International Journal of Engineering Technology Science and Research
IJETSR
www.ijetsr.com
ISSN 2394 – 3386
Volume 4, Issue 6
June 2017

Effect of Harmonics on Distribution Transformer Losses and Capacity

Jaspreet Singh
Punjab State Power Corporation Ltd,
Moga, Punjab, India

Sanjeev Singh
EIE Department
SLIET Longowal, India

Amanpreet Singh
Punjab Technical University
Jalandhar

Abstract— The nonlinear loads are increasing day by day due to the use of controlled power electronic devices, the harmonics produced by the nonlinear load affecting the power system. Transformer is basic component of power system and designed to work on linear load. Harmonics produced by nonlinear load increases losses, heating, ageing of insulation, reduces capacity and results in premature failure of transformer. In this paper effect of nonlinear load is studied as per IEEE standard to calculate derating of transformer due to harmonics. Case study of two transformers of Punjab State Power Corporation (PSPCL) presented for calculating capacity reduction under harmonic load after measuring the power quality data. Transformer loss of life are also evaluated under nonlinear load.

Keywords— Transformer losses, eddy current loss, stray loss harmonic distortion , power quality (PQ).

I. INTRODUCTION

In Power distribution system, distribution transformer is most important apparatus. It is designed to operate on power frequency with linear load. The characteristics of the electric loads have changed dramatically from linear to nonlinear with the proliferation of new solid state controlled devices and sensitive computer type equipment. The Electric Power Research Institute (EPRI) gives a rough estimation that in 1992, 15 to 20% of the total electric utility load was nonlinear and this trend in rising and is expected to reach 50 to 70% in the year 2020. The rapid change in the electric load profile from being mainly a linear type to greatly nonlinear, has created continued power quality problems which are difficult to detect and is in general complex. Power quality is defined as any problem manifested in voltage, current or frequency deviation which results in failure or malfunction of customer equipment [1]. The most important contributor to power quality problems is the customers' (or end-user electric loads) use of sensitive type nonlinear load in all sectors (Industrial, Commercial and Residential). A major power quality concern is harmonics distortion which is caused by non-linearity of customers loads [2]. Harmonics are currents or voltage with frequencies that are integer multiples of fundamental power frequency. Nonlinear loads draw current in high amplitude short pulses, which creates distortion in current and voltage wave shape which is measured in term of total harmonics distortion (THD) [3]. Total harmonics distortion of current is the contribution of all the harmonic frequency currents to the fundamental. Harmonics generated causes additional heating in transformer components which results in higher losses, degradation to transformer insulation which decreases the useful life of transformer and premature failure of transformer. Harmonics distortion increases both no load and full load losses. Increase in eddy current losses causes rise in temperature of transformer which results in premature failure of transformer. Harmonics also causes derating in transformers capacity and may need to be derated to as much as 50% capacity when feeding loads with highly distorted current waveform. Loads with highly distorted current waveforms have a very poor power factor and due to this, they use excessive power system capacity and causes overloading [4].

Punjab State Power Corporation (PSPCL) is a utility responsible for Generation and Distribution of Power in the state of Punjab in India. It has a very large consumer base consisting of domestic, commercial, industrial and agriculture loads divided in four zones. It has large number of distribution transformers feeding the consumers. The transformer failure rate is above 15% which is a huge loss to the organization. Power utilities are facing problems of transformer failure due to capacity degradation because of harmonics produced by increasing nonlinear loads. In this paper two failed transformer of city based subdivision of PSPCL are selected supplying IT offices, shopping complexes and education institutes supplying nonlinear load to find out effect of harmonics on losses and capacity of transformer. Harmonic data of transformers measured. This study will investigate on transformer losses and loss of life due to harmonics.

