An Approach to Quantify the Technical Impact of Power Quality in Medium Voltage Distribution Systems

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***Abstract*—This paper provides a useful guidance in the interpretation and analyses of the technical impact of power factor correction in a power system. It is intended to raise awareness in order to achieve correct measurements, calculations and the key dynamics of the power system when quantifying the impact of power quality (PQ) in a non-linear power system. This paper is therefore targeting the power producing utilities, municipalities and the bulk end users of electricity.**

Keywords— power factor correction; total harmonic distortion; resonance; losses

I. INTRODUCTION

The shortage of power in South Africa has led to an immediate and effective need for upgrading the efficiency of the system. It has been a norm for the industry to operate a system with low power factor and transfer the economic impact to the consumers. These charges are based on cosφ which does not take the effect of harmonics into consideration [1], [12]. Furthermore, the increase in the use of power electronics devices has also introduced added harmonics on the power network which aggravates the low power factor and losses in the system [2], [18]. However, this scenario can be redeemed by the appropriate employment of Power Factor Correction (PFC) applications in order to improve the efficiency of the system.

II. PROBLEM DISCUSSION

The problem proposed for discussion in this paper is one approach to quantify the impact of the power factor in medium voltage (MV) distribution system. This implies the analysis of technical losses of MV distribution system. There are several classifications of technical losses, namely: copper losses (I^2R), dielectric losses, corona losses and iron losses. The I^2R losses are directly affected by power factor (PF or λ) of the system [3].

Although nonlinear loads do not draw reactive power at the fundamental system frequency (50 Hz), they add more losses through harmonic distortion and also deteriorate PF in the distribution system for a given load by virtue of drawing higher RMS currents [4]. This phenomenon has been augmented by the increase in consumers' power electronic equipment. This equipment includes the non-linear devices such as direct current (DC) drives, variable speed drives, solid state or switched power supplies, etc. Although these devices are aimed to improve the efficiency of machinery operation, they, depending on the drivers' front end, also result in low PF as the relationship is illustrated in Fig. 1 [5].

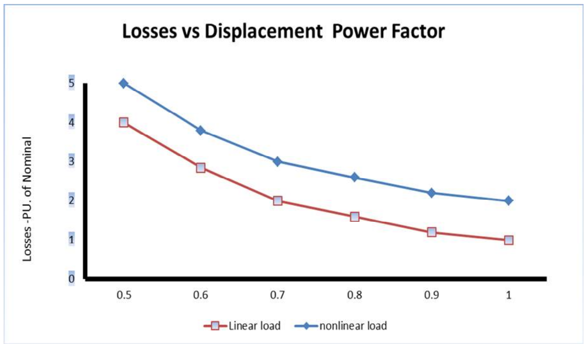

Fig.1: Relation between the losses and power factor.

The main factors that influence technical losses in any distribution system are cables' resistance, power factor of the load and harmonics injected by the loads. The dielectric losses, corona losses and iron losses are not included in this study.

A. *Cable resistance*

The cable resistance is directly involved in I^2R or copper losses. The harmonics also add to the copper losses due to the increased temperature of the conductors. The resistance of the conductor increases with the increase in the temperature as it is illustrated in equation 1.

$$R = R_{ref}\left[1+\alpha\cdot(\theta-\theta_{ref})\right] \tag{1}$$

where: R is the resistance of the conductor at temperature "θ", R_{ref} is resistance of the conductor at the reference temperature θ_{ref}, usually 20°C, α is specific temperature coefficient of resistance for a given conductor material, θ is conductor temperature in degrees Celsius, θ_{ref} is the reference

temperature at a specified corresponding α for a given conductor material [6].
The presence of harmonics in the system increases the resistance due to skin effect.

B. Power Factor

In linear systems, the displacement angle between the voltage and current waveforms is termed power factor angle (φ) and the cosine of that angle is called power factor (λ) [7],[8], [11]. In nonlinear systems, λ is defined as the ratio of the total active power dissipated in an electric circuit to the total equivalent volt-amperes applied to that circuit. This power factor is referred to as a total or true power factor [4], [8], [11]. Furthermore, the true PF is a combination of two forms of PF, namely, the displacement power factor (λ_1) and distortion power factor (λ_D). Thus true power factor [8], [11] can be represented by:

$$\lambda_{true} = \lambda_1 \times \lambda_D = \frac{P}{S} \tag{2}$$

where P is the total active power which is the sum of the fundamental component of active power (P_1) and the harmonic component of power (P_H), represented by [8], [11]:

$$P_{total} = P_1 + P_H \tag{3}$$

And S is the total apparent power given by [8], [11]:

$$S = \sqrt{S_1^2 + S_N^2} \tag{4}$$

The two components of S, namely the fundamental component (S_1) and the nonlinear component (S_N) of the apparent power can be further formulated as [8], [11]:

$$S_1 = V_1 I_1 = P_1 + jQ_1 \tag{5}$$

$$S_N = \sqrt{D_I^2 + D_V^2 + S_H^2} \tag{6}$$

where the subscripts V_1, I_1, Q_1 are the fundamental voltage, current and reactive power, respectively; the D_I, D_V and S_H are current distortion power, voltage distortion power and harmonic apparent power, respectively.

