STATIC DEYICE TO KEEP SYMMETRY OF 3-PHASE SUPPLY FEEDING LARGE 1-PHASE LOADS

وسيلة استاتيكية للمحافظة علي توازن المنبع الكهربائي ثلاثي-الطور عند تغذية أحمال كبيرة أحادية-الطور

By
AZZA M.ABDEL-HAMID

Electrical Engineering, Power Department, Cairo University, Cairo, Egypt

خلاصة : عادة يطلب من شبكات توزيع القوي الكهربائية ثلاثية-الطور تغذية أحمال كبيرة أحادية-الطور مثل محولات اللحام والأفران الكهربائية.ومن المعلوم أن هذه الأحمال لها تأثيرات ضارة علي توازن الشبكة المغذية ثلاثية-الطور، مما يعرض الأحمال الأخرى المغذاة من نفس المصدر- مثل المحركات الحثية ثلاثية الطور- الي أداء غير سليم وارتفاع درجة حرارة الملفات مما يعرضها للتلف.
ويقدم هذا البحث طريقة استاتيكية للمحافظة علي اتزان المصدر الكهربائي ثلاثي-الطور وذلك باضافة مفاعلين الي الحمل الكبير أحادي الطور لتكّونا معه حمل جماعي موصل بطريقة الدلتا ويؤدي الي احتفاظ الشبكة بالتوازن المطلوب لتغذية الاحمال الثلاثية الأخري.والبحث يقدم قيمة المفاعلين (ك.ف.أ) ونوعيها، وتغير قيمتها مع طبيعة ومقننات الحمل أحادي-الطور ومعامل قدرته. ومن الواضح ان الوسيلة المقدمة لا تستهلك أي طاقة كهربائية اضافية.

ABSTRACT

Utility systems must nowadays handle a variety of a large 1-phase industrial loads which ean have a serious effect on the symmetry of a 3-phase supply system. This paper introduces a method by whieh 1-phase loads can be reflected as symmetrical three phase in order to avoid unbalaneing the feeding 3-phase supply. For this purpose, a statie wattless device is presented which proves to be practieable for any single-phase load. Additionally, the device is more important when the power-factor of the 1-phase load is equal or near unity.

keywords: Static device, 1-phase loads, Symmetry of supply.

NOMENCLATURE

a	= operator e^{j120}.
I_0, I_1, I_2	= Zero-, positive -, and negative-sequence components of the current "I".
P_l	= Power cumponent of the single-phase load, Watt.
P_p	= Pulsating douhle-frequeney component of the 1-phase load.
P_r	= Pnwer of the 3-phase supply.
R_l	= Resistanee of the 1-phase load, Ohm.
U_{io}, Ui_2	= Current unbalance- factors of zero- and negative-sequence currents, respectively.
U_{v0}, U_{v2}	= Voltage unbalance-factors of zero-, and negative-sequence voltages, respectively.
$(VA)_l$	= Apparent-power of the 1-phase load.
$(VAR)_2, (VAR)_3$	= Reaetive-power of the two balancing reactances (X_2) and (X_3) respeetively.

Accepted June 9, 2001

$(VAR)_s$	=	Reactive-power of the 3-phase supply .
X_l	=	Reactive -component of the 1-phase load ,Ohm .
X_2, X_3	=	Reactances of the static device .
Z_l	=	Impedance of the 1-phase load ,Ohm .
$\cos\varphi_l$	=	PF. of the 1-phase load .
$\cos\varphi_s$	=	PF . of the 3-phase supply .
β_2	=	Ratio of $(VAR)_2$ to $(VA)_l$.
β_3	=	Ratio of $(VAR)_3$ to $(VA)_l$.