II. TRANSFORMER LOSSES

Transformers are designed to deliver the required power with maximum efficiency and minimum losses. Transformer losses are classified into no load losses and load losses [5]

$$P_T = P_{NL} + P_{LL} \qquad (1)$$

P_{NL} is no load losses or excitation loss due to induced voltage in core and due to magnetic hysteresis and eddy currents. P_{LL} is the load loss and consists of I^2R loss and stray loss caused by electromagnetic field in the windings, core, clamp, magnetic sheets, enclosures or tank walls etc. I^2R is calculated by measuring the dc resistance of winding and multiplying it with square of the load current. The stray losses can be further divided into winding stray loss and stray loss in components other than winding (P_{OSL}). The winding stray loss includes winding conductor strand loss and loss due to circulating currents between strands or parallel winding circuits. The total load loss can be expressed as:

$$P_{LL} = P_{I^2R} + P_{EC} + P_{OSL} \qquad (2)$$

The total stray losses are determined by subtracting I^2R from the load losses measured during the impedance test.

$$P_{TSL} = P_{LL} - P_{I^2R} \qquad (3)$$

A. Eddy current losses in winding

This loss is due to time variable electromagnetic field across windings. There are two effects that can cause increase in eddy current loss in windings, skin effect and proximity effect. In transformers, internal windings adjacent to core have more eddy current loss, in comparison to external windings. This is due to high electromagnetic intensity near the core that covers these windings. The winding eddy current loss in the power frequency spectrum tends to be proportional to the square of the load current and the square of frequency, which are due to both the skin effect and proximity effect [6].

$$P_{EC} \; \alpha \; I^2 \times f^2 \qquad (4)$$

The impact of lower order harmonics on the skin effect is negligible in the transformer winding.

A portion of stray loss is taken to be eddy current loss. For oil type transformer the winding eddy loss is assumed to be:

$$P_{EC} = 0.33\, P_{TSL} \qquad (5)$$

For dry type transformer the winding eddy loss is assumed to be:

$$P_{EC} = 0.67\, P_{TSL} \qquad (6)$$

$$P_{OSL} = P_{TSL} - P_{EC} \qquad (7)$$

The division of eddy current loss and other stray loss is assumed to as follows [6]

a) 60% in low voltage winding and 40% in the high voltage winding for all transformers having a maximum current rating of less than 1000A (regardless of turn ratio).

b) 60% in low voltage winding and 40% in the high voltage winding for all transformers having a turn ratio of 4:1 or less.

c) 70% in low voltage winding and 30% in the high voltage winding for all transformers having a turn ratio greater than 4:1 and also having one or more winding with a maximum cooled current rating greater than 1000 A.

a. Proximity Effect

In transformer HV winding produce a flux density due to charging current. The LV winding and core cuts the flux density. The flux density that cuts the LV winding induces an emf that produces circulating or eddy currents. This effect is called proximity effect, which is caused by a current carrying conductor, or magnetic field that induce eddy currents in other conductor or magnetic fields. These eddy currents will dissipate power, $P_{EC,}$ and contribute to the electrical loss in the windings in addition to those caused by normal dc losses [7]. The proximity loss can be expressed as:

$$P_{PE} = \frac{\mu^2 N \omega^2 I^2 n d^4}{128 \rho l} G_r \qquad (8)$$

Where n is number of strands, d is the strand diameter, I is the maximum current. G_r is proximity

effect factor and by considering $\delta = \sqrt{\frac{1}{\omega\mu\sigma}}$,

If d / δ decreases to unity then $G_r \to 1$.

Eddy current loss may also be calculate from the equation too.

$$P_{TSL} = P_{LL\_R} - [(R_1 I^2_{1\text{-}R} + R_2 I^2_{2\text{-}R})] \tag{9}$$

The winding eddy current loss is then calculated by using assumption (5).

B. Other stray losses in Transformer

Each metallic conductor by electromagnetic flux experiences an internally induced voltage that causes eddy currents to flow in that ferromagnetic material. The eddy current produce losses that are dissipated in the form of heat, producing an additional temperature rise in the metallic parts over its surroundings. The eddy current losses outside the windings are other stray losses. The other stray losses in core, clamp and structural parts will increase at a rate proportional to the square of the load current but not a rate proportional to the square of the frequency as in eddy current winding losses [6]. Experimental results to find out change of other stray losses at low frequency shown that the ac resistance of the other stray losses at low frequencies (0 - 360Hz) is equal to [7].

$$R_{OSL} = 1.29\left(\frac{f_h}{f_1}\right)^{0.8} \quad m\,\Omega \tag{10}$$

And at high frequencies (420-1200Hz) the resistance is

$$R_{OSL} = 9.29\text{-}0.59\left(\frac{f_h}{f_1}\right)^{0.9} \quad m\,\Omega \tag{11}$$

Thus this loss is proportional to square of the load current and the frequency of to the power of 0.8.