C. Harmonics

From the formulae and definitions above it is evident that power factor analysis cannot be done in isolation from the harmonics consideration. The IEEE 1159-2009 standard defines harmonics as sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate [8]. These harmonics are caused by loads drawing nonlinear currents thereby increasing the total current drawn from the system. Subsequently, they add to the system losses, reducing equipment lifespan and interfering with metering and protection equipment [8].

The impact and levels of harmonics can be measured and monitored by the individual harmonic distortions or total harmonic distortions (THD). There are regulated limits and are set by NRS 048 as shown in Table I.

There is a severe stress impact on equipment and losses in the system if the limits in Table I are exceeded. The direct relation to λ_D is given by:

$$\lambda_D = 1/\sqrt{1 + THD_I^2} \tag{7}$$

By substituting (7) into (2), the true power factor can be derived as:

$$\lambda_{true} = \lambda_1 / \sqrt{1 + THD_I^2} \tag{8}$$

TABLE I

COMPATIBLE LEVELS FOR HARMONIC CURRENTS [9]

1	2	3	4	5	6
Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3^a			
Harmonic order h	Magnitude %	Harmonic order h	Magnitude %	Harmonic order h	Magnitude %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,5	6	0,5
13	3	21	0,3	8	0,5
$17 \le h \le 49$	$\{2{,}27 \times (17/h)\} - 0{,}27$	$21 \le h \le 45$	0,2	$10 \le h \le 50$	$\{0{,}25 \times (10/h)\} + 0{,}25$

^{a} The levels given for odd harmonics that are multiples of 3 apply to zero sequence harmonics. Also on a three-phase network without a neutral conductor or without load connected between phase and earth, the actual values of the third and ninth harmonics might be much lower than the compatibility levels, depending on the voltage unbalance of the system.

D. Resonances

Power factor can be corrected by applying reactive power compensation through the use of capacitor banks (classic power factor). This method is most suitable for linear loads. However, the use of capacitor banks often creates resonance in the system. Resonance occurs when the capacitive reactance is equal to the inductive reactance for a given system at a given system frequency. This can be either series or parallel resonance (taking the harmonic load as the source) as illustrated in Fig. 2 below.

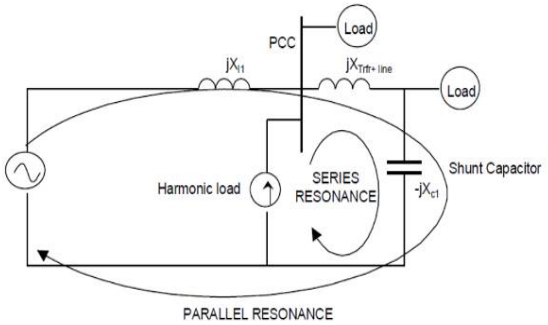

Fig. 2: Series and parallel resonance [3]

At resonance critical harmonic currents are amplified adding more losses to the system. In order to avoid resonance at critical harmonic orders, equation (9) can be used to determine the resonance frequency to be considered when designing or tuning a harmonic filter.

$$f_r = f_1\sqrt{\frac{X_{C1}}{X_{L1}}} \tag{9}$$

where: f_r is the resonance frequency, f_1 is the fundamental frequency (50 Hz), X_{C1} is the capacitive reactance and X_{L1} is the inductive reactance at the fundamental frequency respectively.

III. FEEDER MODELLING FOR TECHNICAL LOSSES EVALUATION

Any distribution system consists from a number of feeders. As many other authors recommend [13], [14], this study starts with a simplified model of a radial feeder Fig. 3.