(1) INTRODUCTION

Three-phase networks are required nowadays to feed large 1-phase loads like traction systems , welding transformers , arc furnaces , etc [1] . Such loads may have harmful effects npon the 3-phase system , especially voltage symmetry . The limit to voltage unbalance was set at 2% in BS2613 for the satisfactory operation of 3-phase motors , since values higher than this could cause exeessive heating of motor-windings [2,5] . However , to allow for a measure of unbalanee from other causes , the supply authorities have recommended maximum unbalance figures of 1-3% below 33 KV. Obviously , the presence of large 3-phase induction-motors and 3-phase synchronous-machines help to maintain the symmetry of the 3-phase supply within the permissible limits [1,3]

It is therefore highly required to reflect such large 1-phase loads in effect to 3-phase to keep the balance of the 3-phase distribution system . Clearly any method serving this purpose must compensate the double-frequency power component drawn from the supply by 1-phase loads .

In this paper a static device, applying two reactances to counter the 1-phase load , is presented and analyzed . Clearly , no extra electric- energy is eonsumed by the device , but the values of the reactances are eritical and depend on the power-factor of the 1-phase load . It will be shown that the method is always practicable , but it becomes more useful with 1-phase load power-factor equal to or near unity .

(2) POWER CONSIDERATION

(2.1) 1-PHASE CIRCUIT

In a 1-phase circuit fed from a voltage "v", and drawing a current "i" given by :

$$v = v_m.\sin(\omega t + \theta_v)$$
$$i = i_m.\sin(\omega t + \theta_i)$$

the instantaneous- power is the product of both , thus :

$$p = VI[\cos(\theta_i - \theta_v) - \cos(2\omega t + \theta_v + \theta_i)] \quad (1)$$

The last expression shows that the steady power consumed is:

$$P = VI\cos(\theta_i - \theta_v) = VI\cos(\varphi) \quad (2)$$

and the component of power pulsating at double-frequency is:

$$P_p = -VI\cos(2\omega t + \theta_v + \theta_i) \quad (3)$$

Obviously , the pulsating component has an average value equal to zero . Also , the power-factor angle of the 1-phase current is equal (θ_i-θ_v)=φ ,or with θ_v taken zero , i.e voltage is the reference vector , the PF. angle will be $\varphi = \theta_i$ .With pure inductive load "φ"is then (-π/2) and eq. (3) yields for the alternating- component :
It is observed that the amplitude of the alternating-component is equal to the apparent-power of the 1-phase load .

$$P_p = VI\sin(2\omega t) \quad (4)$$

(2.2)3-PHASE SYMMETRICAL CIRCUITS

In a symmetrical 3-phase circuit , the 3-phase voltages v_a , v_b , v_c form together a balanced system , similarly will be the 3-phase currents i_a , i_b , i_c . Summing up the three instantaneous phase power $v_a i_a$,$v_b i_b$, $v_c i_c$,as illustrated for the 1-phase circuit above , we finally get the constant power component .

and the sum of the instantaneous-components of the three phases alternating at double-frequency boils down to zero .

$$P = 3.V.I\cos(\varphi) \quad (5)$$

(2.3) 3-PHASE ASYMMETRICAL CIRCUITS

The usual method of analyzing such circuits is by the use of the principle of symmetrical-components in which the unbalanced systems of voltages and currents are generally analyzed into three systems , namely the positive-, the negative- , and the zero-sequence systems [6] . The positive-sequence voltage and current components represent the normal case of balanced operation . The negative-sequence components are the same but with reversed phase-sequence . But the zero-sequence components represent in-phase voltages and in-phase currents and , consequently , the condition will be similar to those existing in 1-phase circuits .
The total power in the 3-phase unbalanced circuit is equal to the sum of positive-negative and zero-sequence powers , thus given by :

$$P = P_0 + P_1 + P_2 \quad (6)$$

in which P_1 , P_2 can be obtained exactly as in ordinary balanced 3-phase circuits , and P_0 as in 1-phase circuits . According to the sequence-rule for unbalanced circuits [6] , the only terms which contribute to the total power are those in which

$$\begin{aligned}(Total\ \mathrm{VA}) &= 3.[V_0^{*}.I_0 + V_1^{*}.I_1 + V_2^{*}.I_2] \\ &= P + j.Q \end{aligned} \quad (7)$$

the voltage and current have the same sequence order . The total Volt-ampere is then expressed by :

in which subscripts 0,1,2 express zero- , positive-, and negative-sequence quantities ; values with the dash (') are conjugates . The power component " P " and the reactive component " Q" in eq. (7) yield the so called aggregate or total PF. as given by :

