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Original Article

Assessment of Damages Caused by Low Power Quality Indicators in the Transmission Network

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Abstract

Due to the increasing non-linear loads in power systems and furthermore, the increase of loads sensitive to power quality pollution, power quality issues have become important. Power quality disturbances in general cause many problems for power systems. One of the most important problems is economic issues and costs imposed on the network. In this paper, the classification of the origin of power quality problems and the most important technical damages caused by power quality are addressed. Therefore, in this article the effect and distortions of power quality on losses and lives of equipment i.e. cables and overhead lines, power transformers, capacitor banks are formulated. Furthermore, the costs and damages caused by these disturbances on various equipment of power system have been investigated. In this regard, using the results of power quality measurement in Khizrabad (Yazd) Industrial Substation, the amount of damage to the system has been calculated in this pilot.

Keywords: Harmonic damage, Power quality, Transmission network.

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1. INTRODUCTION

Fundamental changes in the electricity industry and the competitive electricity market, including restructuring and increasing the penetration of distributed renewable generation resources, expansion of microgrids and smart networks, have transformed the power quality to an important concept. Furthermore, the vulnerable extension of polluting loads lead to damage for sensitive loads from the power quality point of view. Also, increasing the knowledge and awareness of the consumers regarding the quality of electricity has forced the electricity companies to pay serious attention to this issue and try to provide the desired quality of the consumers.

Another important issue in this field is the issue of direct and indirect costs and damages of power quality on power grid equipment and investment to ensure the desired quality. Therefore, the trustees of the electricity industry should, while formulating appropriate regulations, prevent the injection of pollution by consumers into the network, and when necessary, take action to correct and reduce power quality pollution in the power networks, and finally, by conducting the necessary studies regarding planning, formulating the necessary regulations and investment to guarantee the provision of standard power quality and prevent the subsequent huge losses of power quality.

To discuss the sources of power quality problems, two perspectives can be considered. The first perspective includes equipment problems and network incidents that are related to power companies. These events and issues are mainly derived from atmospheric conditions such as elemental electricity, power factor correction equipment such as capacitor bank switching and transient errors that occur in the network. While the second view includes the effect of consumers on the quality of network power.

Considering the widespread use of power electronics-based equipment in the network, this category of equipment can be considered as an independent source for creating power quality problems. Variable frequency drives, battery chargers, smart grids, microgrids, lighting control systems, large motors, uninterruptible power supplies (UPS), and electric arc furnaces fall into this category. Figure 1 shows the classification of the origin of power quality problems.

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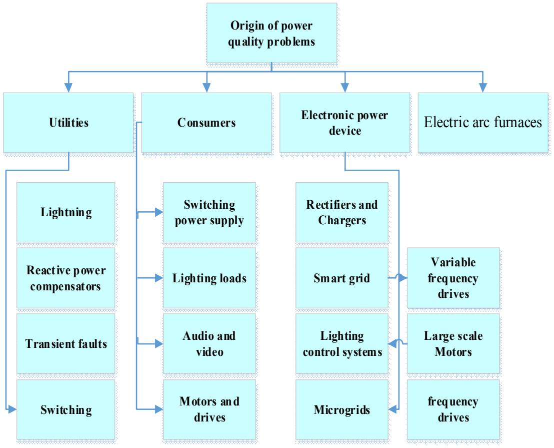

Fig. 1. Sources of power quality pollution

With the development of society and economy and the use of advanced equipment, the structure of electrical loads in the modern power system has changed greatly. Therefore, under electricity market, the relationship between power quality and customer demand has been considered more among electric energy suppliers and customers [2]. Due to the restructuring of the power system and the noticeable increase in the use of non-linear loads, unfavorable power quality can cause a lot of damage to the network, such as reducing the reliability of power delivery, increasing power network harmonics, reducing energy efficiency, depreciation and equipment failure, etc. [3, 4].

