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MICROCAP SIMULATION TO DEVELOP A PHASE-CONTROLLED POWER-FACTOR CORRECTOR

Bence FOLTÁNYI

Department of Microwave Telecommunication
Technical University of Budapest
H–1521 Budapest, Hungary
Phone and fax: 36 1 186–9231
email: d-foltanyi@nov.mht.bme.hu

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Abstract

This paper describes an optimization method how a traditional phase-controlled rectifier can be used as a power-factor corrector. In order to maximize the power factor and respectively minimize the harmonic content of the input current of this corrector, optimal values of smoothing inductance and firing angle must be selected. To find and provide this operating point the MICRO-CAP II electrical circuit analysis program is used. The power-factor correcting methods are summarized and compared with this system. The problems caused by the line-current harmonics and standards are introduced to call attention to the importance of use of these converters.

Keywords: phase-controlled rectifier, energetical disturbances, IEC 555–2, power-factor, active low frequency PFC.

1. Introduction

In recent years, in accordance with the increase of the power requirement of electrical equipment, the role of the line-connected switchmode power supplies has gained great importance. The input current of these non-linear loads due to direct rectifying is not sinusoidal but rather a series of pulses. Since the current pulse lasts for only a small portion of each half-period of the voltage, harmonics in the line current are generated and this reduces the power factor. The lowered power factor disturbs both the AC line and the consumer side and is a significant source of many energetical problems.

The correction of reduced power factor caused by line current harmonics has become very important primarily in the US, where the line voltage is the half of the commonly used value. Nowadays in most countries of the European Community many standards to limit the line current harmonics are being planned. As Hungary has expressed its intention of joining the European Community, IEC proposals should be integrated in the Hungarian National Standards. Because of that the problem has not only technical but also legal aspects.

The power factor is generally defined as the ratio of the real and apparent power. Since in practice the apparent power is always greater than the real power, the optimum value of the power factor is one.

Different types of electrical equipment reduce the power factor in different ways. The input current of the reactive loads (e.g. motors, transformers, etc.) is sinusoidal, but it has an angular displacement with relative to the line voltage. In this case the power factor is known as the displacement power factor and is regarded to be the classical power factor:

$$\text{Real Power} = \text{Apparent Power} \times \cos\phi.$$

The input current of the non-linear loads (e.g. rectifiers, phase-control power regulators, inverters for motor drives, etc.) causes distortion. In this case the power factor can be described only in generic terms:

$$\text{Real Power} = \text{Apparent Power} \times \text{Power Factor}.$$

In real life the general definition for power factor (PF) is as follows:

$$\text{PF} = \text{Displacement PF} \times \text{Distortion PF}$$

where

$$\text{Distortion PF} = \text{Fundamental Current/Total Current}.$$

According to this definition usually the power factor is known as total power factor.

2. Power Supplies Cause Problems on the Line

The off-line power supplies using direct line rectifying without intervening transformer present non-linear load to the AC line. The typical power factor is about 0.5–0.6. This paper examines the problem of the power factor only in the case of single-phase off-line power supplies. The model of a typical input rectifier circuit is shown in *Fig. 1.* The typical input voltage and current waveforms can be seen in *Fig. 2.*