Considering P_1 and P_2 in eq. (6) , they contain no alternating instantaneous -

$$\text{Aggregate Power - Factor} = \frac{P}{\sqrt{P^2 + Q^2}} \tag{8}$$

power component ; but the zero-sequence power component P_0 results in a power component alternating at double-frequency . Consequantly, symmetrical distribution of the load in 3-phase networks is always aimed at . With large rating 1-phase loads , this is not easy to achieve and such 1-phase loads are preferably converted so as to be reflected as 3-phase on the 3-phase supply .

The unbalance in a 3-phase supply is normally measured by voltage and current unbalance factors : U_{v0} , U_{v2} , U_{i0} , U_{i2} as follows :

$$\begin{aligned} U_{v0} &= V_0 / V_1 \\ U_{v2} &= V_2 / V_1 \\ U_{i0} &= I_0 / I_1 \\ U_{i2} &= I_2 / I_1 \end{aligned} \tag{9}$$

(2.4) SEQUENCE COMPONENTS OF 1-PHASE LOAD

If a single -phase load is connected between lines S and T of a 3-phase RST supply, the three line -currents I_R , I_S ,and I_T will then be equal to (0) , (I_L) and(-I_L) respectively, as shown in Fig.(1). The sequence-components of the three line-currents will be :

$$\begin{aligned} I_{R0} &= 0 \\ I_{R1} &= +j.I_L / \sqrt{3} \\ I_{R2} &= -j.I_L / \sqrt{3} \end{aligned} \tag{10}$$

This shows that the zero-sequence component disappears , while the positive- and negative-sequence currents are equal .

(2.5) HARMFUL EFFECTS OF SUPPLY ASYMMETRY

The following main effects are caused by supply asymmetry :

1- Distribution and transmission losses are increased with asymmetrical loading which may add negative- and zero-sequence currents to the normal positive-sequence current in case of symmetrical loading . When feeding small consumers , like lighting loads and house appliances, symmetry may more or less be maintained in 3-wire or 4-wire distribution systems by observing the lines to which such large number of small loads are connected . But with high-rating loads, this would not be possible.

2- With 3-phase synchronous-machines, the negative-sequence magnetic-field loads the damper-windings and heats them up, together with the insulating materials applied in the machine. Such overheating greatly affects the longevity of the machine . Furthermore , the negative-sequence currents cause harmonics in stator- and rotor-circuits which lead to over currents especially when capacitors are used.

3- Asymmetrical loading causes in turn asymmetrical voltage-drop, therefore load-voltage will be asymmetrical . Operation of synchronous and induction machines will then suffer from the negative- and zero-sequence voltages leading to reduction of torque and efficiency, dips in the (T/ speed) characteristics that may endanger the running-up process; moreover the longevity of the machine may be greatly affected . Further effects include interference with electric equipments, computers, and fluctuation of the candle-power of tungsten lamps.

It follows that it is worthwhile to maintain the symmetry of a 3-phase supply as far as possible, though this aim necessitates some extra cost.

(1) CONVERSION OF 1-PHASE LOAD TO 3-PHASE BY TWO REACTANCES

When a 1-phase load, $Z_1\angle\varphi_1$, is connected between any two lines R and S of a 3-phase symmetrical supply RST as in Fig. (2), the idea presented here is to connect 2 reactances to form a delta-loop with the 1-phase load and connected to the same 3-phase supply so that the delta-load will then represent a symmetrical 3-phase network . For the analysis, we start with the two reactances replaced by the impedances Z_2 and Z_3 as in Fig.(2).

