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Power Losses Reduction in Low Voltage Distribution Networks by Improving the Power Factor in Residential Sector

Marwan M. Mahmoud and Imad H. Ibrik
Energy Research Centre - An Najah National University
Nablus P.O.Box 721 West Bank - Palestine

Abstract: The residential sector in Nablus - Palestine represent 48% of the total electric power consumption while the power losses in it amount to 8.1%. Implementing of a project aiming at energy conservation in households which included wide range of diversified power measurements, had led to creating this paper. Measurement results, had shown that power losses in the residential sector are mainly caused due to low power factor of the household - loads varying in the range: 0.55 - 0.75 . After developing a proper mathematical model representing the power losses in the residential sector, which represents a main load to the low voltage distribution network in Ch.4, evaluation of measuring results show that an energy saving of 53.18%, by improving the power factor in the households to 0.95, is possible. This percentage corresponds to 3242430 kWh / year or to money saving of 353035 US $ / year. This result is not only applicable for Nablus electrical network but also for other Palestinian cities where similar conditions are prevailing .

Key Words: Power Losses In Low Voltage Distribution Networks, Energy Conservation, Power Factor Improvement

Introduction

Most electrical loads do not consume only active power but also reactive power. The higher the reactive power transported by the distribution network to cover the load requirements, the lower will be the Power Factor (PF) (John and Stevenson, 1994). The PF is defined as the ratio of active power (kW) to the total apparent power (kVA) of an electric network (Saadat, 1999), (Gross, 1983), (John and Stevenson, 1994).

Low power factor has negative impacts on the electric distribution network represented in voltage and power losses, as well as on large consumers (factories, municipalities) represented in high penalties. Usually, improvement of PF is limited on factories and on other large reactive power consumers. The situation of PF in Palestinian households was until now totally neglected. The aim of this paper is to assess the PF in the households and to investigate its impacts on the power losses in the low voltage distribution networks . In addition, it aims also at determining the amount of annual energy saving and the corresponding financial saving through improvement of the PF value in the households.

To achieve this goal, a measurement campaign embracing 100 households, using computer aided measuring instruments was carried out.

Analysis and obtained results show that improvement of PF in the households will significantly contribute in decreasing the power losses in the low voltage distribution networks and in reducing the PF penalties paid by the municipalities to IEC.

Present Electrical Situation in Palestine: The electrical power generation in Palestine is very limited. Most of the required electrical power is supplied by the Israeli Electric Company (IEC) . Existing sources of power include a lot of municipality - owned power generators where the largest unites are in Nablus Power Station. During the last few years, this power station has been used mostly as a standby source to supply water pumping stations, hospitals and other essential sensitive loads in case of power cuts.

The distribution network in West Bank consists of approximately 500 km of 33 kV lines, 900 km of 11 and 6.6 kV lines and 8000 km of 0.4 kV lines (Palestinian Energy Authority, 1999).

The major consumers include the Jerusalem District Electric Company (JDECO) and the municipalities of Nablus, Hebron, Jenin, Tulkarem and Qalqiliah, where all these operate their own distribution systems.

Most of municipalities and village councils have problems in the electrical sector represented mainly in the following:

- High percentage of electrical losses which reaches 20% .
- High cost of power due to the high prices determined by the IEC.
- Low power factor in the Palestinian electrical projects resulting in penalties paid to IEC.
- Inefficient use of electricity, represented in using not proper domestic electrical appliances.

The most significant problem in the electricity sector is the high power losses, varying in the range 11- 20% of the energy imported and generated. Losses result form technical and non-technical reasons. The non-technical losses result form theft, unpaid bills and any other illegal ways of accessing the network. Technical power losses are the results of generation, transmission, distribution and operation systems. Under normal operation conditions, such losses amount to about 6% of the total generation.

Technical losses of the main municipalities are illustrated in Table (1) (Palestinian Energy Authority, 1999).