Many case studies and surveys have been conducted in different countries to estimate the adverse effects of power quality on consumers. In this research, it has been determined that industries are especially vulnerable to voltage interruptions (short and long term). Undervoltage is a major power quality problem for the semiconductor industry, continuous manufacturing process, and telecommunications sectors. Low voltage and interruptions are especially dangerous for a group of costumers called sensitive costumers. For these costumers, even short-term voltage lacks may have the same economic impact as a long-term outage. In the case of network equipment such as cables and power transformers and power capacitors, harmonics are effective, which cause energy losses, occupy the capacity of the equipment and reduce the amount of exploitation and depreciation and reduce the life of these equipment.

The most important technical damages caused by power quality that have been identified so far are:

- Failure of network equipment and consumers;
- Increasing energy losses;
- Depreciation and premature aging of network equipment and consumers;
- Reducing the capacity of network equipment and consumers;
- Reducing the power factor of the network;
- Increasing the current of the neutral wire in four-wire distribution systems;
- Unwanted blackouts and interruption of industrial production line and commercial customer service

In this paper, the effect of power quality on the losses and life of network equipment has been investigated; then, the damages caused by power quality disturbances have been determined in a pilot.

2. INVESTIGATING THE IMPACT OF POWER QUALITY DISTORTION ON NETWORK EQUIPMENT LOSSES AND LIFE

The most important effects of power quality caused by harmonics are on losses and lifetime of power network equipment. Therefore, in this section, the loss and life time of the main equipment of the power system, including cables and overhead lines, power transformers and capacitor banks have been investigated.

2.1. Investigating the effect of bad power quality on losses and life of cables and overhead lines

According to the IEC-60287 standard, cable losses can be investigated in three parts.

2.1.1. Losses of conductors

The change in the current flow pattern from the cross-sectional surface of the conductor due to skin effect and proximity causes a change in the effective resistance and inductance of the cable conductor. Alternating current resistance in the unit of conductor length, according to the IEC-60287-1-1 standard, is defined as Eq. 1:

$$\boldsymbol{r_{ac}} = \boldsymbol{r_{dc}}(\mathbf{1} + \boldsymbol{Y_s} + \boldsymbol{Y_p}) \tag{1}$$

In this relationship, r_{dc} is the direct current resistance of the conductor, Y_s indicates the influence of skin effect and Y_p indicates the outcome of proximity effect. In the harmonic environment, the conductor loss of a transmission cable can be calculated with the Eq.2:

$$\boldsymbol{P_{co}} = \sum_{\boldsymbol{h=1}}^{\infty} \left[\boldsymbol{l} \times \boldsymbol{r_{ac}}(\boldsymbol{h}) \times \boldsymbol{I_h^2}\right]_{\boldsymbol{A}} + \left[\boldsymbol{l} \times \boldsymbol{r_{ac}}(\boldsymbol{h}) \times \boldsymbol{I_h^2}\right]_{\boldsymbol{B}} + \left[\boldsymbol{l} \times \boldsymbol{r_{ac}}(\boldsymbol{h}) \times \boldsymbol{I_h^2}\right]_{\boldsymbol{C}} \tag{2}$$

In this relation, l is the length of the cable and I_h is the harmonic current of the h-th order.

2.1.2. Shield losses

Shield loss coefficient depends on factors such as shield resistance, current passing through it, and system type. The metal loss coefficient or the cable top, which is defined as the ratio of shield losses to conductor losses. It is expressed as the Eq. 3.

$$\boldsymbol{\lambda_1 = \lambda_1' + \lambda_1''} \tag{3}$$

where, λ_1' and λ_1'' are respectively related to circulation and eddy current losses. Circulating current losses are present in single-conductor cables and in systems where the shield is grounded at two or more points. Moreover, there are eddy current losses in three-conductor or single-conductor cables regardless of the type of ground system. Obviously, the amount of eddy current losses in single-conductor cables grounded on both sides is much lower than the circulating current losses and is ignored.
The amount of circulating current loss for a cable in a triangular structure with reactance X_1 and resistance R_s grounded on both sides is illustrated as the Eq. 4.