The line voltages of the symmetrical 3-phase supply are expressed by :

$$\begin{aligned} V_{RS} &= V \\ V_{ST} &= a^2.V \\ V_{TR} &= a.V \end{aligned} \tag{11}$$

The 3-phase currents in the delta-loop, and the 3 line-currents are given by :

$$\begin{aligned} I_{RS} &= V / Z_1 \\ I_{ST} &= a^2.V / Z_2 \\ I_{TR} &= a.V / Z_3 \end{aligned} \tag{12}$$

And

$$I_R = I_{RS} - I_{TR}$$
$$I_S = I_{ST} - I_{RS} \quad (13)$$
$$I_T = I_{TR} - I_{ST}$$

From the 3 last equations , we get :-

$$I_R = V.(\frac{1}{Z_1} - \frac{a}{Z_3}) \quad (14)$$

and

$$I_S = V.(\frac{a^2}{Z_2} - \frac{1}{Z_1}) \quad (15)$$

Since for the required symmetrical line-currents , the following relation is to be obtained :

$I_S = a^2.I_R$,

then , substituting from equations (14) and (15) , we get :-

$$(\frac{a^2}{Z_2} - \frac{1}{Z_1}) = (\frac{a^2}{Z_1} - \frac{1}{Z_3}) \quad (16)$$

Therefore , equation (16) leads to the following relation which is necessary for symmetrical line-currents :

$$a^2.Z_3.(Z_1 - Z_2) = Z_2.(Z_3 - Z_1) \quad (17)$$

Now , assuming 2 reactances jX_2 and jX_3 replacing respectively Z_2 and Z_3 , and substituting the following in equation (17) :-

$$Z_1 = R_1 + jX_1 = Z_1\angle\varphi_1$$
$$Z_2 = j.X_2 \quad (18)$$
$$Z_3 = j.X_3$$

then , the following condition of symmetry will be obtained :

$$ja^2.X_3.(R_1 + j.X_1 - j.X_2) = j.X_2.(j.X_3 - R_1 - j.X_1) \quad (19)$$

It is to be noted that positive- and negative- signs for the reactances represent respectively inductive and capacitive cases . The load is considered to have lagging power-factor , $\cos\varphi_1$,which represents the general case .

Now equating the real and imaginary parts on both sides of equation (19),we get respectively :

$$(-1/2).R_1.X_3 + (\sqrt{3}/2).X_3.(X_1 - X_2) = -R_1.X_2$$

and

$$(\frac{-\sqrt{3}}{2}).R_1.X_3 - (-1/2).X_3.(X_1 - X_2) = X_2.(X_3 - X_1)$$

The above equations can be modified to :-

$$-R_1.X_3 + \sqrt{3}.X_3.X_1 = \sqrt{3}.X_3.X_2 - 2.R_1.X_2 \quad (20)$$

$$-3.R_1.X_3 - \sqrt{3}.X_3.X_1 = \sqrt{3}.X_3.X_2 - 2.\sqrt{3}.X_1.X_2 \quad (21)$$

The last two equations lead to the following results :

$$\frac{X_2}{X_3} = \frac{\sqrt{3}.\tan\varphi_1 + 1}{\sqrt{3}.\tan\varphi_1 - 1} \quad (22)$$

Substituting from equation (22) in equation (21), we get for X_3 the following expression :

$$X_3 = \sqrt{3}.R_1.\frac{1+\tan^2\varphi_1}{1+\sqrt{3}.\tan\varphi_1}$$

or :-

$$X_3 = \frac{(\sqrt{3}.R_1)}{(\cos\varphi_1)^2.(\sqrt{3}.\tan\varphi_1 + 1)} \quad (23)$$