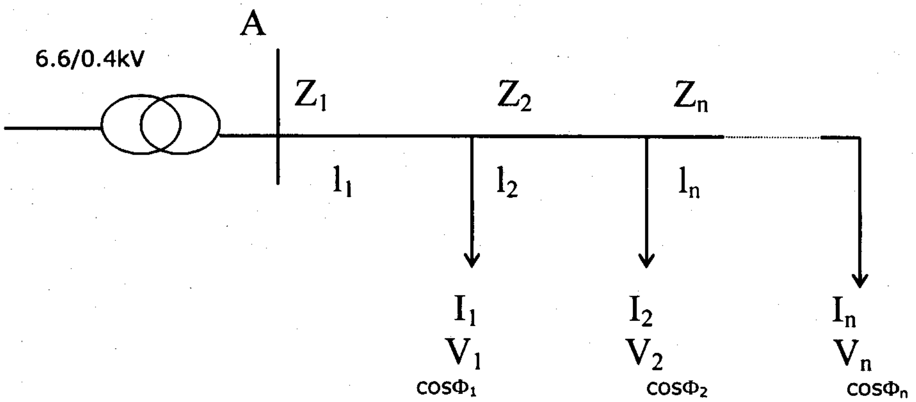

Fig. 1: Typical Low Voltage Distribution Network in Nablus

Table 1: Power Losses in the Main Palestinian Municipalities

Municipality	Consumption kWh/Year	Losses (%)
Jenin	39947520	12.0
Tulkarem	51237520	20.0
Nablus	156818065	10.3
Hebron	158674520	19.0
Qalqilaih	31946083	13.0
JDECO	668107000	19.0

Nablus - Electrical Network: Nablus has two main electric connection points, one is situated near Askar substation, and the other is situated near Qouseen junction road. Each of Askar and Qouseen junction is limited by IEC to 20 MVA. Three 33/6.6 kV substations are operating within Nablus network .

The distribution to load sites occurs via fifteen 6.6 kV and two 33kV feeders. The interior loads in Nablus city are fed by 6.6/0.4kV while the exterior loads are supplied via 33/0.4kV distribution transformers.

The consumers are categorized according to Table (2) issued in Dec. 2000 (Ibrik and Hammami, 1999).

Table 2: Consumer Sectors in Nablus Electrical Network

Sector	Number of Consumers	Share in Electricity Consumption (%)
Residential	28128	48%
Commercial	6836	10%
Industrial	1190	16%
Institutions	525	13%
Water pumping	17	12%
Total	36681	

In addition, the network includes 220 distribution transformers rated at 33/0.4 kV or 6.6/0.4 kV where both outdoor pole mounted and indoor types are used. The impedance of these transformers is about 4%. The majority of the transformers have 5% tap range, with tap steps of 2.5%, and are generally set to give maximum voltage boost to the Low oltage (LV) .

The 0.4kV distribution system consists mainly of overhead line feeders. 70% of the LV circuit use aluminum conductors and the remaining 30% use PVC covered overhead lines.

The electrical losses in Nablus network are summarized as follows (Ibrik and Zagha, 1997):

Total Losses in Nablus Network	Medium Voltage Losses	Low Voltage Losses
10.4%	2.3%	8.1%

The electrical losses in Nablus Network were reduced from 22% in 1994 to 10.4% in 1999 (Ibrik and Hammami, 1999). This result was achieved due to exceptional efforts in collection of electrical bills, discovering the illegal connections, as well as the technical improvement of the electrical system through extending new medium voltage cables and building new distribution substations.

Mathematical Modeling of Power Losses in the Low Voltage Distribution Network: To develop a mathematical model representing the power losses in the low voltage network , we consider a feeder supplied at the point A by 6.6/0.4 kV transformer as shown in Fig (1).

I_1 I_2 … I_n the load current per consumer (residential), Z_1 Z_2 … Z_n the impedance of respective distributor length (l_1 l_2 … l_n) , $\cos\Phi_1$ $\cos\Phi_2$ $\cos\Phi_n$ the power factor of each consumer .

$$Z_k = R_k + J X_k \quad (k = 1 \dots n) \tag{1}$$

The total active power losses in the distributor (ΔP) is computed as:

$$\Delta P = R_1 (I_1 + I_2 + \dots + I_n)^2 + R_2 (I_2 + I_3 + \dots + I_n)^2 + R_k (I_k + I_{k+1} + \dots + I_n)^2 + R_n I_n^2 \tag{2}$$

$$\Delta P = \sum_{k=1}^{n} R_k \left(\sum_{j=k}^{n} I_j \right)^2 \tag{3}$$

The load current (I_j) injected into bus j is calculated as:

$$I_j = \frac{P_j}{V_j \cos\Phi_j} \tag{4}$$

Substituting eq. (4) in eq. (3), we obtain

$$\Delta P = \sum_{k=1}^{n} R_k \left[\sum_{j=k}^{n} \frac{P_j}{V_j \cos\Phi_j} \right]^2 \quad (5)$$

where, n the number of buses in the distributor, V_j and P_j are voltage and power at bus j resp. , R_k the resistance of the distributor branch k, cos Φ_j the power factor for j - load (Saadat, 1999) (John and Stevenson, 1994).