$$\boldsymbol{\lambda_1' = \frac{R_s}{R}\frac{1}{1+\left(\frac{R_s}{X_1}\right)^2}} \tag{4}$$

Furthermore, the circulating current loss in a cable grounded on one side or a cable that is properly transposed is expressed as the Eq. 5.

$$\boldsymbol{\lambda_1'' = \frac{R_s}{R}\left[g_s\lambda_0(1+\Delta_1+\Delta_2) + \frac{(\beta_1 t_s)^4}{12}10^{-12}\right]} \tag{5}$$

where, $g_s, \lambda_0, \Delta_1, \Delta_2, \beta_1$ and t_s are parameters that can be calculated from standard relationships according to the type of cable system and their flat or triangular placement.

2.1.3. Insulation losses

Dielectric losses caused by the flow of capacitive charging reason heat generation in the insulation. For a unit length of cable, the amplitude of the charging current is a function of the dielectric constant of an insulator, the dimensions of the cable, and the operating voltage. Dielectric losses can be calculated using the Eq. 6.

$$\boldsymbol{W_d = (2\pi f_1)CU_1^2 \tan\delta} \tag{6}$$

where, C is the insulation capacitance, U_1 is the effective voltage of the main component, f_1 is the main frequency of the system, and $\tan\delta$ is the insulation loss coefficient. In the harmonic environment, this relationship changes as Eq. 7.

$$\boldsymbol{W_d = 2\pi f_1 C \sum_{h=1}^{h=h_{max}} hU_h^2 \tan\delta} \tag{7}$$

where, U_h is the effective value of the harmonic voltage of the h-th order.
The presence of harmonics in cables and transmission lines affects the resistance of the conductor and increases its operating temperature. This issue can ultimately lead to their premature aging. The heat generated in a cable including m conductor and h harmonic component can be calculated using Eq. 8 [5].

$$\boldsymbol{Q(m) = \sum m\, I_h^2 r_{ac}(h)} \tag{8}$$

where, Q(m) is the heat produced per unit of cable length, I_h is the effective value of the harmonic current of the h-th order and $r_{ac}(h)$ is the resistance of the conductor per unit of cable length for the harmonic of the hth order. The thermal destruction of the equipment is mainly caused by the increase in temperature beyond the nominal value. In general, the temperature of the equipment in sinusoidal operation conditions is equal to [6]:

$$\boldsymbol{Trat = Tamb + Triserat} \tag{9}$$

where, $Tamb$ is the temperature of the environment and $Triserat$ is the increase in the temperature of the equipment compared to the environment. The life time of an equipment is highly dependent on this increase in temperature, and if this increase in temperature exists for long periods of time, it will reduce the life time of the equipment. In general, the temperature of the equipment in the harmonic environment is equal to Eq. 10 [6]:

$$\boldsymbol{T = Tamb + Triserat + \Delta T} \tag{10}$$

where, ΔT is the increase in temperature caused by the presence of harmonics. The increase in insulation temperature, caused by losses, causes the loss of insulation materials or premature aging of an electrical equipment. Thermal degradation is best represented by the Arrhenius reaction rate relationship. Now, if it is assumed that the typical lifetime of the equipment is known, it can be written as Eq. 11.

$$\boldsymbol{ln\,t - ln(t_{rat}) = \left(\frac{E}{K}\right)\left(\frac{1}{T_{rat} + \Delta T} - \frac{1}{T_{rat}}\right)} \qquad (11)$$

where, t_{rat} shows the nominal life of the equipment and t shows its life due to the increase in temperature by ΔT. After simplifying the above relationship, the expected lifetime of an equipment (such as cable, transformer, capacitor bank, etc.) can be calculated as Eq. 12 [6].

$$\boldsymbol{t = t_{rat} e^{-\left(\frac{E}{K}\right)\frac{\Delta T}{T_{rat}(T_{rat}+\Delta T)}}} \qquad (12)$$

where, K is the gas constant (Boltzmann).

