Optimal sizing of distribution network transformers considering power quality problems of non-linear loads

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Abstract: Transformers are important equipment in distribution networks which their optimal siting and sizing is one the important issues in planning and operation of distribution networks. In traditional methods, the optimal capacity of transformers is determined considering the average load consumption and temperature. In the presence of non-linear loads, the current and voltage distortions are increased which increase the power losses of transformers, increase their temperature and decrease their lifetime. Therefore, in this study, a new method is proposed to determine the optimal size of distribution transformers in the presence of non-linear loads. To evaluate the effectiveness of the proposed method, it is applied on two commercial complexes with high non-linear loads.

1 Introduction

Optimal capacity of distribution transformers is determined based on their operation to meet the average load considering some environment indices. Low loading of these transformers increases the extra capacity of them which installed in distribution network. On the other hand, high loading of these transformers increases their temperature, power losses and decrease their lifetime.

Nowadays, the non-linear loads are increased in distribution networks due to industrialisation, converter-based loads and so on. These loads increase the distortion of voltage and current in the network. Transformers are main equipment in distribution network. In the presence of non-linear loads and increasing current and voltage distortions, the power losses and loading of transformers are increased. Therefore, if the effects of harmonic loads are not considered in optimal sizing of distribution transformers, their loading and temperature are increased and their lifetime are decreased.

The effects of non-linear loads on the transformers are reviewed in [1] and the IEEE standard procedures for optimal sizing of distribution transformers under harmonic loads is investigated [2]. The effect of harmonics on transformers is discussed in [3] and to predict a transformer hot spot temperature, a thermal model is proposed. To online monitor the harmonic losses of distribution transformers, a new method is presented in [4]. The harmonic losses of transformers are calculated and relationship between it and the harmonic current distortion rate is investigated in [5]. In this paper, the main contribution is to determine the optimal size of distribution transformers in the presence of non-linear loads. For this purpose, the two important IEEE standards consisting of IEEEC57.110 and IEC60354 [6] are used.

The paper is organised as follows. The problem is modelled in the next section. In other one, simulation results are discussed and in the end conclusions are presented.

2 Problem modelling

The optimal size of distribution transformers in Iran is determined based on IEC60354 standard. Although, this standard is one of the important world standards to determine the optimal size of distribution transformers, the harmonic effects of non-linear loads is not considered in it. These harmonic effects decrease the operational capacity of distribution transformers, increase the temperature of it, and reduce its lifetime. The optimal size of distribution transformers in the IEC60354 standard is determined using Fig. 1 and (1) and (2) and three parameters consist of average apparent power in peak and low-load periods, environment temperature and the period of peak load

$$\frac{S_1}{S_2} = \frac{K_1}{K_2} \quad (1)$$

$$S_r = \frac{S_1}{K_1} = \frac{S_2}{K_2} \quad (2)$$

where S_1 and S_2 are apparent power in low and peak load periods, respectively. k_1 and k_2 are the load factor (load current/rated current) and S_r is the rate power in MVA. In the presence of non-linear loads, the harmonic current is increased which increases the temperature of the transformers and reduces their lifetime. The reduction amount of distribution transformers capacity in the presence of harmonic loads is calculated according to the IEEEC57.110 standard. Based on this standard, the maximum current of distribution transformers is calculated as follows:

$$P_{LL} = P + P_{EC} + P_{OSL} \quad (3)$$

$$P_{LL} = RI^2 + P_{EC} + P_{OSL} \quad (4)$$

$$P_{EC}(\text{p.u.}) = P_{EC-R}(\text{p.u.}) \sum_{h=1}^{h=h_{max}} I_h^2(\text{p.u.}) h^2 \quad (5)$$