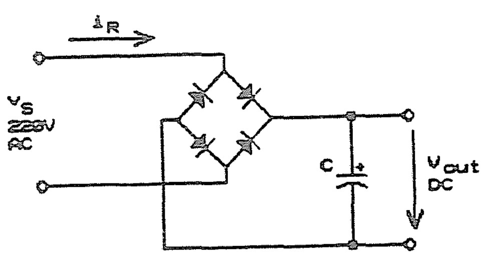

Fig. 1. Typical input rectifier of an off-line power supply

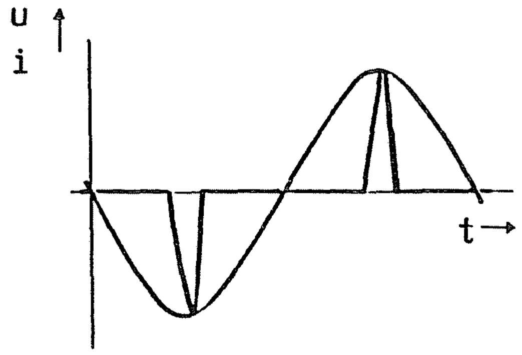

Fig. 2. Typical line voltage and input current waveforms

Choosing the correct value for capacitor C in *Fig. 1*, one can achieve low ripple of the V_{out} voltage and its average value is near to the peak value of the line voltage. In this case the current through the rectifier diodes flows for only a little part of the half-period and its peak value is very high. The current pulse generated in this way has high harmonic content and results in a reduced power factor.

The low power factor and respectively the high harmonic content of the input current imply respectable disadvantages on the consumer side and numerous problems on the AC line;

- The maximum power available to the consumer is less than the specified value for the AC outlet.
- The losses in the transmission and distribution lines, and transformers are lusher. The current harmonics will generate 'real power' on the internal resistance of the line.
- The third harmonic of the current does not cancel in the 4–wire 3–phase system, it may produce excessive neutral currents. The neutral line designed only for the equalizational currents can be overheated and make fire.
- The current pulse can cause clipping of the voltage waveform due to the finite line impedance. This voltage distortion may disturb the operation of other equipment.
- High harmonic voltages may be generated due to the resonances of the inductances and capacitances of the system. As a result, the peak value of the line voltage and current increase and as a consequence, the line circuit breakers may trip unnecessarily, the capacitors of compensation stations may be damaged.
- The harmonics may cause low frequency EMI.

The problems listed above are known as the energetical disturbances. The frequency range of the energetical disturbances extends from 0 Hz to 2500 Hz [1, 2, 3, 5].

3. The Planned IEC 555–2 Standard

In the field of energetical disturbances there is no prevailing standard neither in the former COMECON countries nor in the European Community that rules the amplitude and the distortion of the current harmonics on the AC line. After June 1994, in some members of the European Community the complement to the IEC 555–2 standard will be binding on all parties nevertheless the IEC 555 proposal has already been existing [1].

The planned IEC 555–2 (77A–60) standard [4] classifies electrical equipment according to the following classes:

Class A: 3–phase equipment and any other equipment that do not fit into the classes below,

Class B: portable tools,

Class C: lighting equipment,

Class D: equipment having the current waveshape shown in *Fig. 3.*

Note: the input current waveshape is within the shaded area in 95% of the time in each half-period [3, 4, 5].

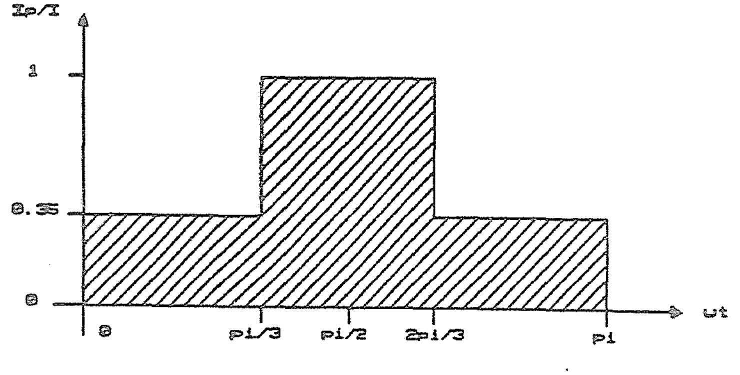

Fig. 3. Current waveform mask for class 'D'

The off-line power supplies belong to class D of the IEC 555–2 standard. The equipment classes defined above relate to the following harmonic limits in *Fig. 4.*