Given equation can be used to calculate the other stray losses.

$$P_{OSL} = P_{TSL} - P_{EC} \tag{12}$$

III. Effect of Harmonics on Transformer

A. Effect of Voltage Harmonics

According to Faraday's law the terminal voltage determines the transformer flux level

$$N\frac{d\phi}{dt} = v\,(t) \tag{13}$$

Transferring this equation in frequency domain shows the relation between the voltage harmonics and the flux components:

$$Nj\,(h\omega)\,\varphi_h = V_h \tag{14}$$

This equation shows that the flux magnitude is proportional to the voltage harmonics and inversely proportional to harmonic order h. Furthermore within most power systems the harmonic distortion of the system voltage THD is well below 5% and the magnitude of voltage harmonics components are small compared to the fundamental component, rarely exceeding a level of 2-3%. Therefore neglecting the effect of harmonic voltage and considering the no load losses caused by the fundamental voltage component will only give rise to insignificant error. If THD_V is not negligible, losses under distorted voltage can be calculated based on ANSI-C.27-1920 standard

$$P = P_M\left[P_h + P_{ec}\left(\frac{V_{hrms}}{V_{rms}}\right)^2\right] \tag{15}$$

Where V_{hrms} and V_{rms} are the rms values of distorted and sinusoidal voltages, P_M and P are no load losses under distorted and sinusoidal voltages, P_h and P_{ec} are hysteresis and eddy current losses, respectively [8]

B. Effect of Current Harmonics

In most power systems, current harmonics of significance. These harmonics current components cause additional losses in the windings and other structural parts.

a. Effect of Harmonics on dc losses

If the rms value of the load current is increased due to harmonic components, then these losses will increase with the square of the current.

$$P_\Omega = R_{dc} \times I_{2A} = R_{dc} \times \left(\sum_{h=1}^{h_{max}} I^2{}_{h,rms}\right) \tag{16}$$

a. Effect of harmonics on eddy current losses

The eddy current losses generated by the electromagnetic flux are assumed to vary with the square of the rms current and the square of frequency:

$$P_{ec} = P_{ec-R} \sum_{h=1}^{h=\max} h^2 \left(\frac{I_h}{I_R} \right)^2 \qquad (17)$$

The harmonic loss factor for winding eddy currents is derived as:

$$F_{HL} = \frac{\sum_{h=1}^{h=\max} h^2 I^2{}_h}{\sum_{h=1}^{h=\max} I^2{}_h} = \frac{\sum_{h=1}^{h=\max} h^2 \left(\frac{I_h}{I_1} \right)^2}{\sum_{h=1}^{h=\max} \left(\frac{I_h}{I_1} \right)^2} \qquad (18)$$

To get the true value of eddy current losses under harmonic loads, eddy current losses in winding must be multiply with harmonic losses factor *(F_{HL})* when the transformer supplying nonlinear load.

b. Effect of harmonics on other stray losses

The other stray losses assumed to vary with the square of the rms load current and the harmonic frequency to the power of 0.8:

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

The harmonic loss factor for other stray losses are also expressed in a form as for the winding eddy currents:

$$F_{HL-STR} = \frac{P_{OSL}}{P_{OSL-R}} = \frac{\sum_{h=1}^{h=\max} \left[\frac{I_h}{I} \right]^2 h^{0.8}}{\sum_{h=1}^{h=\max} \left[\frac{I_h}{I} \right]^2} = \frac{\sum_{h=1}^{h=\max} \left[\frac{I_h}{I_1} \right]^2 h^{0.8}}{\sum_{h=1}^{h=\max} \left[\frac{I_h}{I_1} \right]^2} \qquad (20)$$

To obtain the true value of other stray losses, it must be multiplied by harmonic loss factor *(F_{HL-STR})* while supplying nonlinear load.

IV. PROCEDURE FOR EVALUATION OF LOSSES AND CAPACITY OF TRANSFORMER SULLPYING NON LINEAR LOAD

The equation that applies to linear load condition is [6]:

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu) + P_{OSL}(pu) \qquad (21)$$

Where P_{LL-R} rated load losses, 1 is dc losses is, P_{EC-R} is rated winding eddy current loss, P_{OSL} is rated other stray losses at rated current.