$$I(\text{p.u.}) = \sqrt{\sum_{h=1}^{h=h_{max}} I_h^2(\text{p.u.})} \quad (6)$$

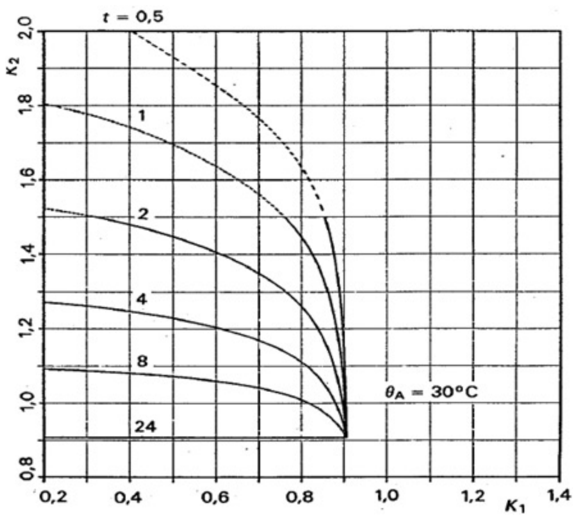

Fig. 1 *Sample curves to determine distribution transformers in IEC60354 standard*

$$F_{\rm HL} = \frac{\sum_{h=1}^{h=h_{\max}} [I_h/I_1]^2 h^2}{\sum_{h=1}^{h=h_{\max}} [I_h/I_1]^2} = \frac{\sum_{h=1}^{h=h_{\max}} I_h^2({\rm p.u.}) h^2}{\sum_{h=1}^{h=h_{\max}} I_h^2({\rm p.u.})} \quad (7)$$

$$P_{\rm LL}({\rm p.u.}) = I^2({\rm p.u.}) + P_{\rm EC-R}({\rm p.u.}) \sum_{h=1}^{h=h_{\max}} I_h^2({\rm p.u.}) h^2 \quad (8)$$

$$P_{\rm LL}({\rm p.u.}) = I^2({\rm p.u.}) \times (1 + F_{\rm HL} \times P_{\rm EC-R}({\rm p.u.})) \quad (9)$$

$$I({\rm p.u.}) = \sqrt{\frac{P_{\rm LL}({\rm p.u.})}{1 + F_{\rm HL} \times P_{\rm EC-R}({\rm p.u.})}} \quad (10)$$

$$I_{\max}({\rm p.u.}) = \sqrt{\frac{P_{\rm LL-R}({\rm p.u.})}{1 + F_{\rm HL} \times P_{\rm EC-R}({\rm p.u.})}} \quad (11)$$

where $P_{\rm LL}$ is the load loss, $P_{\rm LL\text{-}R}$ is the load loss under rated conditions, $P_{\rm EC}$ is the winding eddy-current loss, $P_{\rm EC\text{-}R}$ is the winding eddy-current loss under rated current, $F_{\rm HL}$ is the coefficient of harmonic losses for eddy current of winding, $P_{\rm OSL}$ is the other stray losses, P is copper losses, I is the load current in amperes, $I_{\max}$ is the maximum transformer current in the presence of harmonic loads in per unit, I_h is the the load current in harmonic h, and h is the harmonic order. The equations of (5)–(7) are included in (4) to obtain (10). In this procedure, the value of $P_{\rm OSL\text{-}R}$ is zero as described in the mentioned standard. Equation (11) is the harmonic load current for rated current operation.

The reduction amount of distribution transformers lifetimes according to the transformer temperature when the peak load accrued is accrued in 24 h period is shown in Table 1. As described in Table 1, when the transformer temperature is increased as 6°C, the lifetime of transformer will be decreased by 50%. Moreover, in other cases, the relation between increasing of distribution transformers temperature, loading, and lifetime is described in (12) and (13) as described in IEC60354 standard

$$\theta_{\rm h} = \theta_{\rm a} + \Delta\theta_{\rm or}\left[\frac{1 + RK^2}{1 + R}\right]^X + Hg_{\rm r}K^y \quad (12)$$

$$V = \frac{\text{ageing rate at } \theta_h}{\text{ageing rate at } 98^\circ C} = 2^{(\theta_h - 98)/6} \quad (13)$$

where $\theta_{\rm h}$ is the hot spot temperature, $\theta_{\rm a}$ is the ambient temperature, R is the ratio of load losses at rated current to no-load losses, X is the oil exponent, Y is the winding exponent, V is the relative ageing rate, K is the load factor, Hg_r is the hot spot to top-oil gradient in kelvin.