eq. (5) shows that the power losses are inversely proportional to the power factor squared and the minimum losses ΔP_{min} are obtained at cos $\Phi = 1$:

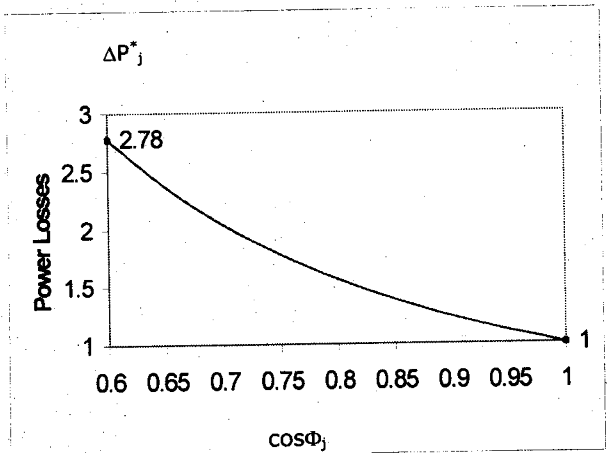

Fig. 2: The power Losses (per unit) as a Function of Power Factor

$$\Delta P_{min} = \sum_{k=1}^{n} R_k \left(\sum_{j=k}^{n} \frac{P_j}{V_j} \right)^2 \quad (6)$$

Considering ΔP_{min} as a reference, we obtain the power losses in per unit form ($\Delta P^* = \Delta P / \Delta P_{min}$) :

$$\Delta P^* = \sum_{k=1}^{n} \frac{1}{\cos^2 \Phi_j} \quad (7)$$

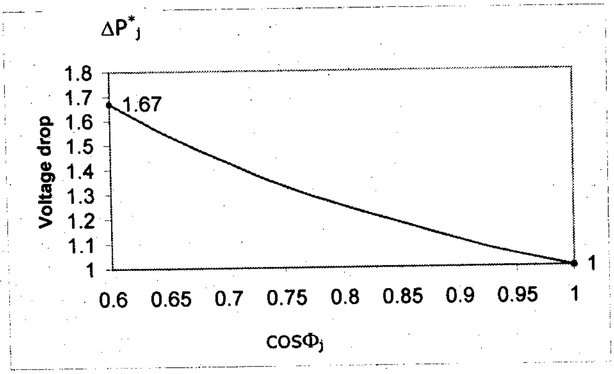

Fig. 3: Voltage Drop (per unit) as a Function of Power Factor

The graphical presentation of eq. (7) is illustrated in Fig (2).

On other hand, voltage drop along the distribution network (Fig. 2) is obtained as :

$$\Delta V_j = |Z_j| \frac{P_j}{V_j \cos\Phi_j} \quad (8)$$

The minimum voltage drop is achieved also when cos $\Phi_j = 1$. Taking this case as a reference we obtain the voltage drop in per unit form (ΔV^*) (Gross, 1983) (John and Stevenson, 1994):

$$\Delta V^*_j = \frac{1}{\cos\Phi_j} \quad (9)$$

eq. (9) shows that the voltage drop along the distribution network is inversely proportional to PF at the individual bus (Fig. 3) .

The total active and reactive power (P_s , Q_s resp.) delivered by the source at point A are given as :

$$P_s = \sum_{j=1}^{n} P_j + \Delta P \quad (10)$$

$$Q_s = \sum_{j=1}^{n} Q_j + \Delta Q \quad (11)$$

Where, ΔP and ΔQ are the total active and reactive power losses in the distribution network (John and Stevenson, 1994). The power factor (PF) of the j - household load is related to the corresponding P_j and Q_j as :

$$\cos\Phi_j = \cos \tan^{-1} \left(\frac{Q_j}{P_j} \right) \quad (12)$$

Beside reduction of active and reactive power losses, by improving the power factor , keeping the voltage V_j within an acceptable range ($V_{jmin} \le V_j \le V_{jmax}$), should also be respected .