3. INVESTIGATING THE EFFECT OF DISTURBANCES AND POWER QUALITY DISTORTIONS ON LOSSES AND LIFE OF POWER TRANSFORMERS

The IEEE C57.110 standard divides transformer losses into no-load losses and load losses. Figure 2 shows the division of transformer losses.

3.1. Classification of losses in transformers

As a result, the total loss of a transformer is obtained from the sum of no-load P_{NL} and load P_L losses:

$$\boldsymbol{P_{tr} = P_L + P_{NL}} \qquad (13)$$

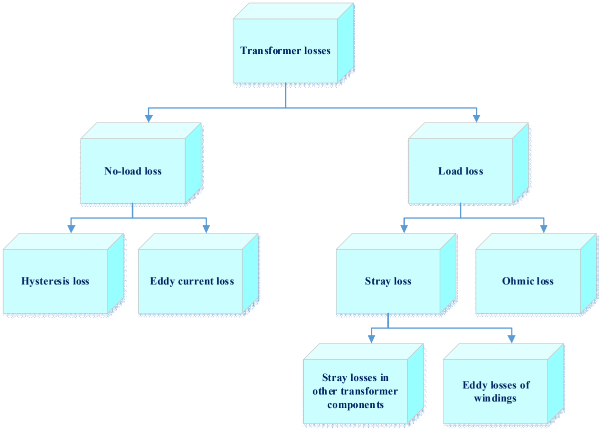

Fig. 2. Classification of losses in transformers

No-load losses are independent of load and caused by the flux in the transformer core. This type of loss includes two components: hysteresis (H) and eddy current loss (E). No-load losses can be calculated as follows [7]:

$$\boldsymbol{P_{NL} = H + E = k_h.f.B_m^n + k_e.f^2.B_m^2} \qquad (14)$$

where, k_e and k_h are constants related to iron core and B_m is the maximum flux density and n depends on the type of iron core. Load losses are divided into two sections: ohmic losses (P_{DC}) and stray losses (P_{TSL}); Therefore, it can be written:

$$\boldsymbol{P_L = P_{DC} + P_{TSL}} \qquad (15)$$

Ohmic loss has a direct relationship with the square of the effective current of the load and is calculated as follows [8]:

$$\boldsymbol{P_{DC} = P_{DC-R} \times \sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2} \qquad (16)$$

where, P_{DC-R} is the loss caused by the resistance of the transformer winding at the main frequency and I_h is the effective current of the h-th order.

Stray losses refer to losses caused by stray magnetic fluxes in windings, core, core clamps, magnetic shields, etc. Stray losses are divided into eddy losses of windings (P_{EC}) and stray losses in other transformer components (P_{OSL}). Stray losses can be calculated as follows [8]:

$$\boldsymbol{P_{TSL} = P_{EC} + P_{OSL}} \qquad (17)$$

where, P_{EC} is the eddy loss of the windings and P_{OSL} is the stray loss in other components of the transformer. The eddy losses of the windings have a direct relationship with the square of the frequency and are calculated as follows [8]:

$$\boldsymbol{P_{EC} = P_{EC-R} \times \sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^2} \qquad (18)$$

where, P_{EC-R} is the eddy loss of the coils at the main frequency. Stray losses in other components of the transformer P_{OSL} are also obtained as follows [8]:

$$\boldsymbol{P_{OSL} = P_{OSL-R} \times \sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^{0.8}} \qquad (19)$$

where, P_{OSL-R} is the stray loss in other components of the transformer at the main frequency. Consequently, it is possible to calculate the load losses of the transformer when harmonics are present in the network, using the following equation [8]:

$$\boldsymbol{P_L = P_{DC-R} \times \sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 + P_{EC-R} \times \sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^2 + P_{OSL-R} \times \sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^{0.8}} \tag{20}$$