In this paper, to consider the effect of non-linear loads on determination of distribution transformers capacity, the new equation is proposed according to the IEC60354 and IEEEC57.110 standards as follows:

$$K_{\rm h} = I_{\max}({\rm p.u.}) = \sqrt{\frac{P_{\rm LL-R}({\rm p.u.})}{1 + F_{\rm HL} \times P_{\rm EC-R}({\rm p.u.})}} \quad (14)$$

$$S_{\rm r} = \frac{S_1}{K_1 \times K_{\rm h}} = \frac{S_2}{K_2 \times K_{\rm h}} \quad (15)$$

Table 1 Relative between ageing rate of transformers and their temperature

$\theta_{\rm h}$	Relative ageing rate
80	0.125
86	0.25
92	0.5
98	1
104	2
110	4
116	8
122	16
128	32

3 Simulation results

To evaluate the proposed method in this paper, two commercial complexes (Golestan and Khedri) are considered in Baneh, Kurdistan, Iran which have the high penetration rate of non-linear loads. For example, there are 6000 of low consumption lamps and 400 computers and laptops in Golestan commercial complex as shown in Fig. 2. To obtain the required data from these loads, a power quality analyser is installed in their substations in point of common coupling (PCC) as shown in Fig. 3. The results are shown in Figs. 4–8. Total harmonic deviation (THD) of current of Golestan and Khedri complexes are 57 and 37% which are shown in Figs. 4 and 5, respectively. These THD of current for these loads are higher than the standard value of current THD for these loads in Iran which is 20%. Also, THD of voltage of Golestan and Khedri complexes are 8.05 and 8.9%, respectively, which are shown in Figs. 6 and 7. THD of voltage for these loads are higher than the standard value of voltage THD for these loads in Iran which is 5%.

Currents of three-phase and null for Golestan complex substation is shown in Fig. 8. As shown, current of three-phase is approximately balance and so it is expected that the null current has the low value. However, due to presence of harmonic loads, the null current is 35%

Fig. 2 *Golestan commercial complex in Baneh, Kurdistan, Iran*

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Fig. 3 *Power analyser which is used in Golestan complex substation*

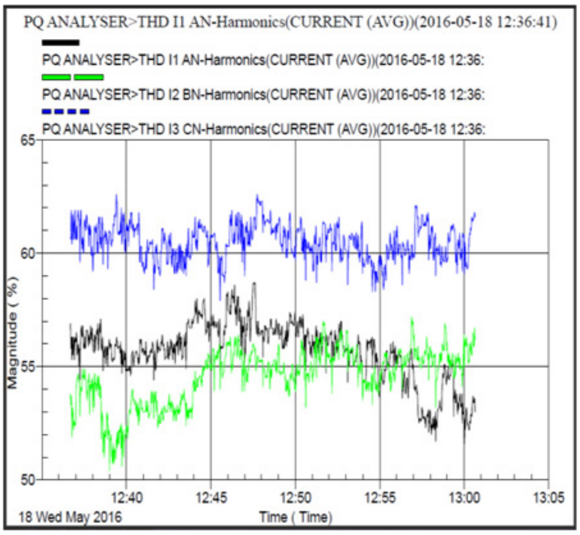

Fig. 4 *THD of current in Golestan complex*

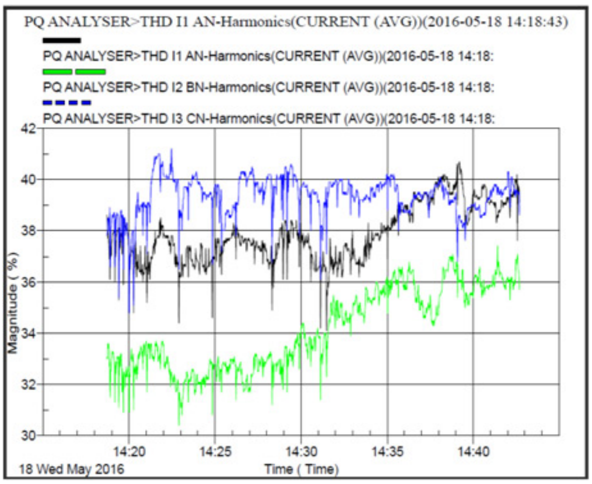

Fig. 5 *THD of current in Khedri complex*

higher than the phase current which increases the temperature of transformer.

