure3 shows transformer hot spot temperature changes during a day in both modes, T0 represents transformer hot spot temperature using initial load curve and T, using improved load curve by TOU.

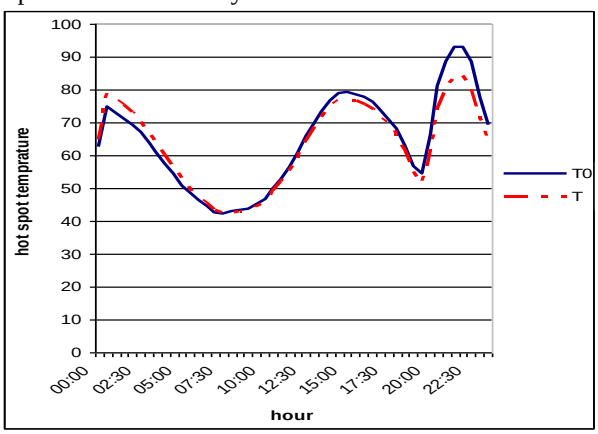

Fig.3: Transformer lifetime

CONCLUSION

This paper examines the implementation of time of use tariff (TOU) which is one of the demand response programs in distribution networks. Transformer aging acceleration factor is calculated based on transformer initial load curve and transformer improved load curve by TOU. The results of the program show that TOU implementation could reduce transformer hot spot temperature and improve transformer lifetime.

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