Furthermore from equation (22), we get :

$$X_2 = \sqrt{3}.R_1.\frac{1+\tan^2\varphi_1}{\sqrt{3}.\tan\varphi_1 - 1}$$

or

$$X_2 = \frac{\sqrt{3}.R_1}{(\cos\varphi_1)^2.(\sqrt{3}.\tan\varphi_1 - 1)} \quad (24)$$

It is obvious from equations (23) and (24) that it is always possible to balance any 1-phase load by the two reactances X_2 and X_3 whatever the power-factor of the load may be ; positive and negative values for the reactances represent respectively inductive- and capacitive-values .

(3.1)SPECIAL CASES OF 1-PHASE LOAD POWER-FACTOR

Equations (23) and (24) give the values of the two reactances required to reflect the 1-phase load at any power-factor as 3-phase on the 3-phase supply side. The following cases will be examined.

(a)1-phase load P.F =1:

For cos φ_l=1 , equations (23) and (24) yield the following :

$X_2 = -\sqrt{3}.R_1$ (capacitive reactance)

$X_1 = +\sqrt{3}.R_1$ (inductive reactance) (25)

For this interesting case, the vector diagram is shown in Fig.(3).

(b) 1-phase load P.F= √3/2 , lagging:

$X_2 = \infty$

$X_3 = +(2.R_1 / \sqrt{3})$ (inductive reactance) (26)

Here φ_l = +30 , and the required reactanecs will be :

This shows that balancing is possible by one inductive-reactance "X_3" connected between lines T and R in the general Fig.(2).

(c)1-phase load P.F =√3/2 ,leading .

The required reactances will be :

$X_2 = (-2.R_1 / \sqrt{3})$ (capacitive reactance)

$X_3 = \infty$ (27)

Again here balancing is achieved by one capacitor connected between the two lines S and T in Fig. (2).

(d)1-phase load P.F = zero , lagging .

Here φ_l =+90 ,, and the following values for X_2 and X_3 can finally be obtained from equations (23) and (27):

$$X_2 = X_3 = X_1 \qquad (28)$$

(e) 1-phase load P.F = zero , leading .

In this case φ_l = -90 , and symmetry is obtained by two capacitive-reactances equal to the load reactance.

$$-X_2 = -X_3 = -X_1 \quad \text{(all capacitive)} \qquad (29)$$

The following table gives the values of the two reactances X_2, and X_3 , in terms of load components , which are required for balancing the 1-phase load , for different values of power-factor.

