AN ECONOMIC COMPARISON OF SOME OF THE OPTIONS FOR IMPROVING THE POWER FACTOR OF LARGE INDUSTRIAL INSTALLATIONS

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ABSTRACT

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Energy reserves are diminishing at an increasing rate, and if society is to maintain or improve the present standard of living, then energy conservation must be included in our way of life.

Power factor improvement conserves energy by reducing the demand on Utilities, and this paper discusses some of the options that are currently available.

Graphs indicating the relative costs of some of the available options are presented here, in an attempt to standardize the method of selecting the most economical option.

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I. INTRODUCTION

Electrical power affects every aspect of an industrialized society, and since unscheduled outages can result in millions of dollars being lost, then supply must at least equal the demand, which tends to increase as the society develops.

Unfortunately, energy resources are limited, and the possibility of the demand for power exceeding the supply capabilities of the utilities is becoming a reality.

Reactive power is necessary to supply the excitation current requirements of alternating current equipment, and must additionally be generated in sufficient quantities to cover system losses, and to maintain reasonable voltage levels on the power system. The reactive power required is a function of the overall power factor of the system, and the problem can be appreciated more readily, when it is considered that an installation with a nominal requirement of 100 MW at 0.8 pf (lag) requires 75Mvar of reactive power, and is therefore equivalent to a requirement of 125 MVA.

The annual budget of any electrical utility for generating reactive power (or imaginary power, as it is often inappropriately termed) will clearly show the costs involved in generating this power, (and indicate that it is a real quantity). Industrial customers can therefore expect to pay their portion of the costs involved in producing this power.

I <u>INTRODUCTION</u> cont'd.

Utilities have traditionally used a rate structure that is dependent on the power factor as a means of recovering some of the costs involved, and as an incentive, to encourage customers to improve the power factor of their installations. The operating power factor of the installation was generally left up to the individual customer, based on the economics of generating reactive power locally, as opposed to paying the penalties for not doing so. This choice was traditionally considered to be the right of the customer.

Utilities are no longer able to supply economically, all of their reactive power requirements, since the economics and reliability criteria of real power generation have resulted in such installations being relatively large, and located remote from the load centers. This has resulted in a decrease in the effectiveness of the generators themselves as sources of reactive power. Additionally, with an increased public awareness of energy conservation, there has been a slowdown in the rate of expansion of generation facilities, with the demand for electricity continuing to increase at approximately 10 percent per year. The solution to this problem is to maximize the use of currently available generation facilities, with one method being to generate reactive power locally, at the load centers.

A modified energy contract is now becoming evident, whereby utilities insist on an installation being operated at a stipulated minimum power factor or better, with no concessions being granted for operation above the stipulated minimum value, and severe economic penalties being imposed for operation below the value. Such contracts effectively remove the right of determining the optimum power factor of an installation from the individual user.

This report will concentrate on mandatory minimum power factor contracts, and their effect on the design of installations.

II GENERAL CONSIDERATIONS IN POWER FACTOR IMPROVEMENT

Reactive power produced by the utility generators is supplemented by reactive power from sources such as high voltage lines, and interconnections. Additional reactive power is required by the utility so as to compensate for system losses, and to maintain reasonable voltage levels on the system.

Large industrial installations generally operate at several voltage levels, and utilize large numbers of induction motors. This usually results in a relatively low power factor, and reactive power must then be generated and injected into the system if the power factor is to be improved. Several methods are available for improving the power factor of industrial installations, including synchronous capacitors, synchronous motors, and static devices; however, both economic and technical considerations apply to the selection of a particular method, and it should be remembered that the most economic solution will not always be technically best.

Before discussing the selection of an acceptable method of generating reactive power, it may be benificial to describe some of the effects of a power factor improvement scheme. These include:

(a) Release of system electrical capacity;

(b) Lower system losses;

(c) Improved voltage profile;

It may also be useful to discuss:

(d) Energy contracts.