As the effect of the harmonic on losses of transformer evaluated in previous sections, a general equation for calculation of losses when transformer supplying a harmonic load can be defined as:

$$P_{LL}(pu) = I^2(pu) \times [1 + FHL \times Pec - R(pu) + F_{HL-STR} \times P_{OSL-R}(pu)] \qquad (22)$$

The permissible transformer current is expressed as

I_{max} (pu) =

$$\sqrt{\frac{P_{LL-R}(pu)}{1 + [F_{HL} \times P_{ec-R}(pu)] + [F_{HL-STR} \times P_{OSL-R}(pu)]}} \quad (23)$$

From the above mentioned equation, the permissible current and derating of the transformer can be determined.

V. TRANSFORMER LOSS OF LIFE CALCUTATION

Harmonic losses occur in the form of increased heat dissipation in the winding and skin effect. Both are a function of the square of the root mean square current. This extra heat have a significant impact in reducing the operating life on the insulation of a transformer. The estimation transformer loss of life is based the deterioration rate achieved by insulating materials. The transformer loss of life is based on the deterioration rate achieved by insulating materials. About 50% of a transformer loss of life is caused by thermal stress which is produced by the nonlinear load [9]. The top oil temperature rise is calculated as follows [6]

$$\theta_{TO} = \theta_{TO-RATED} \left(\frac{P_{LL-C} + P_{NL}}{P_{LL-rated} + P_{NL}} \right)^{0.8} \qquad (24)$$

The hottest spot winding temperature is calculated as follows

$$\theta_g = \theta_w - \theta_g - R \times \left(\frac{1 + F_{HL} \times P_{EC-R}(pu)}{1 + P_{EC-R}} \right) \times P_{LL}(pu) \quad (25)$$

The hot spot temperature is

$$\theta_H = \theta_{TO} + \theta_g + \theta_A \quad (26)$$

Where,

θ_{TO} = oil temperature rise

θ_w = winding temperature rise

θ_A = ambient temperature

θ_g = hottest spot conductor rise over top oil temperature

θ_H = hot spot temperature

The relative aging factor, the loss of life and real life of a transformer can be expressed as [10]

$$F_{AA} = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_H + 273} \right) \quad (27)$$

$$\%LOL = \frac{FAA \times t \times 100}{normal\_insulation\_life} \quad (28)$$

$$Life(pu) = 9.8 \times 10^{-18} e^{\left(\frac{15000}{\theta_H + 273}\right)} \quad (29)$$

Real life = Life (pu) $\times$ normal insulation life or (30)

Real life = normal insulation life (years)/F_{AA} (31)

F_{AA} =relative ageing factor

%LOL = loss of life in percent

t = time period.

VI. POWER QUALITY MEASUREMENT

Transformer is a static machine with very high efficiency and rugged construction. The rate of failure of distribution transformers in India is higher (12-17%) as compared to developed countries (2-3%). This high failure rate is cause of concern to all the Distribution Companies (Discoms) in the country. Every year, nearly 200 Crore of Indian Rupees (INR) are spent by the Discoms for repair and replacement of distribution transformers. [11].

Transformer failure analysis reveals that insulation failure and line surges are the major cause of the failure of transformer. Transformers are also failing due to manufacturing defects, overloading, improper maintenance, and moisture and oil contamination. 16% transformers failed due to unknown reason, out of which some of transformers may be failed due to power quality problems [12].

To evaluate the effect of harmonics on transformer two no of transformers T1and T2, 100 KVA and 200 KVA respectively given in table I, of city based sub division of PSPCL failed due to over loading while supplying load below their capacity. 100 KVA transformer supplying educational institute and 200KVA transformer Installed at city center supplying shopping complexes and IT offices. In both the cases load connected consists of personal computers, laptops, LCD projectors, printers, CFL lamps, air conditioners, inverters, UPS. Both the failed transformers are replaced with loads of higher capacity.