Power Measurements on Electrical Loads of Households in Nablus and Techno - Economical Aspects

Measurements on Household Equipment: Research related to energy conservation in households is one of the main activities of the Energy Research Centre at An Najah National University. In this framework, a measuring campaign to assess the power consumption, the reactive power and the power factor of 100 households, was carried out by the authors of this paper. Programmable computer aided measuring equipment had been used to perform this task . Mostly, the main household equipment were represented in lighting, refrigerator, freezer, washing machine, television & satellite receiver, electric water heater, iron and some times small kitchen machines.

A representative sample of the obtained measuring results for I , P, Q and PF in function of day time, for two different houses, are illustrated in Fig 4 (a,b). As obvious the consumed reactive power is high and leads to low PF value varying, as seen for these tow houses as well as for other tested houses, in the range: 0.55 - 0.75. Furthermore, at constant active power, it is recognizable that the load current increases when PF decreases, which result in increasing the power losses in the distribution network. This fact coincides with eq (4) in the developed mathematical modell . Consequently, the reduction in the PF value is caused by the poor average PF values measured separately for the main household equipment as shown in Table (3). The remaining household equipment have higher PF values varying in the range from 0.95-1

Table 3: Results of Separately Measured Power Factor for Main Household Equipment

Equipment	Power Factor Range	
Lighting	0.58 - 0.84	(incandescent + flourecent lamps)
Refrigerator	0.52 - 0.78	
Freezer	0.55 - 0.81	
Washing Machine	0.4 - 0.73	

Estimation of Energy and Cost Saving: Due to diversity of electric feeder types with respect to material , length, cross section , number of consumers and load site, it is impossible to illustrate a common feeder that represent all these differences. To visualize the effect of improving PF on reducing the power losses in low voltage distribution networks and to ease determining the percentage of power loss reduction, it will be enough to consider a uniform feeder being used in Nablus as illustrated in Fig. (4) .

The specifications of this feeder are as follows:

Type : aluminum conductor steel - reinforced (ACSR), three phase over headlines : $r = 0.153\ \Omega$ / km , 3 x 185 mm ^{2} , 400V , I(rated) = 535A

Total feeder length $l = 1000$ m .

Number of total consumers: 90 (30 consumer per phase) .

Distance between the individual consumers: $l_1 = l_2 = ... l_n = 33.3$ m

Resistance of line portion : $R_1 = R_2 = ... R_n = 5.1 \times 10^{-3}\ \Omega$

Power consumption of consumers (households) : $P_1 = P_2 = ... P_n$

In this case, the active power losses according to eq. (3) becomes in the easy form :

$$\Delta P = R \sum_{j=1}^{n} (jI)^2 \qquad (13)$$

where, $I = \dfrac{P}{V \cos\Phi}$

$$\Delta P = \frac{RP^2}{V^2 \cos^2\Phi} \sum_{j=1}^{n} (j)^2 \qquad (14)$$

Based on the measurements we carried out on numerous households with various power consumption, the following values can be considered as real averages to perform this example:

$V = 230$ V , $P = 600$ W , $\cos\Phi = 0.65$

Substituting these values in eq. (14) :

$$\Delta P_1 = \frac{5.1 \times 10^{-3}(600)^2}{(230)^2(0.65)^2} \sum_{j=1}^{30} (j)^2 = 776.7\ W$$

Improving the power factor of each household to be 0.95, the total power losses in the feeder will be as $\Delta P_2 = 363.6$ W .

The total power saving achieved for one phase is ΔP_{sav1}

$\Delta P_{sav1} = \Delta P_1 - \Delta P_2$ (15)

$= 776.7 - 363.6 = 413.1$ W

The total power saving in the three phases is ΔP_{sav3} :

$\Delta P_{sav3} = 3 \times 413.1 = 1239.3$ W

The percentage of energy saving through improving the power factor is obtained as ΔP_{sav} :

$$\Delta P_{sav} = \frac{413.1}{776.7} \times 100\% = 53.18\%$$

The share of residential sector - energy consumption in Nablus network (E_r) is obtainable from Table (1 & 2) as :

E_r = 48% x 156818065 = 75272671 kWh / year .