Release of system electrical capacity

System capacity normally tied up in producing reactive power can be released to produce active power, by generating reactive power separately; and as an example, consider a transformer nominally rated at 100 MVA, supplying full load at 0.6 pf lag.

It is possible to increase the connected load to this transformer by 35.4 percent (i.e. 35.4 percent additional load at 0.6 pf lag), if 50 Mvar of reactive power is generated separately. Additionally, the overall power factor of the installation will be improved to 0.81 lag (combination of old load + new load + reactive power generated).

The additional load that may be connected, without exceeding the rating of the equipment is determined by the equation:

$$\left[MW_1 + MW_2\right]^2 + \left[(Mvar_1 - Mvar_3) + \tan(\cos^{-1}\phi_1)\, MW_2\right]^2 = MVA^2 \quad (1)$$

1 - Original load

2 - Additional load

3 - Reactive power generated

II GENERAL CONSIDERATIONS IN POWER FACTOR IMPROVEMENT

Release of system electrical capacity cont'd.

Figure 1 shows the percentage of additional load at the original power factor, that may be connected, without exceeding the full load ratings of the substation.

Lower System Losses

Power factor improvement results in lower system currents (for the same connected load), and hence system losses will reduce. Losses vary as the square of the current and therefore:

$$\text{Loss} = L = K/(\cos \phi)^2 \tag{2}$$

K = System constant

hence the percentage loss reduction equals

$$LR = 100 \left[1 - (\cos \phi_1 / \cos \phi_2)^2\right] \text{ percent} \tag{3}$$

The resultant energy savings will not usually justify the costs involved in improving the power factor, but since the initial assumption is that such improvement is mandatory, then the resultant energy savings can justifiably be deducted from the cost of improving the power factor.

ELECTRICAL CAPACITY RELEASED AS A
FUNCTION OF REACTIVE POWER GENERATED

NOTES

(1) ALL FIGURES ARE SHOWN IN PERCENT OF INITIAL POWER

(2) ——— ORIGINAL POWER FACTOR [$\cos \phi_1$]
- - - - NEW POWER FACTOR [$\cos \phi_2$]