Table I: Distribution Transformer Parameters

	T1	T2
Capacity (KVA)	100	200
Voltage (V)	11000/433	11000/433
No Load Losses	260	
Load Losses	1760	
I_1(A)	5.25	
I_2(A)	133.3	
Connected Load (%) (Maximum Demand)	90	88.5
Winding Temperature Rise	65°C	65°C
Ambient Temperature	40°C	40°C

Harmonics data is logged using power quality analyzer in both the cases for current harmonics, voltage harmonics, active power, reactive power, voltage, current, frequency, power factor for one week.

International Journal of Engineering Technology Science and Research
IJETSR
www.ijetsr.com
ISSN 2394 – 3386
Volume 4, Issue 6
June 2017

VII. Calculation of Transformer Capacity and Losses Under Harmonic Loads

This section will perform calculations losses of and capacity under harmonics load. The parameters of 100 KVA and 200 KVA transformer is given table I.

A. 100 KVA Transformer

a. Under linear load

By using equation (2), (3), (5) and (12), Ohmic loss, total stray loss, eddy current loss and other stray losses are calculated as:

P_{DC}=258W, P_{TSL}=,115W, P_{EC} = 37.95W, P_{OSL} = 82.05W

b. Under harmonic load

To calculate losses and capacity under harmonic load the harmonic load measurements for 100KVA transformer are given in table II.

Using equation (16) the Ohmic losses is calculated as:

P_{dc} = 2154.95 W

Using equation (17) and (18) the eddy current loss and harmonic loss factor are calculated as:

P_{EC} = 40.57W

F_{HL} = 5.99

TABLE II. HARMONIC LOAD SPECIFICATIONS

Harmonic order	1	5	7	11	13	17	19
Magnitude	1	0.2913	0.1932	0.1186	.0255	.0132	.0012

To obtain the true value of eddy current loss it must be multiplied by harmonic loss factor for winding eddy current

P_{EC} = 40.57× 5.99 = 243.01W

By using equation (19) and (20), other stray losses and harmonic loss factor for other stray loss are calculated as:

P_{OSL} = 87.71W

$F_{HL\text{-}STR}$ = 1.40

To obtain the true value of other stray loss it must be multiplied by harmonic loss factor for other stray loss ($F_{HL\text{-}STR}$)

P_{OSL} = 87.71 ×1.40 = 107.122.80W

The calculated transformer losses under linear and nonlinear load are given in table III.

TABLE III. 100 KVA TRANSFORMER LOSSES UNDER LINEAR AND NONLINEAR LOAD.

Type of losses	Rated losses (W)	Losses under harmonics load	Harmonics losses factor	Corrected losses under harmonic load (w)
No Load	258	258	-	258
DC	1645	2154.95	-	2154.95
Winding Eddy Current	37.95	40.57	5.99	243.01
Other Stray	82.05	87.71	1.40	122.80
Total	2023	2541.23		2778.75

By using equations (21), (22) and (23) transformer capability under nonlinear load is calculated as:

PL_L *(pu)* = 1.206

I_{max} *(pu)* = 0.7348

I_{max} = 0.7348 × 133.3 = 97.84A

Equivalent KVA = 0.7348 × 100 = 73.48 KVA

B. 200 KVA transformer

a. Under linear load

By using equation (2), (3), (5) and (12), Ohmic loss, total stray loss, eddy current loss and other stray losses are calculated as:

P_{DC}=1962.84W, P_{TSL}=537W, P_{EC} = 177.21W, P_{OSL} = 294W

b. Under harmonic load

To calculate losses and capacity under harmonic load the harmonic load measurements for 200KVA transformer are given in table III

TABLE III. HARMONIC LOAD SPECIFICATIONS

Harmonic order	1	5	7	11	13	17	19
Magnitude	1	.2311	.1722	.1121	.0875	.0388	.0018

Using equation (16) the Ohmic losses is calculated as:

P_{dc} = 2142.44W.

Using equation (17) and (18) the eddy current loss and harmonic loss factor are calculated as:

P_{EC} = 186.07W

F_{HL} = 6.36

To obtain the true value of eddy current loss it must be multiplied by harmonic loss factor for winding eddy current (F_{HL})

P_{EC} = 186.07× 6.36 = 1183.41W

By using equation (19) and (20), other stray losses and harmonic loss factor for other stray loss are calculated as:

P_{OSL} = 308.70W

F_{HL-STR} = 1.35

To obtain the true value of other stray loss it must be multiplied by harmonic loss factor for other stray loss (F_{HL-STR})

P_{OSL} = 308.70 ×1.35 = 416.75W

The calculated transformer losses under linear and nonlinear load are given in table IV.