3.2. Investigating the effect of power quality distortions on the life of power transformers

Relative Aging Factor F_{AA} expresses the rate of aging of a transformer in a certain period of time, for example, the value of F_{AA} equal to two means that the transformer has a life of half the normal life. F_{AA} is directly dependent on the hot spot temperature of the transformer, and the higher the hot spot temperature, the larger this coefficient is, and the transformer will age faster.

Both IEC and IEEE standards have provided a similar relationship that is empirical to determine F_{AA}. Based on the IEEE C57.91.2011 standard definition, the relative aging factor is defined as the ratio of the aging rate of insulation at a certain temperature to the aging rate of the same transformer insulation at a reference temperature of 110 centigrade degrees. According to these two standards, the F_{AA} value at the hot spot temperature is obtained from the following equation [9]:

$$\boldsymbol{F_{AA} = exp\left[\frac{15000}{110+273} - \frac{15000}{\theta_H + 273}\right]} \tag{21}$$

where, θ_H is the temperature of the hot spot of the transformer coil, if its value exceeds 110 centigrade degrees, the value of the relative aging factor coefficient is greater than unity and the insulation aging rate increases. According to this relationship, the relative aging factor of the transformer at a temperature of 110 degrees is equal to one, which means the normal life of the transformer. However, if the coil temperature exceeds 110 degrees, F_{AA} will be greater than unity, which means that the transformer will have a shorter life than normal. To obtain F_{AA} in a period of time such as a day or a year, the following relationship is used [9]:

$$\boldsymbol{F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA,n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n}} \tag{22}$$

Where, F_{EQA} is equivalent relative aging factor, $F_{AA,n}$ is the relative aging factor in the n-th interval and Δt_n is the length of the time interval in the n-th interval. According to the aging acceleration coefficient of the transformer, the amount of its lost life is determined in a period of time [9]:

$$\boldsymbol{\%LOL = \frac{F_{EQA} \times t \times 100}{(tnormal)}} \tag{23}$$

where, t is the given time period and, $tnormal$ is the useful life of the transformer.

3.3. Investigating the effect and distortions of power quality on losses and life of capacitor banks

Harmonics have a negative effect on power capacitors more than any other factor. Harmonics cause an increase in temperature and electrical stresses in capacitors. The increase in temperature is caused by two ways, i.e. conductive losses and dielectric losses. Conductive losses are the losses in the conductors and the metal plate of the capacitor, and the dielectric losses are related to the insulation between the two plates of the capacitor. Dielectric and conduction losses are represented by a resistor in series or parallel with the capacitor. Harmonic voltage waveform can produce power losses due to conduction and dielectric losses according to the following relationship in a capacitor [10].

$$\boldsymbol{P_{cp} = 3\sum_{h=1}^{h_{max}} C\omega_h (\frac{R}{X_c}) V_h^2 = 3\sum_{h=1}^{h_{max}} C\omega_h \, tan\,\delta \, V_h^2} \tag{24}$$

where, δ is the angle between impedance and capacitive reactance in the main frequency and ω_h is the angular frequency in the h-th order harmonic, C is the capacity of the capacitor bank, and V_h is the harmonic voltage of the h-th order and $tan\,\delta$ is the loss coefficient. As can be seen from this relationship, the total loss of the capacitor is a function of the frequency so that the harmonic amplitude of the voltage can lead to an increase in the loss. As a result, the temperature of capacitors increases and causes thermal failure.