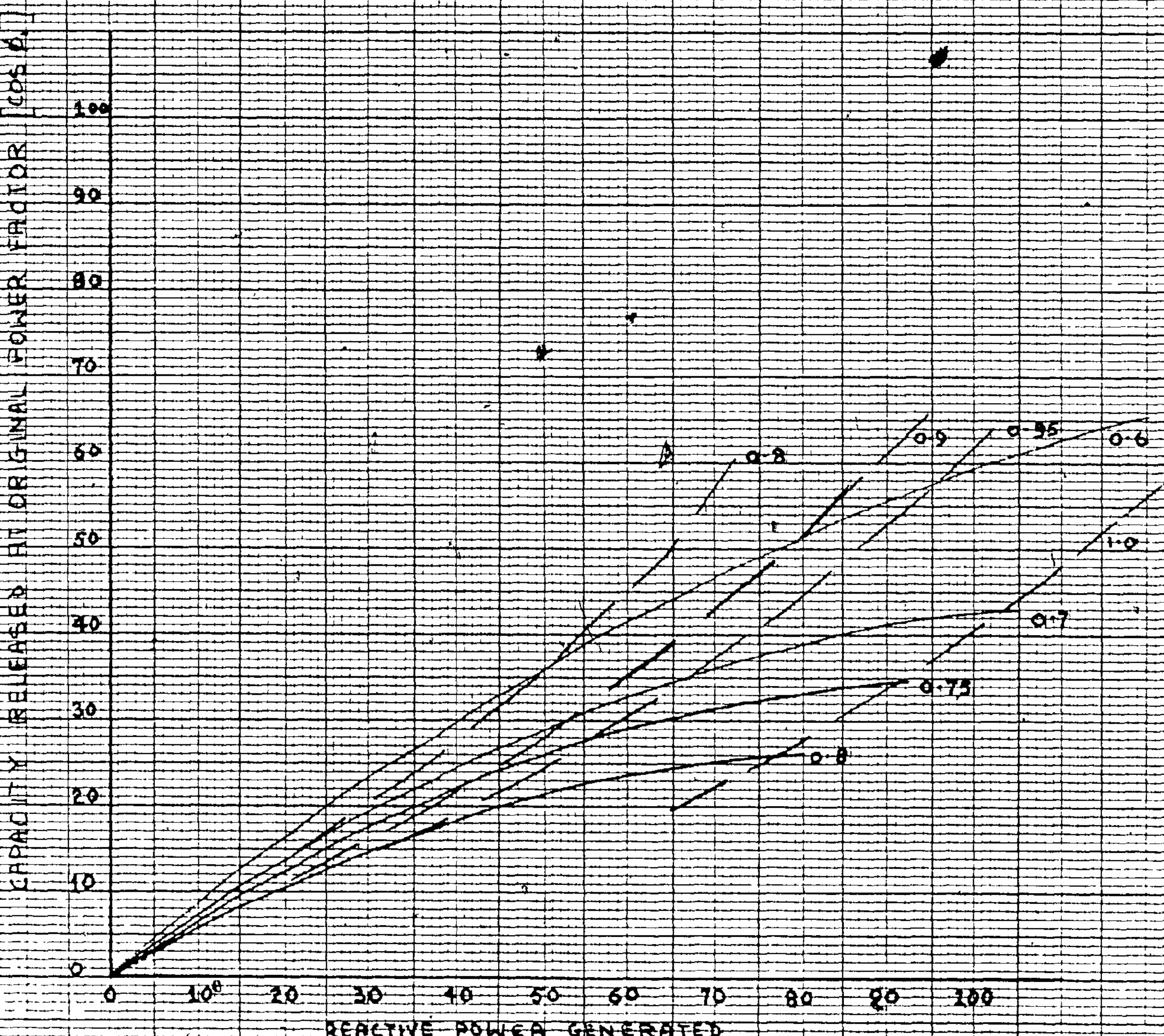


FIGURE 1

Improved voltage profile

Any measures taken to improve the power factor of an installation causes a voltage rise at the terminals of equipment connected to the system. This results in a more effective utilization of the equipment, and will probably reduce maintenance costs. It is very difficult to attach a dollar value to this effect, and it can be considered as being a bonus.

Energy contracts

Before suggesting that reactive power be generated locally (at the installation), it must first be determined that this is necessary. The uncompensated power factor of the installation can be estimated manually; however, a more accurate assessment of the power factor may be obtained by performing a load flow study. Since such a study will normally be required to determine transformer tap settings, circuit breaker overload settings, cable sizes, etc., it can prove economical to use one of the several relatively inexpensive computer programs that are available for this purpose.

The ratio of the reactive to thermal power (vars to watts) demanded from the utility will be an indication of the uncompensated power factor.

II GENERAL CONSIDERATIONS IN POWER FACTOR IMPROVEMENT

Energy contracts, cont'd.

The amount of reactive power that should be generated locally, will depend to a very large extent, on the energy contract that is agreed upon by the utility.

Generally, the two types of energy contracts enforced are:

(a) The rate structure is dependent on the power factor, and usually such as to make it economically feasible to operate the installation at some improved power factor; and

(b) A mandatory minimum operating power factor is stipulated by the utility. Severe economic penalties will be imposed for operation of the installation below the set power factor, and there are no incentives for operation above the set value.

Energy contracts applicable to existing installations are generally of type (a); however, type (b) contracts are becoming more predominant, and at least one major electrical utility will soon be enforcing a mandatory minimum power factor of 0.95 lag on new installations.