The harmonic required data to calculate the reduction capacity of Golestan's transformer is given in Table 2. Using the data of this

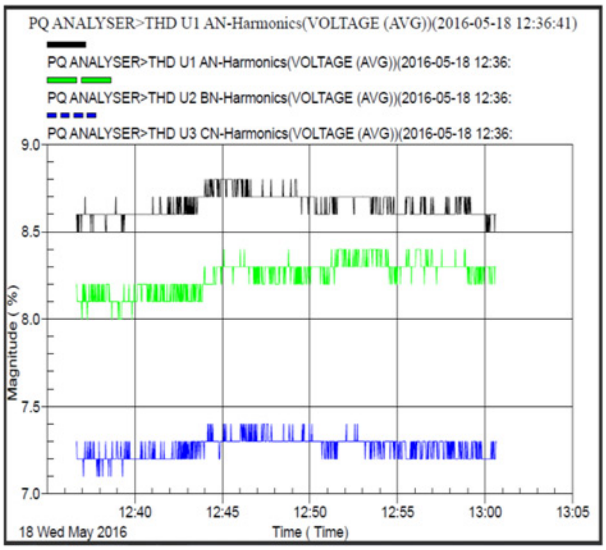

Fig. 6 *THD of voltage in Golestan complex*

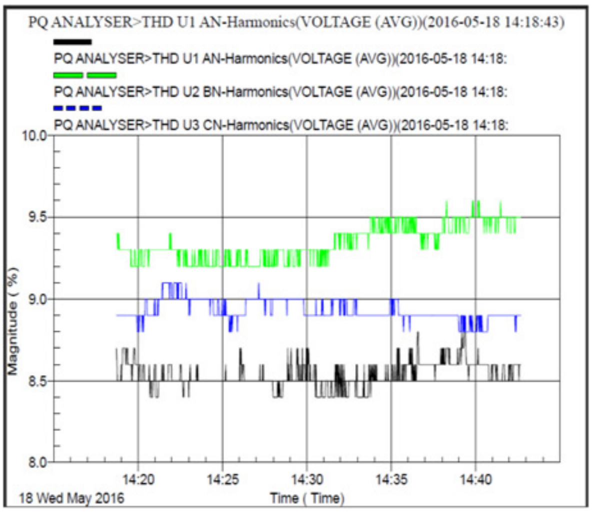

Fig. 7 *THD of voltage in Khedri complex*

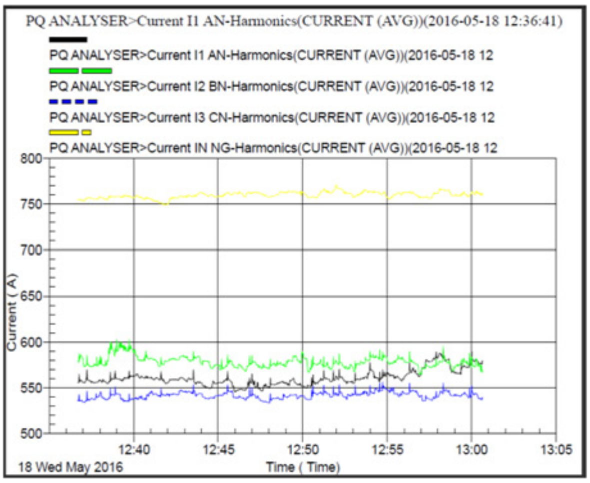

Fig. 8 *Three-phase and null current for Golestan complex*

Table 2 Harmonic required data for Golestan complex

h	I_h/I_1	$(I_h/I_1)^2$	h^2	$(I_h/I_1)^2 h^2$
1	1	1	1	1
3	0.5033	0.25333	1	2.27998
5	0.2188	0.04787	9	1.19673
7	0.0710	0.00504	25	0.247
9	0.0383	0.00147	49	0.119
11	0.0338	0.00114	81	0.1384
13	0.0301	0.00090	121	0.1526
15	0.0129	0.00017	169	0.03715
17	0.0151	0.00023	225	0.06588
19	0.0129	0.00017	289	0.06018
21	0.0081	0.00006	361	0.02867
23	0.0104	0.00011	441	0.05728
25	0.0045	0.00002	529	0.01273
sum	—	1.310512	625	5.3958