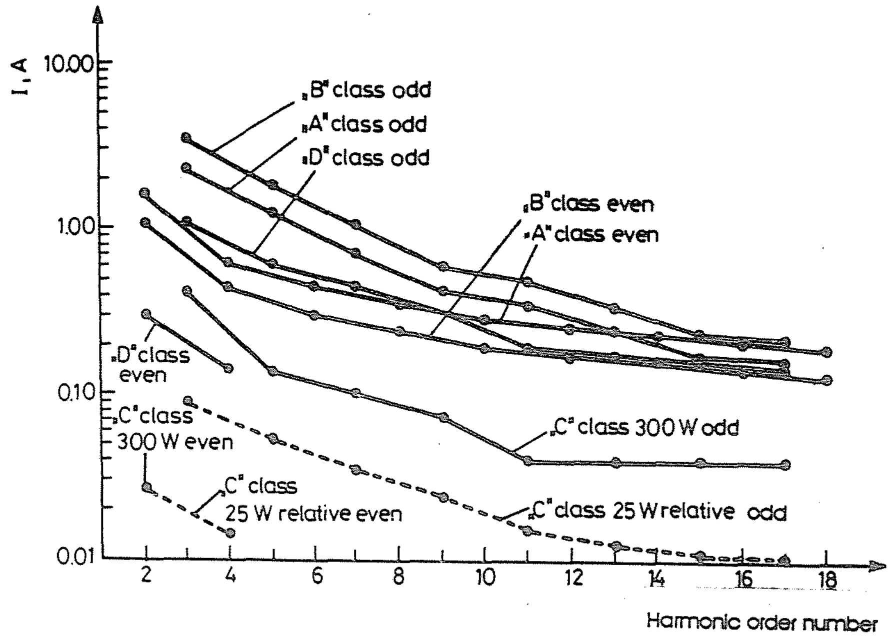

Fig. 4. The IEC 555–2 standard plan

4. Power-Factor Correcting Methods

In order to solve the problems mentioned earlier and to satisfy the harmonic limits of the standard, there are several power-factor correcting (PFC) methods available. Three of the most-used techniques for PFC are passive correction, active high-frequency correction and active low-frequency correction.

Passive PFC techniques shape the input current wave by using a passive input filter consisting of inductors and capacitors. This is the reason why the passive correctors have the greatest reliability among PFC's. This method is effective as front-end box, where the system has an uncorrected power supply, and for cases when the PFC must be implemented without altering the power supply.

Because it operates at the 50 Hz line frequency, the passive filter requires relatively large inductors and capacitors to reduce the low frequency harmonic currents. To produce power factors of 0.90 or greater, sophisticated filters are needed. It is very difficult to achieve power factors of 0.95 or higher with passive filters. There is another problem associated with the very large currents that may circulate in the filter.

Nevertheless, the passive filter can be an effective PFC solution in cases where line frequency, line voltage and load are relatively constant [2, 5, 6].

The active PFC is a better solution compared to the passive method. The circuit is an integral part of the power supply's front-end, performs much better, and is significantly smaller and lighter. Active high-frequency (HF) correction circuits typically operate at switching frequencies of 20 kHz to 100 kHz, far higher than the line frequency, to permit a large reduction in the size and cost of filter elements. HF-circuit functions include switch control of input current flow, filtering of the HF switching, feedback sensing of the source current for waveform control, and feedback control of voltage.

The main disadvantage of active high frequency PFC is the complex circuitry that reduces the reliability, and increases both size and cost. But the technique achieves a power factor of 0.97 to 0.99 with very low harmonic distortion, produces a regulated DC-bus, and provides operation over a wide input voltage range of 90 to 264 V AC [5, 9, 10].

The features of the active low frequency PFC will be described through a concrete solution in the second part of this paper.

5. Active Low Frequency PFC with Phase-Controlled Rectifier

In high power equipment the input full-wave bridge rectifier (*Fig. 5*) often consists of silicon controlled rectifiers (SCR's). The desired output voltage of the rectifier can be regulated by advancing or retarding the firing angle of the SCR's. Because of the phase-control, the input current is discontinuous, distorted, and the fundamental current lags to the line voltage so the power factor is reduced [7, 8].

The converter operates as a standard rectifier. In order to produce the phase-control signal, the error amplifier generates an error signal according to the difference of the output voltage and reference voltage. The comparator compares this signal with a saw waveform synchronized to the zero-crossing of the line voltage. This produces the firing angle signal that the driver uses for the push-pull driving of rectifier bridge.