The use of type (a) contracts introduces an additional variable in the determination of the optimum operating power factor of the installation, Energy contracts cont'd.

and additionally, depends largely on the final form of the contract, (which can vary considerably). Since it is becoming less predominant, it is not intended to discuss the implications of such contracts here.

Type (b) contracts specify the minimum acceptable operating power factor, and additionally eliminates the problems associated with determining the optimum power factor. Using such contracts, it is necessary to determine first the amount of reactive power that must be generated locally, and second the most economical method of generating this power.

As was previously mentioned, a load flow analysis can usually be used quite effectively to determine the amount of reactive power that should be generated locally, and also, to determine its effect on the overall power system.

Several methods are currently available for generating reactive power. These will now be discussed.

III OPTIONS AVAILABLE

The methods currently available, and generally acceptable as being suitable for supplementing the reactive power requirements of industrial installations include:

(a) Synchronous motors
(b) Synchronous capacitors
(c) Shunt capacitors

using either conventional switching techniques or thyristor control.

Synchronous motors

Synchronous motors, when operated with an underexcited field, can be considered to operate similar to induction motors, in that they require reactive power. When the field of the motor is overexcited, it operates at a leading power factor, and may then be considered as a reactive power generator.

The reactive power generated in this manner is available for use elsewhere in the system connected to the terminals of the motor, and is a function, not only of the excitation, but of the load as well.

Figure 2 shows typical curves for such a motor.