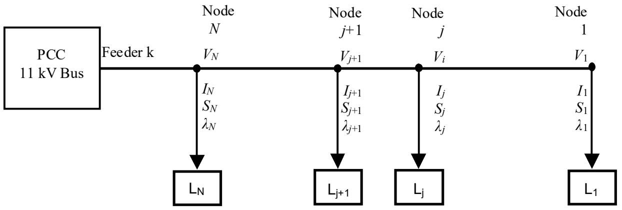

Fig. 3 Simplified distribution feeder model

The feeder has $j = 1 \ldots N$ number of different loads with different power factor. The equation governing this feeder is given as:

$$\begin{bmatrix} I_1 \\ \vdots \\ I_j \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} Y_1 \\ \vdots \\ Y_j \\ \vdots \\ Y_N \end{bmatrix}\begin{bmatrix} V_1 \\ \vdots \\ V_j \\ \vdots \\ V_N \end{bmatrix} \tag{10}$$

where I_j, Y_j and V_j are the parameters presented by load L_j at node j.

Considering $r_{j,j+1}$ being the resistance of feeder k between node j and j+1, the total power losses could be determined as:

$$P_{loss-k} = \sum_{j=1}^{N-1} r_{j,j+1}\left(\sum_{j=1}^{j}\frac{S_j^2}{V_j^2}\right) \tag{11}$$

And considering that $\lambda = P / S$, the overall power factor of feeder k may be expressed as:

$$\lambda_k = \left[P_{loss-k} + \sum_{j=1}^{N}\mathrm{Re}\{S_j\}\right] \Big/ \left[V_N\sqrt{\sum_{j=1}^{N}\frac{S_j^2}{V_j^2}}\right] \tag{12}$$

As long as the apparent power S_i depends on the power factor of each load, then the total losses in the feeder depend as well on it. Using (11) and (12) one can quantify the impact of power factor correction and harmonic pollution.

IV. TECHNICAL IMPACT OF PFC – CASE STUDY

Medium voltage (MV) substation situated in the northern suburbs of Johannesburg was chosen. It comprises of one 88kV busbar and three 11 kV busbar sections as indicated in Fig. 4 and 5 below. There are eighteen active feeders connected to the 11 kV busbar. The feeders are a mix or majority commercial building and few industrial and residential customers. Loads are connected to the 11 kV busbar sections using cross linked polyethene (XLPE) and paper insulated (PILC) cables of 185 and 300 mm^2 cross sectional area depending on the size of the load.

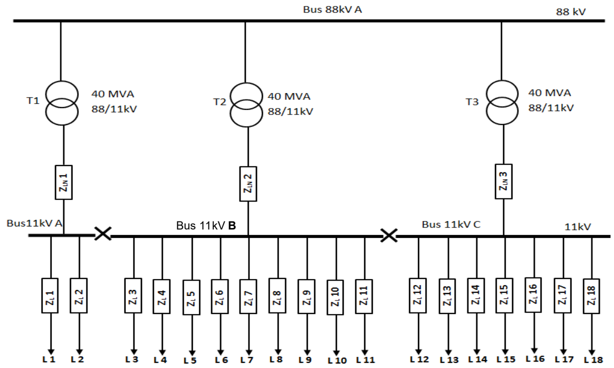

Fig. 4: Schematic representation of the substation under study

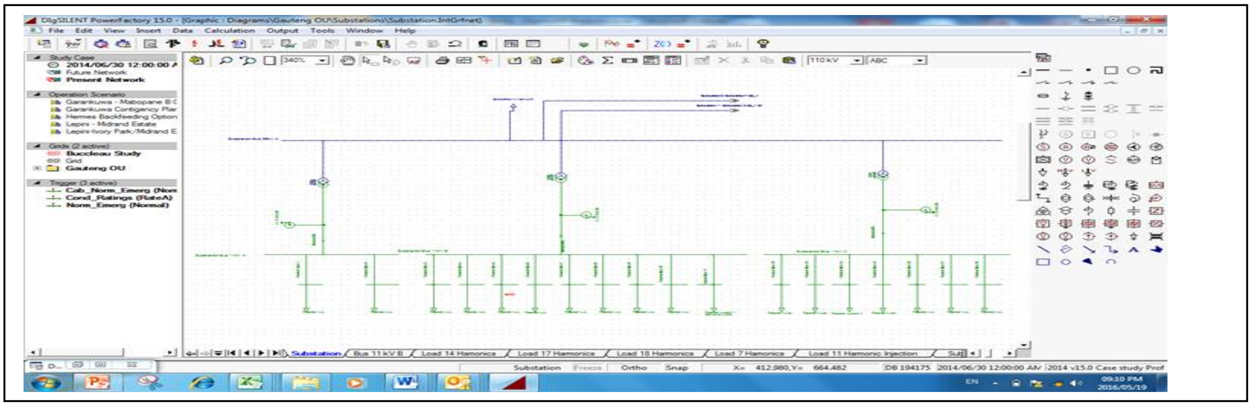

Fig. 5 Digsilent diagram of the substation under study

A. *Case Study Methodology*

The load flow studies were undertaken for "Bus 11 kV B" with different system configurations in order to demonstrate the impact of PFC in linear and nonlinear systems [15], [16], [17]. All the load flow evaluations were performed using the PowerFactory - Digsilent software to illustrate the results obtained at Bus 11kV B on following five system configurations:

Case 1

Run the load flow studies with the existing network (Fig. 4) at 50Hz and measure the initial system parameters and the results are in Table III line 1. Then determine [18] and connect the capacitor bank at L7, L14, L17 and L18 with the linear system condition (no harmonics pollution) and measure the impact of classic PFC on the transferable power, power losses and PF. PFC was aimed to improve PF from 0.92, 0.89, 0.93 and 0.92, respectively to 0.96 as in Fig. 5 and the results filled in Table III line 2.

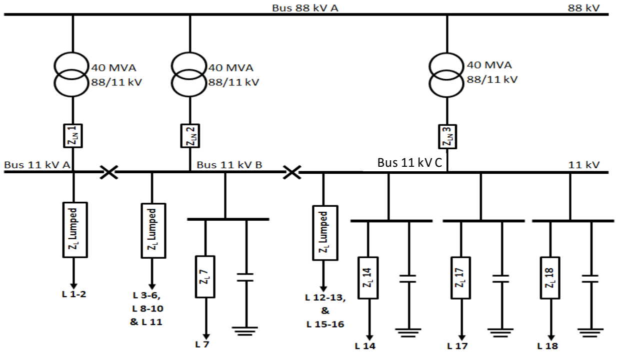

Fig. 5: Classic power factor at fundamental frequency

Case 2

A harmonic current source (similar to [10]) was inserted (in Digsilent model) at L11 with spectral content indicated in Table II and presented in Fig. 6. Run harmonics load flow without PFC connected in order to demonstrate the impact of harmonics on the total power factor of the system and the results presented in Table III line 3.

TABLE II: CURRENT HARMONIC SOURCE AT L11 [10]

11 kV		
Harmonic Order	% of 50Hz Current	Angle
1	100	0
5	69.75	-174
7	47.03	-171
11	6.86	17
13	4.52	-178
17	7.56	9
19	3.81	9
23	2.59	11
% THD	84.99	

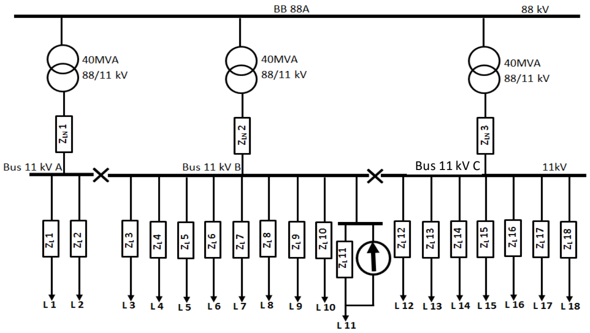

Fig. 6: Illustration of harmonic source created at L11

Case 3

Now, run harmonics load flow with capacitor banks connected as a classic PFC, as presented in Fig. 7 and demonstrate the negative impact of classic PFC in nonlinear system with results presented in Table III line 4.

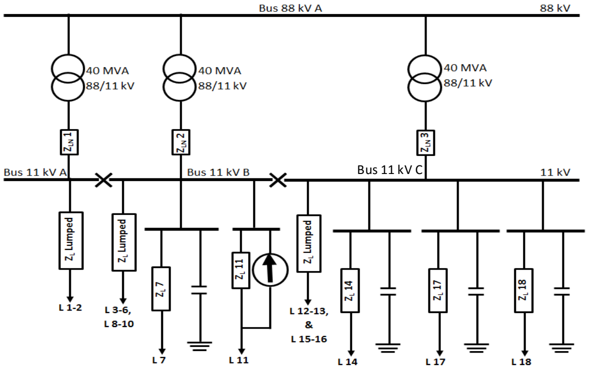

Fig. 7: Demonstration of classic PFC applied in nonlinear system at L7

Case 4

In this case, the harmonic source is still connected at load L11, but now harmonic filters are connected, as presented in Fig. 8 to eliminate harmonic orders above the IEEE limits, in parallel with capacitor bank at L7.