In practice this circuit is a low frequency, voltage step-down AC-to-DC converter. In order to produce stable output voltage, L_0 can have any arbitrary value in a given range. The role of L_0 is to smooth the ripple of the output voltage and to reduce the peak value of the input current.

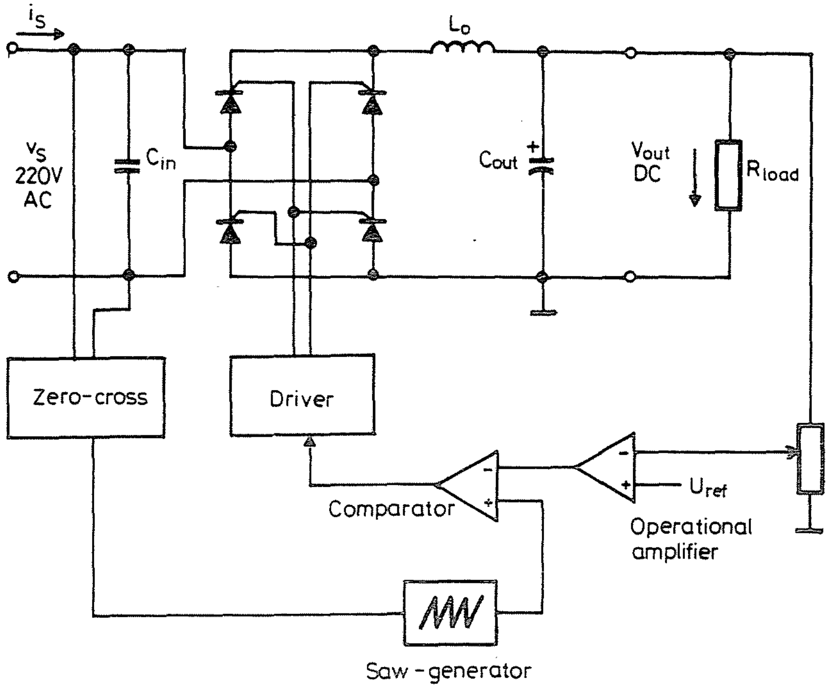

Fig. 5. Block schematic of the low-frequency power-factor corrector

By choosing the optimal value of L_0 inductance that also determines the value of the firing angle, the minimum harmonic content of the input line current can be reached.

We have been working on a development project to design a power supply with the following specifications:

input voltage	$v_{in} = 220$ V AC $+10/-15\%$
output voltage	$V_{out} = 158$ V DC
ripple	$v_{rp} < 15$ V (100 Hz)
output power	$P_{out} = 500$ W
distortion	according to class D
power factor	of the IEC 555–2
displacement	PF > 0.90
power factor	

In this case, according to the harmonic limits of class D of the IEC 555–2 standard, the distortion power factor has to be PF$>$ 0.845.