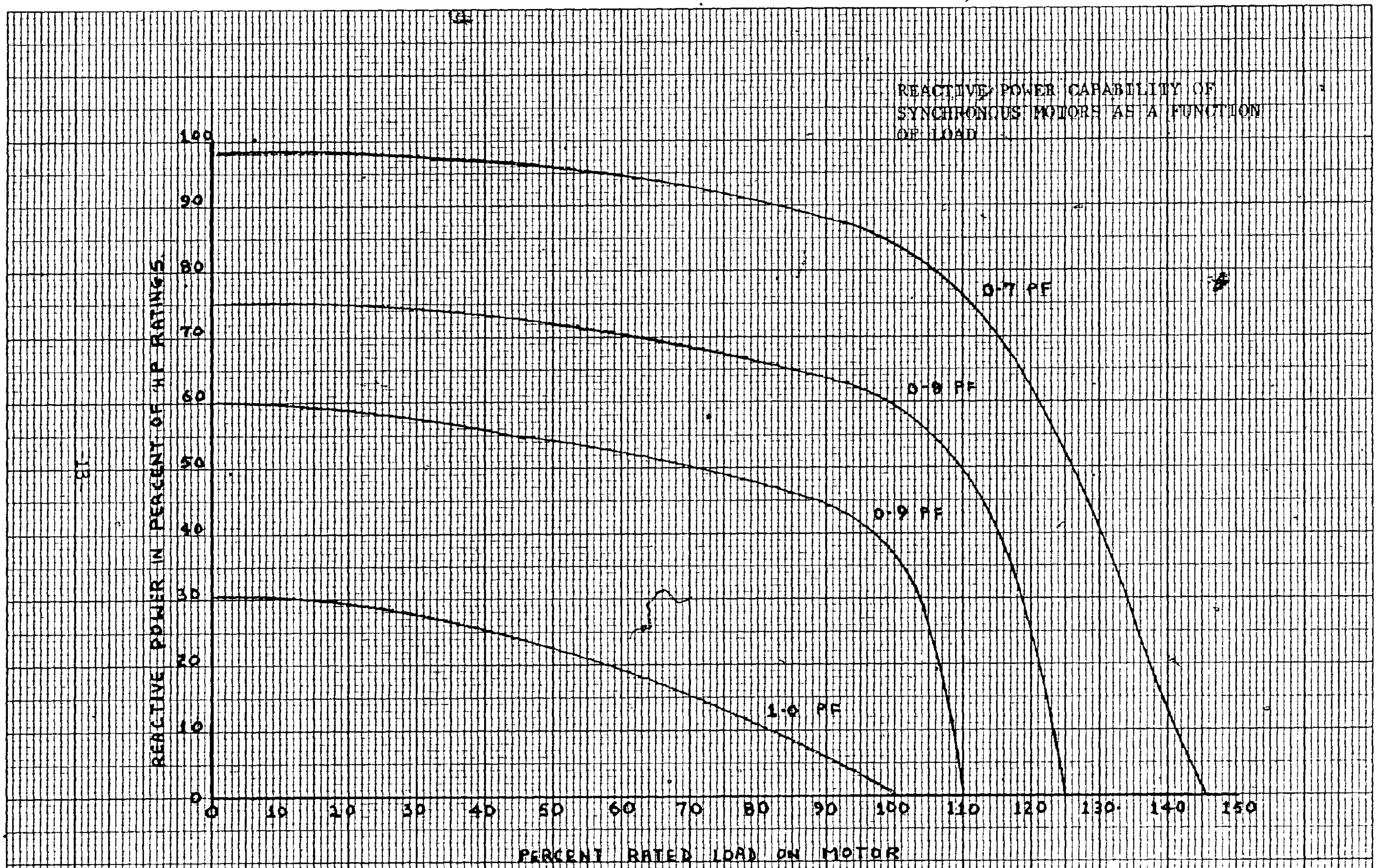

REACTIVE POWER CAPABILITY OF
SYNCHRONOUS MOTORS AS A FUNCTION
OF LOAD
REACTIVE POWER IN PERCENT OF HP RATINGS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0.7 PF
0.8 PF
0.9 PF
1.0 PF
PERCENT RATED LOAD ON MOTOR

FIGURE 2

III OPTIONS AVAILABLE

Synchronous motors cont'd.

The use of overexcited synchronous motors reduces the overall reactive power requirements of the installation, and it is quite conceivable that the reactive power generated in this manner will be sufficient to improve the operating power factor to well above any contractual requirements.

As an example, consider an installation requiring 100 MVA at 0.78 pf lag which includes the use of 6 induction motors of 7250 Hp, 0.8 pf lag each. Assuming that these motors were replaced by equivalent synchronous motors, and operated at full load, 0.8 pf lead, then, from Figure 2, a total of approximately 26 Mvar of reactive power may be generated, together with an associated reduction in the reactive power requirements of the installation, from 62 Mvar to 10 Mvar.

The load requirements of the installation reduces to 78 MW and 10 Mvar, with the overall operating power factor being improved to 0.99 lag.

Technical considerations that will affect the choice of motors include system stability, and overall plant reliability, since production will be affected.

III OPTIONS AVAILABLE

Synchronous motors cont'd.

Synchronous motors are constant speed devices (assuming a constant supply frequency), and the operation is more "rigid" than that of an induction motor; i.e., fluctuations in the supply voltage, frequency, or load, may cause irregular running, instability, and breakdown. As an example, the constancy in speed of a synchronous motor does not permit rapid fluctuations of the load to be absorbed and supplied by the flywheel effect of the rotating parts. Therefore, these load fluctuations may cause large variations in torque and current. This inherent instability of the synchronous motors should be thoroughly investigated, since it can adversely affect the overall reliability and production output of the plant. Additionally, synchronous motors are more expensive than induction motors of comparable rating, and because of the auxiliary equipment required, a more rigorous maintenance program would have to be set up.

Generally, synchronous motors are used in preference to induction motors only in situations where either constant speed is essential, or high outputs at low speeds are required (the efficiency is higher).

Synchronous capacitors

Synchronous capacitors are essentially synchronous motors designed to

III. OPTIONS AVAILABLE

Synchronous capacitors cont'd.

run unloaded, and overexcited, and serve as a load, on power systems with a lagging power factor, Overexcited synchronous generators can also be similarly used.