Thermal stress is one of the most important factors affecting the useful life of capacitor banks. Considering the factor of thermal stress caused by harmonic losses in the life of the capacitor bank, the Arrhenius thermal model is used to calculate the life of the capacitor bank. In this model, the insulation life of the capacitor bank is expressed according to the following relationship:

$$\boldsymbol{L} = \boldsymbol{L_0} \boldsymbol{e}^{-\left(\frac{W_b}{b}\right)\left(\frac{1}{T_0}-\frac{1}{T}\right)} \tag{25}$$

where, L is the life of the capacitor bank at the operating temperature, L_0 is the normal life of the capacitor bank at the reference temperature T_0, W_b is the insulation activation energy and b is Boltzmann's constant.

4. DETERMINING DAMAGES CAUSED BY POWER QUALITY DISTURBANCES AS A PILOT AT ONE POINT

In order to study power quality, Khizrabad substation of the Yazd regional electric company has been selected as a pilot. Considering the industrial nature of Khizrabad substation and the existence of a large number of steel consumers, increasing the reliability of the network and reducing disturbances caused by polluting loads and preventing equipment breakdowns and increasing their life are very important in this substation. The target network has two types of transformers with conversion ratio of 230/20/63 kV and 63/20 kV. The single-line diagram of the target network is shown in Figure 3. In this figure, the red color represents the voltage level of 230 and the blue color represents the voltage of 63 kV. The installation points of the power quality measuring device are also shown with green squares.

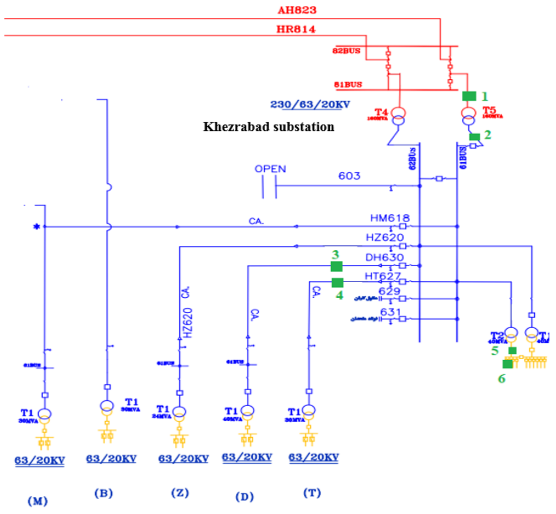

Fig. 1. 230/63/20kV Khizrabad substation single line diagram

Power quality parameters were measured by class "A" accuracy devices and according to IEC 61000-4-30 standard. From the set of measured points, one point is at the voltage level of 230 kV, three points are at the voltage level of 63 and two points are at the voltage level of 20 kV. The summary of voltage and current harmonics measured for the primary of transformer T5 with a capacity of 160 MVA is shown in Table 1. The specifications of this transformer are also given in Table 2.

In the following, the influence of the measured current harmonics in this transformer is examined, and then the effect of harmonics on the losses and the increase in the temperature of the transformer and finally the life of the transformer is studied.

Table 1. Values of voltage and current harmonics in the primary of transformer T5

Harmonic order	Ia		
	Max	CP95%	UP%
THDi	23.01	14.84	99.91
HD2	0.00	0.00	0.00
HD3	3.44	2.61	0.86
HD4	0.00	0.00	0.00
HD5	1.88	1.66	0.00
HD6	0.00	0.00	0.00
HD7	1.38	1.29	0.00
HD8	0.00	0.00	0.00
HD9	2.74	2.38	0.00
HD10	0.76	0.53	0.35
HD11	4.49	3.72	92.91
HD13	5.29	4.11	59.03
HD15	2.25	1070	14.09
HD17	1.51	1012	5.36
HD19	1.33	0.00	1.12
HD21	1.79	1.18	5.36
HD23	3.80	2.46	44.51
HD25	4.99	2.69	41.40
HD27	2.68	1.56	14.95
HD29	1.96	1.26	6.83
HD31	2.56	1.46	10.89