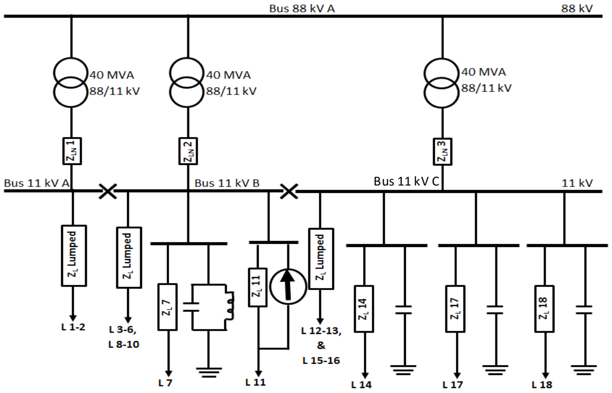

Fig. 8: Schematic representation of a nonlinear system with PFC and harmonic filter at L7

Run harmonics load flow with seven combinations of filters (design to mitigate selected harmonics) to illustrate the recommended methodology which will result in reduced line losses, improved voltage stability and power factor as well as less harmonic distortions in the system. The results are presented in Table III line 5.

B. *Study Results*

The Table III presents the concentrated results of this study, upon “Bus 11 kV B”, concerning important parameters at the point of common connection of the loads L_3 to L_{11}: Total Harmonic Distortion (THD), total current (I_T), total true power (P_{true}), total power losses in the feeders (P_{loss}), total apparent power (S_T) and true power factor (λ) at the PCC.

TABLE III RESULTS OBTAINED AT PCC FOR BUS 11 KV B

System Configuration		THD %	I_T kA	P_{true} MW	P_{loss} MW	S_T MVA	λ
1	Original System	0	1.154	22.62	0.604	22.77	0.99
2	PFC in Linear System	0	1.15	22.63	0.604	22.77	0.99
3	Nonlinear System	22.94	1.184	22.59	0.802	23.59	0.96
4	PFC in Nonlinear System	24.29	1.188	22.62	0.813	23.69	0.96
5	5^{th} harmonic filter	18.48	1.173	22.64	0.811	23.38	0.97
	5^{th} -7^{th} harmonic filter	14.43	1.165	22.66	0.809	23.19	0.98
	5^{th} -11^{th} harmonic filter	12.97	1.163	22.68	0.801	23.11	0.98
	5^{th} -13^{th} harmonic filter	11.59	1.161	22.70	0.794	23.05	0.99
	5^{th} -17 harmonic filter	8.42	1.157	22.73	0.789	22.91	0.99
	5^{th} -19 harmonic filter	7.6	1.156	22.75	0.785	22.88	0.99
	5^{th} -23^{rd} harmonic filter	7.74	1.156	22.76	0.788	22.90	0.99

Analysing the results from Table III one can observe the followings:

- System configuration *Case 2* shows an improvement in power and less current draw from the system as compare to condition in *Case1* when applying classic PFC for a “linear system”. These results show a slight difference in total current and reactive power due to the fact that initial system was well compensated for majority of loads.
- Introduction of harmonics in configuration *Case 3* shows an increase in current drawn, lower power factor and less transferable active power by 40 kW to the loads.
- Applying a classic PF in the present of harmonic pollution (as in configuration *Case 3*), the system deteriorated the results further by increasing the THD by 1.35% and apparent power by 100 kVA as compared to configuration *Case 2*. This may be explained due to resonances that appears on harmonics.
- When running Digsilent model with combinations of seven harmonic filters (*Case 4*) for , namely: 5th, 7th, 11th, 13th, 17th, 19th and 23rd being switched on adding one filter at a time, all the parameters in the nonlinear system show a significant and gradual improvement as compare to configuration *Case 3*: THD decreased from 24.29% to 7.6%, current decreased by 28 A, available active power increased by 170 kW, required apparent power decreased by 690 kVA and true power factor improved from 0.96 to 0.99. Power losses do not improve significant due to some residual harmonics still flowing through the system creating further resonances.

V. CONCLUSIONS

The discussion in this paper indicates the significance of PFC and harmonics pollution. With the correct methodology and consideration of other limiting and aggravating factors such as resonance and harmonics respectively, PFC lead to energy savings. It is to be noted that the results above are as a result of one substation, the injection of harmonics at one point in the network and PFC at only four feeders and a harmonic filter at one feeder only. The losses in the lines and transformer are not computed in this study as it was not yet completed at the time of compiling this article. Thus, a significant improvement in the system efficiency can be realised if the improvement of PF and elimination of harmonics can be applied in the whole network.

This study can be further investigated and serve as a guide to implement a pilot power quality mitigation in MV distribution system in Republic of South Africa for which the authors are busy collecting data and exploring further.

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