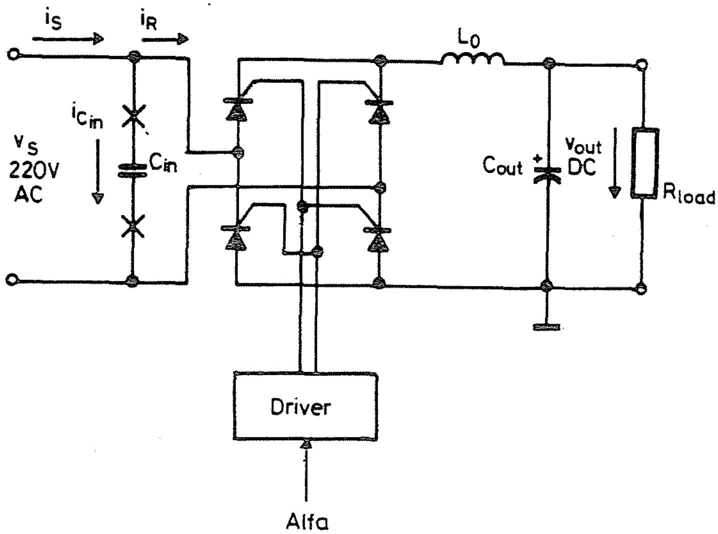

Fig. 6. Network for the analysis

6. Analysis for Maximum Distortion Factor

In order to determine L_0 and the firing angle values, a series of analysis were made by the MICRO–CAP II electronic circuit analysis program. To achieve the optimum choice, the harmonic distortions of the input current and the output voltage were examined. At first, a transient analysis was done by the program to get the input current and output voltage waveforms and then for the input current waveform a Fourier analysis was performed. The distortion factor and the phase-lag of the fundamental current given by the Fourier analysis were used in the evaluation of the power factor. For the analysis the network in *Fig. 6* was created. During the first examinations C_{in} was not in the network.

Table I

v_S	220 V AC
f_S	50 Hz
R_{line}	0.1 Ohm
C_{out}	660 μF
R_{load}	50 Ohm
α	1° to 50°
L_0	1 mH to 500 mH

During the series of analysis only the value of one circuit component was always changed through a series of monotonically increasing steps with all others held constant. *Table I* shows the set of values used in the analysis. The values of v_S, R_{line}, C_{out}, and R_{load} were the same during the whole series of analysis. For each of the following six constant values of the firing angle $\alpha = 0°$, $10°$, $20°$, $30°, 40°$, and $50°, L_0$ was logarithmically incremented through 30 values beginning with 1 mH and ending with 500 mH. *Fig. 7(a),(b)* and *(c)* show the rectifier performance characterized by the displacement power factor $\cos\phi_{R(1)}$, the distortion power factor $I_{R(1)}/I_R$, and the total power factor PF_R, as a function of α and L_0.

Examination of *Fig. 7* shows that the displacement power factor $\cos\phi_{R(1)}$ and the distortion power factor $I_{R(1)}/I_R$ conspire to keep the rectifier total power factor $PF_R < 0.90$ regardless of L_0 and that PF_R becomes progressively smaller for larger α values.

The distortion power factor $I_{R(1)}/I_R$ has a local maximum, but it should not be chosen for optimum operating point of the rectifier. With the change of α and L_0 the output voltage changes continuously so in *Fig. 7(b)* the constant voltage curve belonging to the desired output voltage $V_{out} =$ 158 V was drawn. The control circuit of the rectifier depending on L_0 regulates α according to this curve. In order to minimize the harmonic contents of the input current, $L_0 = 102$ mH and $\alpha = 50°$ were chosen as the operating point. The distortion power factor is 0.97 that satisfies the IEC 555–2 standard. The current and voltage waveforms are shown in *Fig. 8*.