Synchronous capacitors have been used extensively by utilities as a means of providing reactive power to the system; however, because of high costs, operating losses, and maintenance requirements, additional synchronous capacitors have not generally been installed on power systems in recent years.. These comments are equally applicable to industrial installations.

Synchronous generators connected to industrial power systems are usually sources of emergency power, and if these units are provided with a clutch arrangement, they can be used to generate reactive power. Such usage will require that the generators be operated continuously, and this can result in a dramatic decrease in the reliability of the emergency power system.

Use of synchronous capacitors as a means of improving the power factor of industrial installations is therefore, not generally recommended.

III. OPTIONS AVAILABLE cont'd.

Shunt Connected Capacitors

Power capacitors may be considered as reactive power generators in that they are capable of supplying the magnetizing requirements (vars) of induction devices when connected in shunt, with them.

Two methods of utilization are possible:

(a) connected in shunt with induction motors; and,

(b) connected in shunt with the supply buses.

These two methods are described here:

(a) Capacitors in shunt with induction motors

Induction motors are among the prime users of reactive power, and capacitors can be used to supply the required vars, and so improve the power factor. Various connections are possible, as shown in Figure 3, with connection (a) being the preferred method, and (b) the second choice.

This technique for power factor improvement is quite feasible, and has been successfully used on several installations; however,

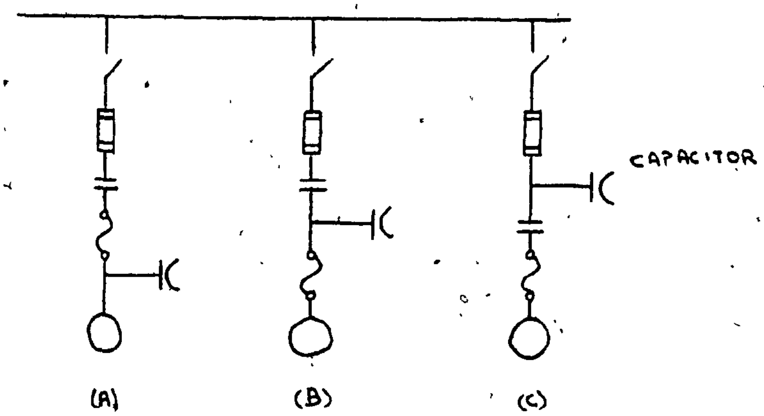


FIGURE 3
Options for the connection of capacitors in Shunt with Induction Motors

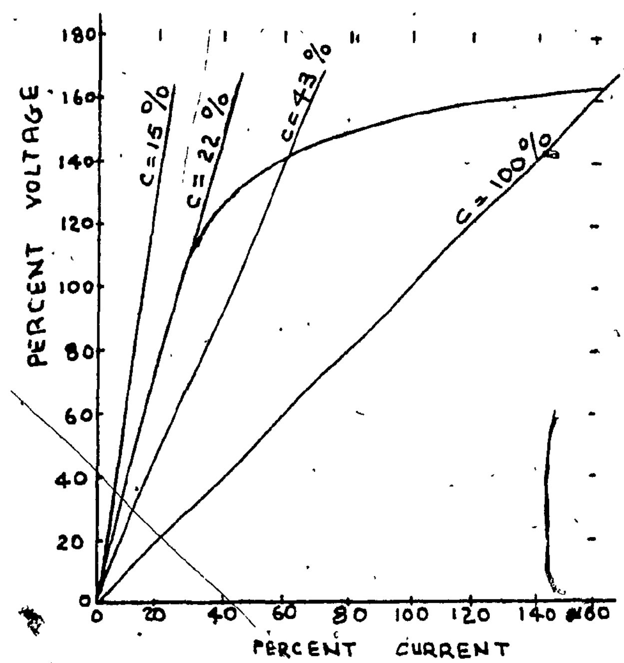


FIGURE 4
The Effect of Shunt Capacitors on the Excitation characteristics of Induction Motors

III OPTIONS AVAILABLE

Shunt Connected Capacitors

(a) Capacitors in shunt with induction motors cont'd.

problems do exist, and this method therefore requires care in application.