The total power losses in residential networks (Ibrik and Salam, 1997) is ΔE_r :

ΔE_r = 8.1% x 75272671 = 6097086 kWh / year .

The total energy saving in residential network through improving the power factor is ΔE_{sav} :

ΔE_{sav} = 53.18% x 6097086 = 3242430 kWh / year

Considering the kWh - price paid by Nablus Municipality to IEC and the additional administrative cost, assembling 0.45 NIS / kWh (net) , the saving in money will be ΔC :

ΔC = 0.45 x 3242430 = 1459094 NIS / year (1US $ = 4.15 NIS)

Technical Measures for Improvement of the Power Factor: Most electrical loads do not consume only active power but also reactive power. While the active power provides motors, incandescent lamps, electrical boilers, electrical heaters with useful energy, the reactive power is necessary for magnetic circuits of inductive loads represented in transformers, motors, fluorescent lamps and inductive furnaces. The relation between active power, reactive power and power factor is illustrated in eq. (12). The higher the reactive power transported by the distribution network the lower will be the power factor. Due to high cost of electric energy transport, it is more feasible to generate the required reactive power directly at the inductive loads by installing capacitors.

The necessary reactive power (Q_c) to be installed in a capacitor to improve the power factor from $\cos\Phi_1$ to $\cos\Phi_2$ is obtained as follows (John and Stevenson, 1994):

$Q_c = P (\tan\Phi_1 - \tan\Phi_2)$ (16)

Applying this formula on our realistic household example, we obtain the reactive power (Q_{ch}) necessary to improve PF from 0.65 to 0.95 :