Harmonic order	Va		
	Max	CP95%	UP%
THDv	2.31	1.77	21.18
HD2	0.13	0.00	0.00
HD3	0.14	0.13	0.00
HD4	0.00	0.00	0.00
HD5	1.77	1.10	10.04
HD6	0.00	0.00	0.00
HD7	0.77	0.59	0.00
HD8	0.11	0.00	0.00
HD9	0.13	0.09	0.00
HD10	0.17	0.00	0.00
HD11	0.61	0.54	0.00
HD13	1.06	0.79	0.43
HD15	1.25	0.54	0.35
HD17	2.03	1.10	9.87
HD19	0.56	0.41	0.00
HD21	0.21	0.14	0.00
HD23	0.31	0.17	0.00
HD25	0.12	0.08	0.00
HD27	0.00	0.00	0.00
HD29	0.00	0.00	0.00
HD31	0.00	0.00	0.00

The amplitude of current harmonics is not a constant value and changes at every moment of time. For this reason, in order to use the mentioned relationships and perform related calculations, at any moment of time, taking into account the harmonics of the flow at the same moment, the relevant coefficients are calculated and then the average is taken from them. Figure 4 and Figure 5 illustrate the effect of harmonics on the circulating current loss (FHL) of the winding and stray losses (FHL-STR) consequently.

Table 2. No-load losses of 160 MVA transformer

Voltage percent	Voltage rms, kV	I_0 U (A)	I_0 V (A)	I_0 W (A)	I_0^* (%)	P1 meas.kW	P2 meas.kW	P3 meas.kW	Sum(P) meas.kW	Losses corrected kW
110%	22	10.193	10.275	13.200	0.2430	10.83	52.46	45.64	108.93	109.36
100%	20	1.830	2.343	2.908	0.0511	17.19	23.98	30.22	71.39	71.38
90%	18	1.396	1.945	2.215	0.0401	13.90	17.40	22.53	53.83	53.80
80%	16	1.228	1.770	1.912	0.0354	10.80	13.88	17.33	42.01	41.98
70%	14	1.066	1.572	1.667	0.0311	8.22	10.84	13.26	32.32	32.30

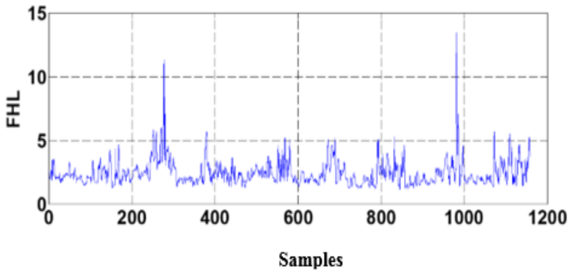

Fig. 2. The effect of harmonics on the circulating current loss (FHL) of the winding

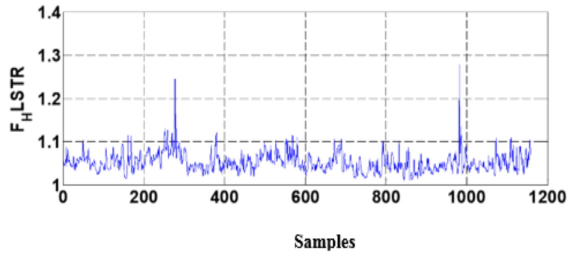

Fig. 3. The effect of harmonics on other stray losses (FHL-STR)

Therefore, using the displayed diagrams, the ratio of losses to nominal losses is calculated and shown in Figure 6.

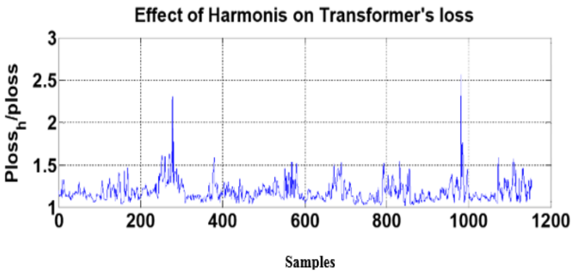

Fig. 4. Ratio of losses in harmonic conditions to nominal losses

Figure 7 shows the ratio of the power passing through the transformer to the rated power in order to keep its life constant. In this figure, the average value is marked with red color and is equal to 0.91.