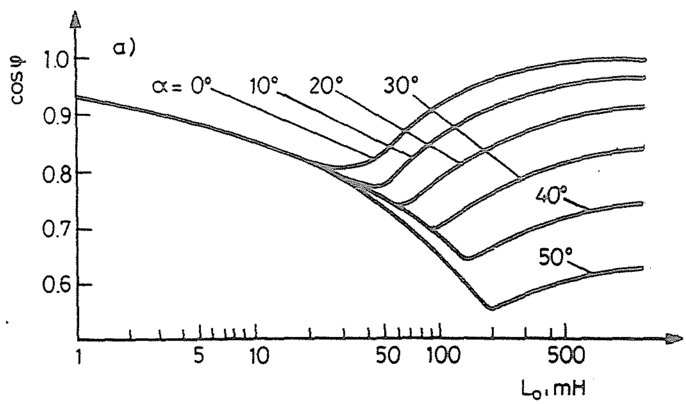

Fig. 7. (a) Displacement power factor as a function of L_0 and α

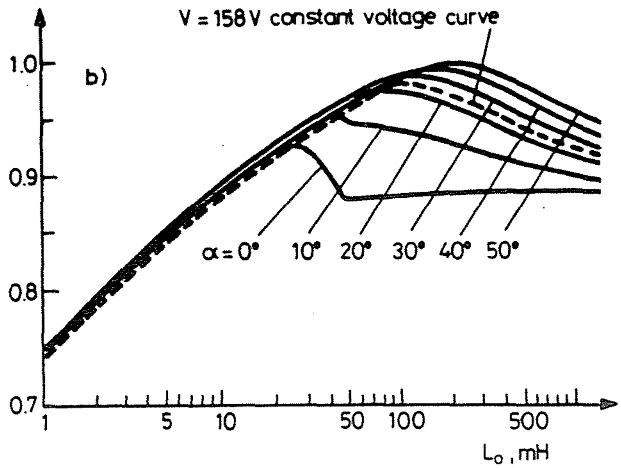

Fig. 7. (b) Distortion power factor as a function of L_0 and α

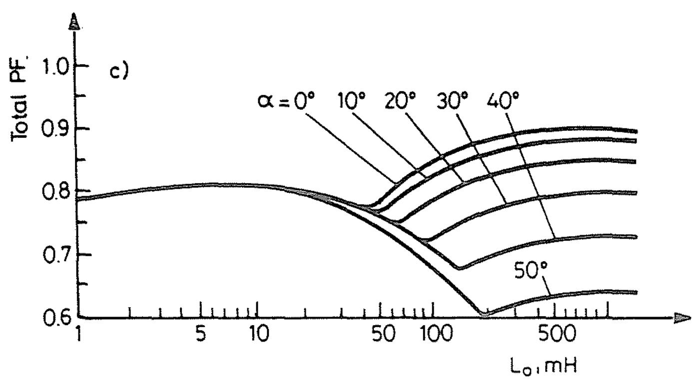

Fig. 7. (c) Total power factor as a function of L_0 and α

7. Correction of the Displacement Power Factor

The role of the input capacitor C_{in} shown in *Fig. 6* now becomes obvious. The Fourier analysis is used to decompose i_R into fundamental $i_{R(1)}$ and the higher-order harmonics. The $i_{R(1)}$ fundamental current component can be further decomposed into a component in phase with v_S and a component that lags v_S by 90°. As determined from $i_{R(1)}$, a capacitor value $C_{in} = 40\mu$F is selected to draw an i_{Cin} which leads v_S by 90° and cancels the 90°- lagging component of $i_{R(1)}$. The optimum waveforms of v_S, i_{Cin} and i_S are shown

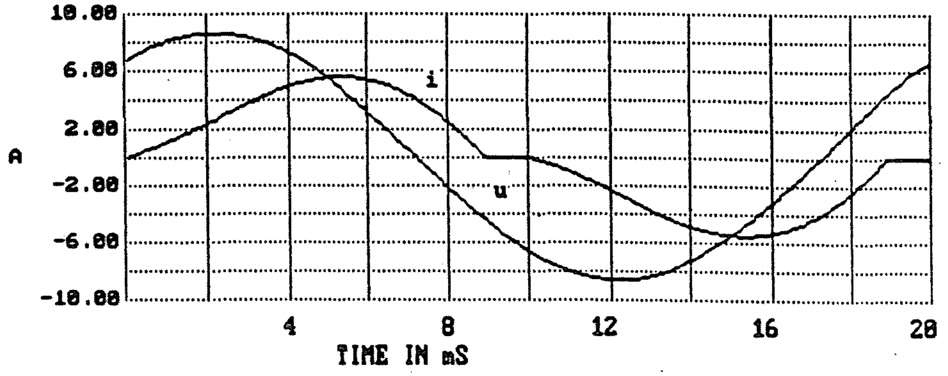

Fig. 8. Performance at the operating point

in *Fig. 9.* The source delivers power with $\cos\phi_{S(1)} = 1$, $i_{S(1)}/i_S = 0.95$, and $PF_S = 0.95$. Therefore, the optimization method to reach the maximum total power factor of a single-phase AC–to–DC converter with a phase-controlled rectifier is to minimize the harmonic content of i_R and ultimately of i_S by proper selection of the rectifier operating point and correction of the displacement power factor with C_{in}.