Induction motor shafts can be subjected to very severe transient torques if the power source is disconnected, and quickly reconnected. This is because, after disconnection, induction motors may act as self-excited induction generators, and power frequency voltages will therefore be maintained at the terminals for a period of time, depending on the time constant of the machine. The effect of shunt capacitors will be to increase the time constant of the particular motor, and the overall result will be to increase the probability of subjecting the shaft to damaging transient torques due to out-of-phase reclosing.

This effect requires careful analysis, particularly when used on high inertia drives, since it may require a modification of the motor control circuits, and may even reduce the reliability and availability of the overall system.

III OPTIONS AVAILABLE

Shunt Connected Capacitors

(a) Capacitors in shunt with induction motors - cont'd.

Figure 4 tends to suggest that it may be possible to minimize the problem by limiting the capacitor size to a value equivalent to the no load magnetizing current requirements of the motors (usually of the order of 20 percent of the motor kVA rating).

Additionally, shunt capacitors should be connected so as to derive the maximum benefit from their use, and since, on large installations operational reliability considerations often require that several motors within a plant be installed for standby operation mainly, this tends to limit the possible locations for these capacitors.

The overall result is that usually, only a fraction of the reactive power requirements of the plant can be supplied in this manner, and additional compensating equipment will therefore be required, thus increasing the costs.

III OPTIONS AVAILABLE

Shunt Connected Capacitors cont'd.

(b) Capacitors in shunt with supply buses

Large banks of capacitors may be connected in shunt with the power supply buses of an industrial system, and used to supply all of the reactive power requirements of the system. This method is widely used, and has proven to be flexible, effective, and reliable, requiring little maintenance.

Operational difficulties do exist, but these may be minimized by proper system design.

Some of the problems that may exist are:

1) Overvoltages under light load conditions.
2) Self excitation of induction motors on loss of power.
3) Improper operation of ground fault relays.
4) Capacitor unit failures caused by overloads due to harmonic currents and voltages.
5) Equipment failures caused by transient voltages and currents due to capacitor switching.

III OPTIONS AVAILABLE cont'd.

Static Compensators

These devices are a relatively new concept in reactive power compensation, and two general types are available: Static var-controlled systems (SVS) and thyristor controlled capacitors (TCC).

(a) The SVS concept is the older method, and is essentially a combination of shunt capacitors in parallel with a thyristor controlled reactor. SVS's have been used for some years on industrial networks for compensating symmetrical and asymmetrical voltage drops by rapidly modifying the power factor. These devices have been used on some installations for fast power factor modification, and for the short period considered operational experience has been good.

(b) The TCC concept is relatively new, and consists of a shunt capacitor bank, each of whose phases is in series with a thyristor switch. It is possible to vary the reactive power generated, from zero to its rated Mvar value, by varying the firing angle of the thyristors.

Reliability of this system has been good for the period considered, and it may prove to be an economical alternative to traditionally switched capacitor banks.

IV COST COMPARISONS

The selection of any particular method of generating reactive power depends on numerous factors, and both technical and economic considerations apply. The graphs presented here show the relative costs of some options available for improving the power factor of different sizes of installations. Several assumptions were made in arriving at these graphs, including:

(a) The cost differential in the maintenance of synchronous motors as opposed to induction motors, has not been included, because of the variables involved.