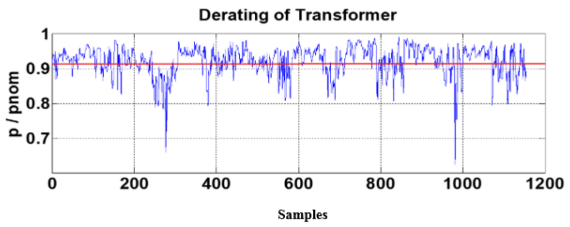

Fig. 5. The ratio of the power passing through the transformer to the rated power in harmonic conditions in order to keep the life time constant

Accordingly, the damage caused to the transformer and transmission line is calculated and represented in Table 3.

Table 3. Estimation of damage caused to T5 transformer at load factor of 0.5 due to power quality distortions (thousand Rials per year)

Operation cond. Parameter	In normal load condition without harmonic	In normal load condition with measured harmonic	Amount of cost increase
Harmonic loss	2.409.000	6.175.800	3.766.800
Life reduction	0	366.000	366.000
Increase in total cost	-	-	4.132.800

5. CONCLUSION

In this paper, the analytical relationships related to the damages of the power quality phenomena and its impact on each of the components of the power system were introduced, and a damage to a pilot power transformer in a substation was investigated. According to the reviewed materials, the illegitimacy of power quality indicators can lead to huge damages to network equipment. Therefore, from the point of view of preventing damage caused by power quality phenomena, it is necessary to formulate and consider preventive measures. Among these solutions, we can point out the imposition of fines for consumers with unauthorized power quality.

REFERENCES

[1] E. Hossain, M. R. Tür, S. Padmanaban, S. Ay, and I. Khan, "Analysis and mitigation of power quality issues in distributed generation systems using custom power devices," *IEEE Access,* vol. 6, pp. 16816-16833, 2018.

[2] B. Zhou and R. Gong, "Study on Pricing Method of Power Quality Differentiated Market Service in Distribution Grid," *IEEE Access,* vol. 7, pp. 147021-147028, 2019.

[3] T. Zang, Y. Xiang, and J. Yang, "The tripartite game model for electricity pricing in consideration of the power quality ",*Energies,* vol. 10, no. 12, p. 2025, 2017.

[4] A.Saadat, R.-A. Hooshmand, A. Kiyoumarsi, M. Tadayon, and Distribution, "Harmonic pricing in power systems based on identifying the appropriate contribution of customers," IET *Generation, Transmission,* vol .13 ,no. 1, pp. 73-80, 2018.

[5] S. Bhattacharyya, J. Myrzik, and W. Kling, "Consequences of poor power quality-an overview," *2007 42nd International Universities Power Engineering Conference,* pp. 651-656, 2007.

[6] E. Fuchs and M. A. Masoum, Power quality in power systems and electrical machines. Academic press, 2011.

[7] M. Shareghi, B. Phung, M. Naderi, T. Blackburn, and E. Ambikairajah, "Effects of current and voltage harmonics on distribution transformer losses," *2012 IEEE International Conference on Condition Monitoring and Diagnosis,* pp. 633-636, 2012.

[8] "IEEE Recommended Practice for Establishing Liquid-Immersed and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents," *IEEE Std C57.110(TM)-2018 (Revision of IEEE Std C57.110-2008),* pp. 1-68, 2018, doi: 10.1109/IEEESTD.2018.8546832.

[9] IEEE Guide for Loading MineralOil-Immersed Transformers and Step-Voltage Regulators, 2011 .

[10] A.Eberhard, Power quality. BoD–Books on Demand, 2011.