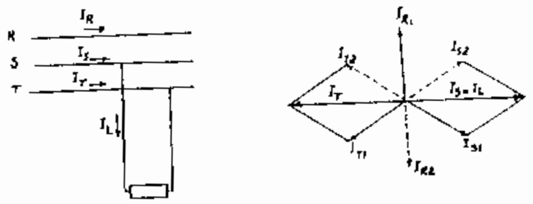

FIG.1- SYMMETRICAL COMPONENTS OF 1-PH LOAD

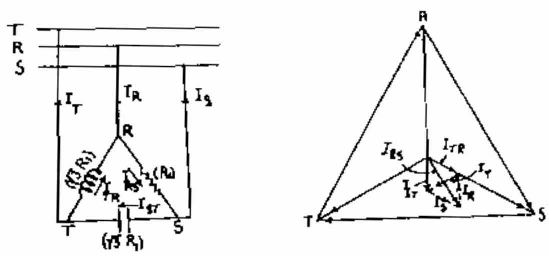

FIG.3- CASE OF RESISTIVE LOADING

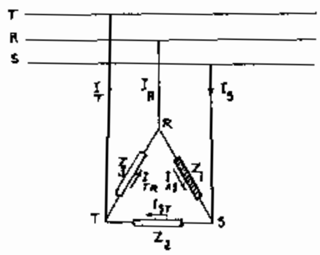

FIG.2 - GENERAL CASE OF UNBALANCED LOAD

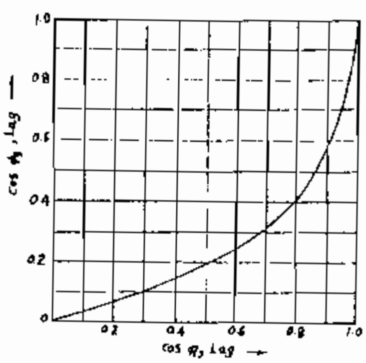

FIG.4-VARIATION OF 3-PH SUPPLY PF

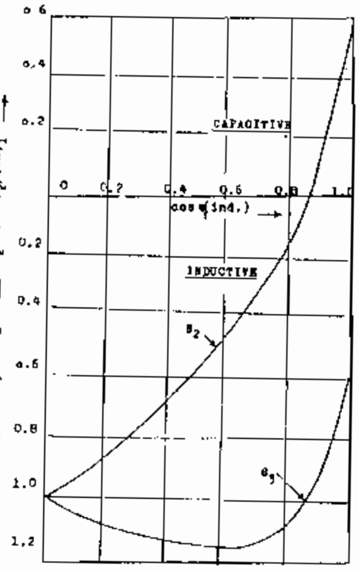

FIG.5 (REACTIVE VOLT-AMP.) of X_2 and X_3

Table (A)

Load P.F	φ_1	X_2	X_3
1	0	$-\sqrt{3}.R_1$	$+\sqrt{3}.R_1$
0.87 lagging	+30	-	$+2.R_1/\sqrt{3}$
0.5 lagging	+60	$+2\sqrt{3}.R_1$	$+\sqrt{3}.R_1$
Zero , lagging	+90	$+X_1$	$+X_1$
Zero , leading	-90	$-X_1$	$-X_1$
0.5 , leading	-60	$-\sqrt{3}.R_1$	$-2.\sqrt{3}.R_1$
0.87 , leading	-30	$-2.R_1/\sqrt{3}$	-

(4)P.F OF THE 3-PHASE SUPPLY AFTER RESTORING SYMMETRY AND THE (VAR) OF THE EXTERNAL REACTANCES

It has been shown that applying the two critical reactances X_2 and X_3 maintains the symmetry on the 3-phase side . Consideration of total power and the total (VAR) leads to the power-factor on the 3-phase side .

The total power is obviously equal to the power of the 1-phase load , therefore :

$$P_t = V^2.(\cos\varphi_1)^2 / R_1 \tag{30}$$

The VAR component of the 1-phase load is given by :-

$$(VAR)_1 = V^2.\sin\varphi_1.\cos\varphi_1./ R_1 \tag{31}$$

the P.F of the load being considered lagging , which represents the general case .

From equations (23) and (24) , the values of $(VAR)_2$ and $(VAR)_3$ of the reactances X_2 and X_3 , respectively , are expressed as follows :-

$$(VAR)_2 = \frac{V^2}{\sqrt{3}.R_1}.\frac{\sqrt{3}.\tan\varphi_1 - 1}{1+\tan^2\varphi_1} \tag{32}$$

and

$$(VAR)_3 = \frac{V^2}{\sqrt{3}.R_1}.\frac{\sqrt{3}.\tan\varphi_1 + 1}{1+\tan^2\varphi_1} \tag{33}$$

The total reactive volt-ampere on the 3-phase side is obviously the sum of the values given in equations (31) to (33) ; therefore :-

$$(VAR)_s = \frac{V^2}{R_1}.[\sin\varphi_1.\cos\varphi_1 + \frac{2.\tan\varphi_1}{1+\tan^2\varphi_1} \qquad (34)$$

which can be modified to : -

$$(VAR)_s = \frac{V^2}{R_1}.3.\sin\varphi_1.\cos\varphi_1 \qquad (35)$$

Dividing (P_s) by (VAR)$_s$ given respectively by equations (30) and (35) gives the following expression :-

$$\tan\varphi_s = 3.\tan\varphi_1 \qquad (36)$$

or the P.F of the 3 - phase supply will be : -

$$\cos\varphi_s = \frac{\cos\varphi_1}{\sqrt{9-8.(\cos\varphi_1)^2}} \qquad (37)$$