$Q_{ch} = 600 (\tan \cos^{-1} 0.65 - \tan \cos^{-1} 0.95) = 504$ VAr

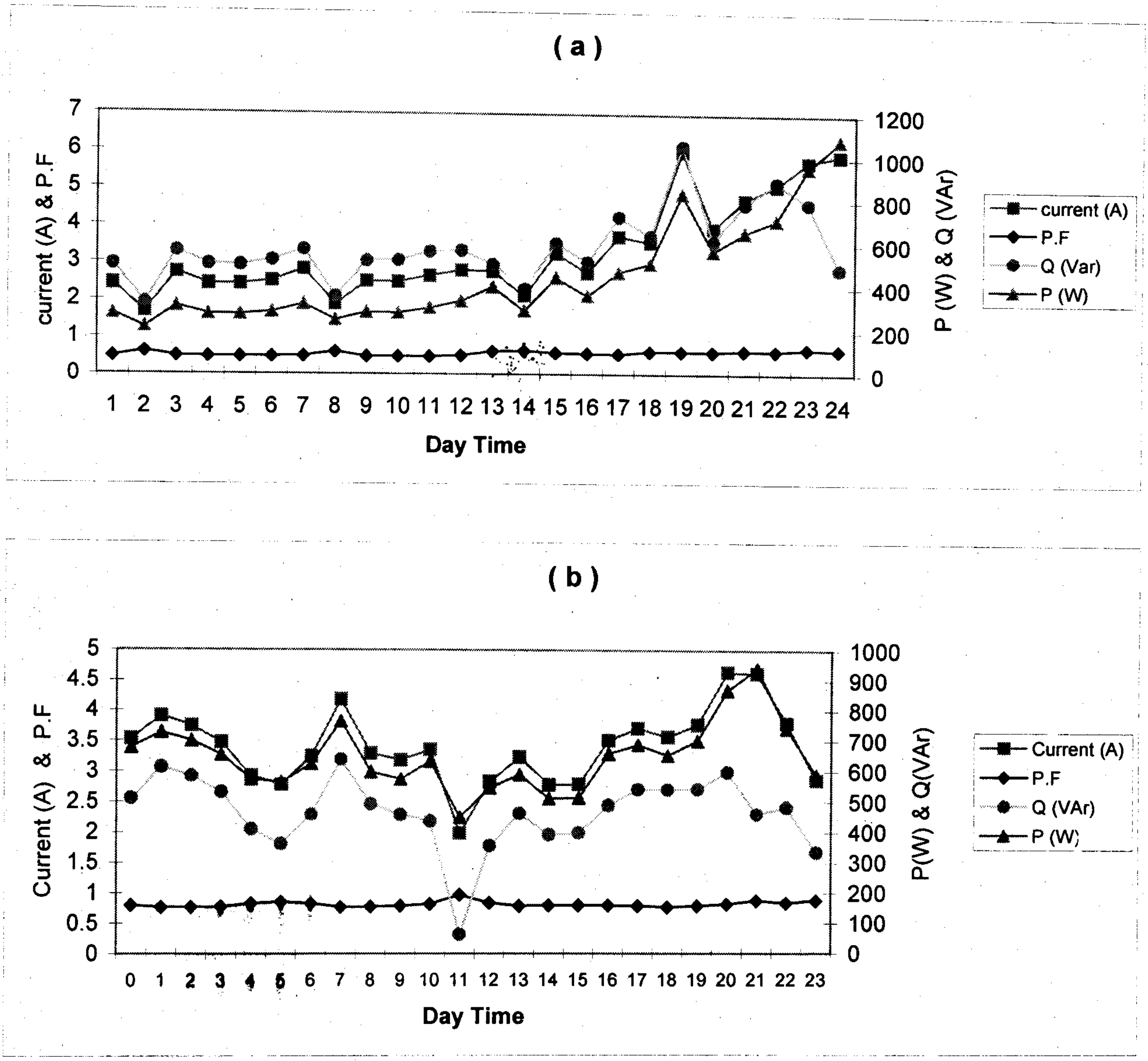

Fig. 4 (a and b): Measuring results of I, P, Q and PF in Function of Day time for Tow Households Representing the Most Household - loads in Nablus (House - Supply Voltage 230V rms , 50 Hz)

To improve PF of the feeder supplying 90 households, a total reactive power to be installed individually (Q_{cf}) will be needed :

$Q_{cf} = 90 \times 504 = 45.36$ kVAr

Ways for Improvement of Power Factor in Households: Due to the variety of electrical loads in individual households with regard to power ratings, daily load curve and load types as well as due to the multiplicity of household kinds (single small or large house, apartment or suite in a large building supplied by 3 phase) , it is impossible to propose a uniform PF - correction capacitor design which can be generalized to fit with all household types. Therefore, it is left to each concerned one to design, as illustrated in this paper, the proper capacitor system that fits with the load characteristics of his household.

However, we propose the following measures to improve the power factor:

a Oblige each household owner to install compensation capacitors on the fluorescent lamps, since lighting represent a high percentage of the total daily load.

b Installation of a capacitor with proper size directly parallel to the inductive equipment (washing machines, fridges, pumps, ... etc.) in the house to operate at the same time with it .

c Installation of a capacitor with an appropriate size on the main circuit breaker of the house to improve the PF of all household equipment.

d Installation of proper variable capacitors at the main distribution boards of the individual residential buildings, where the PF will be improved for all households in the respective building.

e Installation of appropriate outdoor variable capacitors at the poles providing power to the houses.

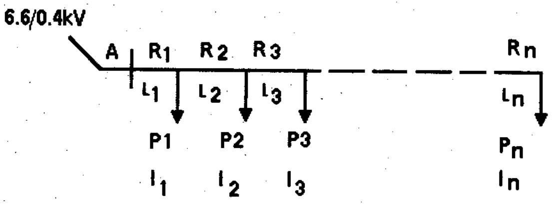

Fig. 4: Uniform Electric Feeder used within Nablus LV Network

Conclusion

Based on the mathematical model developed in Ch. (4), the power loss in the distribution network is inversely proportional to the power factor squared.

Results of measurements carried out on numerous different size households in Nablus show that PF is low, since its average varies in the range : 0.55 - 0.75. Situation in other Palestinian cities will be similar. The improvement of PF in the households is neglected and the attention is mostly limited on the industrial sectors where penalties are imposed . The positive impacts of improving PF in households on reducing the power losses in the low voltage distribution networks at about 53% is verified in this paper. Hence, we recommend the municipalities to develop an appropriate procedure , considering the ways mentioned, to oblige the consumers (households) to improve their PF to a high acceptable value e.g. 95% . This action will save yearly a large amount of energy and money (1459094 NIS / year = 353035 US $ for Nablus) especially because the low voltage distribution networks in Palestine are characterized with high losses.

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