TABLE IV. 200KVA TRANSFORMER LOSSES UNDER LINEAR AND NONLINEAR LOAD.

Type of losses	Rated losses (W)	Losses under harmonics load	Harmonics losses factor	Corrected losses under harmonic load (w)
No Load	500	500	-	500
DC	1962.84	2142.44	-	2142.44
Winding Eddy Current	177.21	186.07	6.36	1183.41
Other Stray	294	308.70	1.35	416.75
Total	2934.05	3137.21		4242.59

By using equations (21), (22) and (23) transformer capability under nonlinear load is calculated as:

P_{LL} *(pu)* = 2.917

I_{max} *(pu)* = 0.701

I_{max} = 0.701 × 266.7 = 186.96A

Equivalent KVA = 0.701 × 200 = 140.2 KVA

VIII. TRANSFORMER LOSS OF LIFE

The effect of increased losses in the form of the extra heat can be calculated form equations (24) - (31) as:

a. 100 kva Transformer

FAA = 1.69

%LOL = 40.83%

Real life =12.16 years

Normal life = 20.55 years

b. 200 KVA Transformer

F_{AA} = 1.8

%LOL = 44.43%

Real life =12.16 years

Normal life = 20.55 years

IX. RESULTS AND DISCUSSIONS

The transformer capacity and losses data is calculated in the previous section for 100KVA and 200KVA transformers is given in table III and IV respectively. For comparison purpose the important parameters are shown in table V.

Table V. Summary of important parameters

Conclusion	100KVA	200KVA
Loss under linear load (W)	2023	2934.05
Loss under nonlinear load (W)	2778.75	4242.59
Percentage increase of losses (W)	37.36	44.60
Capacity under harmonic load (KVA)	73.48	140.20
Percentage decrease in capacity	26.52	29.90
Relative ageing Factor	1.69	1.80
Loss of life in percentage (%LOL)	40.83	44.43

Table V shows transformers losses under harmonic load increase about 37% and 44%. This increase in total losses results from significant increase in eddy current losses in winding which further increases the heat generation in winding and reduces the capacity of the transformer or derated the transformer. The 100KVA and 200 KVA transformer capacity is reduced to 73KVA and

International Journal of Engineering Technology Science and Research
IJETSR
www.ijetsr.com
ISSN 2394 – 3386
Volume 4, Issue 6
June 2017

140.20 KVA, which means a loss of 26.52% and 29.90% loss of capacity respectively. This hampers the load carrying capacity of transformer and severely over loads the transformer. If the load connected to transformer is more than the derated capacity of transformer the transformer can eventually fail. In this case both the transformers are carrying a load (maximum demand) of 90% and 88.5% which are more than the derated capacity of transformers and it can be the cause of failure of both the transformers because both are failed due to over loading with all three phase windings are found to be burnt in tear down analysis. The transformers were installed in 2003 and 2004 and failed in 2015 Further from loss of life calculations and relative ageing factor the percentage loss of life is found to be about 40% and 44%, which means the transformers are failed after about 12 years and 11years respectively. So both the transformers failed prematurely after instaltion before completing the normal life of 20.55 years.

V. Conclusion

In this paper effect of nonlinear load on the transformer capacity and losses is studied as per (IEE standard C57-110) has been studied for derating purpose effect of harmonics on load losses ,eddy current losses and other stray losses have been computed in order to calculate equivalent KVA capacity of transformer while supplying nonlinear load. It shows that losses increase in harmonic load which decreases the capacity of transformer which results in overloading of transformer and reduction in useful life of transformer. Case study of 100KVA and 200 KVA transformers presented to derating purpose to find out cause of failure and concluded that as both were heavily overloaded, so they are failed due to capacity reduction due to harmonics. To check the ageing of transformer further loss relaive ageing factor and percentage loss of life is calculated and find out the transformers are failed about 12years and 11 years respectively before completing his normal life which justified the transformers failure due to capacity reduction due to harmonic load.

VI. ACKNOWLEDGMENT

Authors are thankful to management of PSPCL for permitting them to use transformer and power quality data for writing this paper.

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