This last expression gives the supply PF in terms of 1-phase load P.F . Fig.(4) shows this relation for a lagging ($\cos\varphi_1$) in the range from zero to unity . It is obvious from this figure that the supply P.F is much smaller than that of the 1-phase load except when the latter is equal or near unity .

Since the apparent-power of the 1-phase load equals $V^2 / |Z_1|$, then the relations of $(VAR)_2$ and $(VAR)_3$ to 1-phase load $(VA)_1$ are expressed by β_2 and β_3 ,respectively as follows :-

$$\beta_2 = \frac{R_1}{(X_2.\cos\varphi_1)} \qquad (38)$$

$$\beta_3 = \frac{R_1}{(X_3.\cos\varphi_1)} \qquad (39)$$

In Fig.(5) are shown curves for β_2 and β_3 for 1-phase load lagging P.Fs in the range from zero to unity ; values of X_2 and X_3 being taken from Table (A) given before .

The total (VAR) added externally to attain symmetry determines the extra cost required . For the load PF . $\cos\varphi_1$=1 , this amounts to 1.16 times the apparent-power of the 1-phase load , while this rate rises to 2:1 in the case of pure inductive load . Conclusively , utilization of the static device formed of X_2 and X_3 is at its best with 1-phase load P.Fs equal to or near unity .

(5) CONCLUSIONS

The main harmful effects of 1-phase loads fed from 3-phase supply have pointed out including injection of the alternating double frequency power-component into the supply, and causing it to be asymmetrical. Such asymmetry, leads to large transmission losses, and overheating as well as derating of 3-phase loads supplied from the same 3-phase network. Consequently, large 1-phase loads should, preferably, be reflected as 3-phase on the 3-phase side.

To this extent, this work introduces a static device composed of two reactances, which are to be connected in delta with the load across the 3-phase supply. It has proved that it is always possible, with any power-factor of the 1-phase load, to convert such load to be seen as 3-phase on the side of the 3-phase supply. Thus, the system behaves as a balanced 3-phase network with no extra energy loss due to the applied reactive-device. Since P.F. on the 3-phase side is expected to be less than that of the 1-phase load, except for unity power-factor, thus it is recommended that the device may be applied after improving the load P.F. to unity by an appropriate capacitor to be connected across the load terminals. The advantage of seeking unity P.F. is that no penalty, meaningly no (VAR), is to be added to the 3-phase system.

ACKNOWLEDGEMENT

The author is indebted to her colleagues at the " Electrical Power Department "of" Cairo University " for many helpful discussions.

REFERENCES

1. Merrill ,F. :" The Challenge of Industrial Supplies" . IEE News , July 1976 .
2. Yacamini ,R and Chang , S. :" Noise and Vibration From Induction Machines Fed From Harmonic Sources ". IEEE Trans . (En. Conversion) , 1995 .
3. Borrs, Hand Nittka , H . :" Developments of 3-Phase Cage Induction-Motors For High Ratings ." AEG Mitteilungen , Berlin , 1984 .
4. Emanuel,A.E. et al : " Survey of Harmonic Voltages and Currents at Customers'Buss" IEEE Trans (PWRD) , Jan. 1993 .
5. Leonhard ,A:" Messung , Uberwachung und Regelung der Schieflast in Drehstromnetzen "ETZ-A . 1974 .
6. Lyon,WV."Application of The method of Symmetrical Components " Book ,Mcgraw-Hill Book Co., New York 1957 .