Table 3 Results of harmonic losses calculations for two complexes

Complex name	F_{HL}	P_{EC-R}
Golestan	4.117	0.08
Khedri	2.51	0.08

table, the required parameters are calculated for this complex. Moreover, this data is calculated for other complex and calculation is also done for it. The results are shown in Table 3. The value of P_{EC-R} is determined with notice to the transformer specifications and is obtained based on its manufacture data. Without considering harmonic effect, the transformers' capacity is determined according to (2) and Fig. 1. The required data for this calculation is given in Table 4. It should be mentioned that, for this calculation, some modifications are required in Fig. 1. With considering harmonic effect, the transformers' capacity is determined according to (11) and (15). Then, this resulted capacity is compared with distribution transformers capacity which is made by manufactures to determine the actual capacity which can be installed. In (15), the values of k_1 and k_2 are obtained as mentioned before (in without considering harmonic effect case), and the value of k_h is obtained in (14).

The transformers' capacity of these complexes which are determined in two cases (considering/not considering effects of harmonic loads) is given in Table 5. As shown in Table 5, if the effects of harmonic loads are not considered in Golestan complex, the capacity of its transformer is 400 kVA based on IEC60354 standard which in this manner the loading of transformer is 105% and so the hot spot temperature is increased and its lifetime is decreased. On the other hand, if the effects of harmonic loads are considered, the capacity of transformer is 500 kVA and so the loading of transformer is in normal operation and has no damage for it. The capacity obtained from (15) is 443.8 kVA. Since this transformer capacity is not exist in Iran, the transformer capacity which should be considered to this complex is 500 kVA.

Table 4 Required data to determine transformers' capacity in without considering harmonic effect case

Complex	S_1	S_2	θ_a	t
Golestan	87	338	33	12
Khedri	162	469	33	12

Table 5 Transformers' capacity and their loading in two cases

	Without considering harmonic effects		With considering harmonic effects	
	S_r	Loading, %	S_r	Loading, %
Golestan	400	105	500	84
Khedri	630	83	630	88

Table 6 Hot spot temperature and ageing rate for distribution transformers of two complexes

	Without considering harmonic effects			With considering harmonic effects		
	S_r	θ_h	V	S_r	θ_h	V
Golestan	400	133	2.6	500	111	0.203
Khedri	630	110	0.186	630	115	0.313

For Khedri complex, the capacity of transformer in two cases is 630 kVA. However, the loading of transformer is different in two cases and the actual loading of transformer is equal to the case in which the effects of harmonic loads are considered.

Hot spot temperature and ageing rate of transformers of two complexes in two cases are given in Table 6 which are obtained from (12) and (13). Peak loading period for complexes' transformers are 12 h and their hot spot temperature for normal ageing rate is 124°C. Other required data for calculation is obtained from the IEC60354 standard

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{max}} I_h^2} = \frac{5.3958}{1.3105} = 4.117 \quad (16)$$

$$P_{LL}(\text{p.u.}) = 1.3105(1 + 4.117 \times 0.08) = 1.7421 \quad (17)$$

$$I_{max}(\text{p.u.}) = \sqrt{\frac{1.08}{(1 + 4.117 \times 0.08)}} = 0.9013 \quad (18)$$

4 Conclusion

THD of current and voltage is increased in distribution networks due to presence and development of non-linear loads. This issue should be considered in optimal sizing determination of distribution transformers to avoid from increasing the temperature of transformers and reduction of their lifetime. In this paper, a new method is proposed based on IEC60354 and IEEEC57.110 standards to determine the optimal size of distribution transformers in the presence of non-linear loads. To evaluate the effectiveness of the proposed method, two commercial complexes are considered which have many non-linear loads. The results show that in Golestan complex the capacity of its transformer should be increased from 400 kVA (obtained from traditional method) to 500 kVA (obtained from proposed method in this paper). If the capacity of this transformer is calculated and installed based on traditional method (400 kVA), the ageing ratio of it increases to the 2.6 of its normal value due to presence of harmonic current and voltage. Meanwhile, the results show that the capacity of transformer for Khedri complex from two methods are same and equal to 630 kVA. This occurs due to presence of lower non-linear loads in this complex in comparison to Golestan complex.

5 Acknowledgments

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