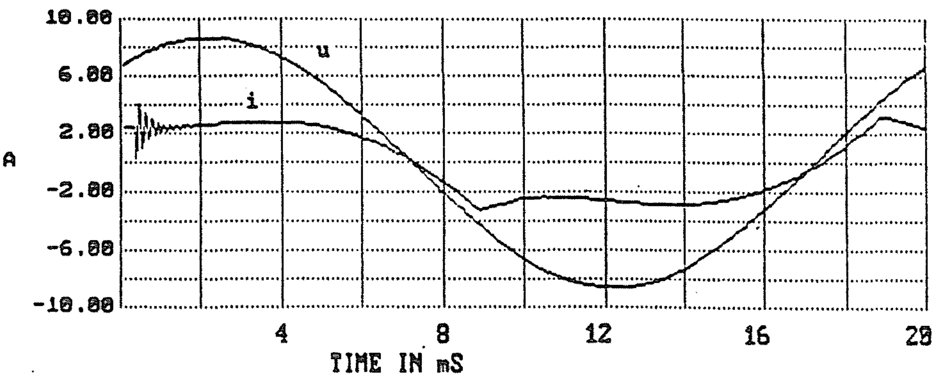

Fig. 9. The input current and line voltage waveforms at the operating point with displacement power factor correction

8. Power Factor as a Function of Line Voltage

Because the analysis was produced at the nominal value of the line voltage, another analysis was made to examine the behaviour of the phase-

controlled PFC in the range of 187 V to 242 V according to the specifications
(220 V +10/−15%). *Fig. 10* shows the displacement power factor ($\cos\phi_S$), the distortion power factor ($i_{s(1)}/i_s$) and total power factor PF as a function of V_S. The output voltage was held constant at V_{out}= 158 V. The distortion power factor decreased a little, but never went under the limits of the IEC 555–2 standard. The displacement power factor $\cos\phi_s$ also decreased with the change of the line voltage because of the change of the 90° lagging component of $i_{R(1)}$. Finally it can be stated that the total power factor did not change considerably, the circuit corrected the total power factor significantly beside regulating the voltage.

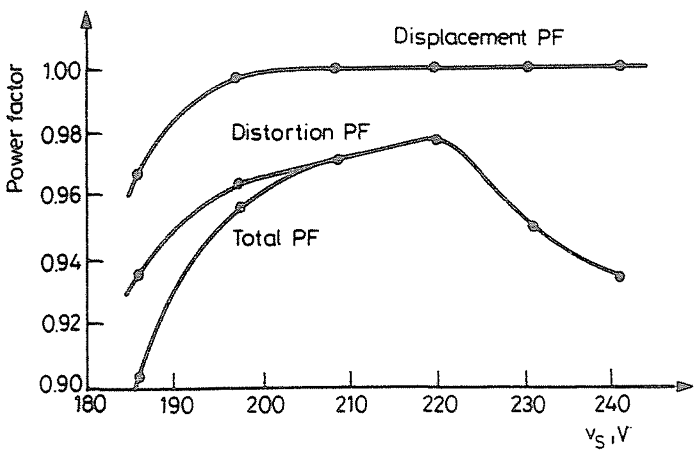

Fig. 10. Displacement, distortion, and total power factors as a function of load

9. Conclusions

This paper describes an active low frequency, single-phase power-factor corrector based on phase-controlling. The optimization problem of the smoothing inductance and the firing angle to reach the maximum power factor was solved with the help of MICRO–CAP II electrical circuit analysis program. Due to the non-linear features of the examined system, an analytical solution would be very difficult to achieve. That is why the simulation method was used to find the optimum choice.

The first step of the optimization method is to determine the possible operating points of the circuit depending on the inductance value and the firing angle at the conditions of nominal line voltage and nominal load. Second, the optimal operating point can be chosen from the constant voltage curve of the desired output voltage. Finally, the value of the phase-correcting capacitance has to be determined.

The main advantages of the examined converter compared with other methods are the simplicity and high reliability beside the high power factor correcting efficiency. There is no high-frequency EMI due to the low switching frequency. The converter has regulated DC output. The main disadvantages of this converter are the large volume and the heavy weight due to the use of the line-frequency components. There is no galvanic separation between the source and load. The circuit has slow response to source and load transients.

Therefore due to the simplicity and robustness of this converter, it is suitable for fixed-location, long-life, high-reliability applications [7, 8].

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