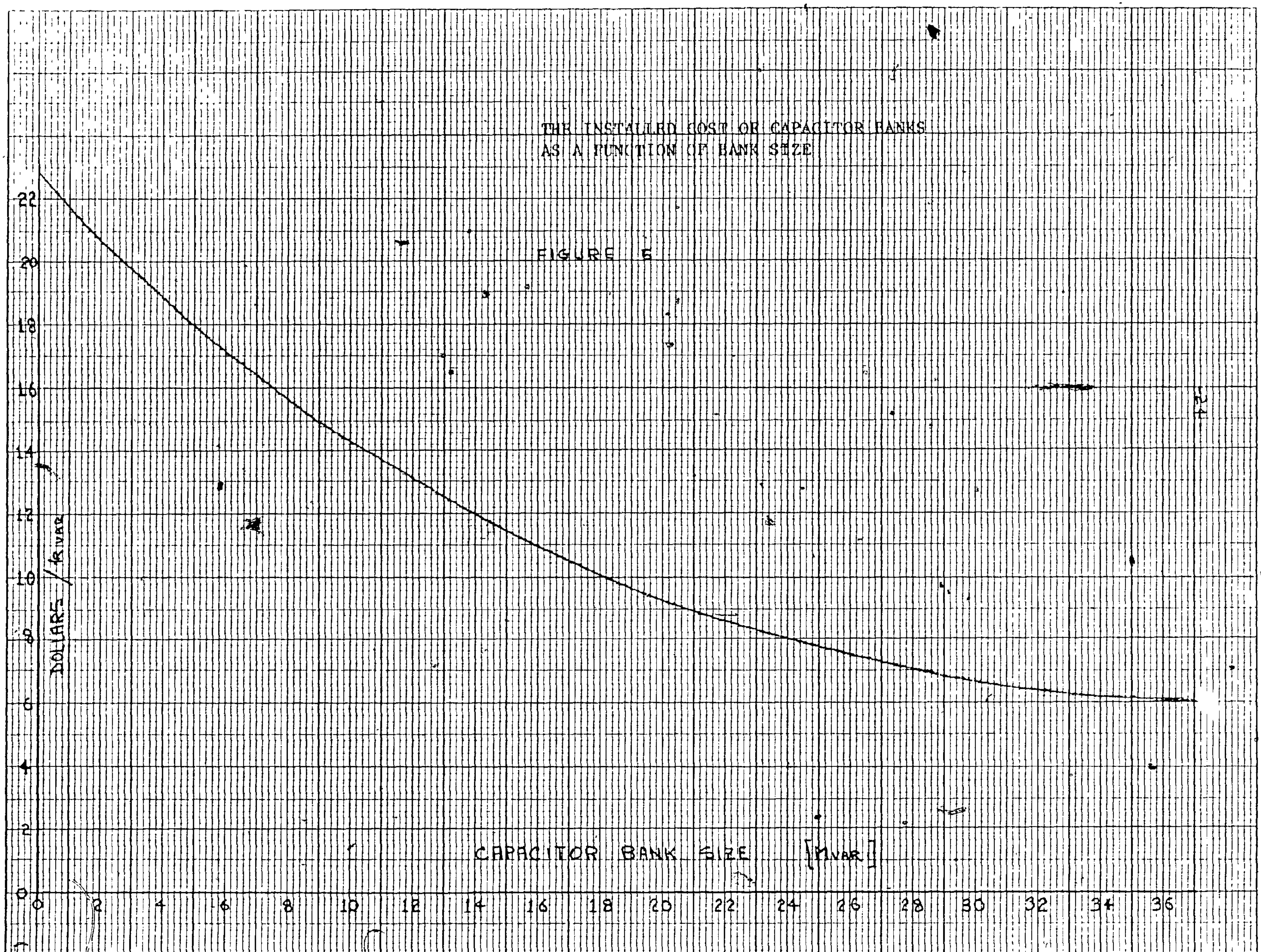
(b) The effect of voltage transformations on the reactive power requirements of the installations has been neglected.

(c) The cost of using 0.8 pf (leading) synchronous motors, was used as the base for all the calculations.

(d) Installations costs of the motors were not included in the figures, since it is felt that these costs will be the same, irrespective of the type of motor.

(e) Installation costs for capacitors were included, since these were considered to be extra.

(f) The original power factor was assumed to be 0.8 pf (lag) in all cases.


THE INSTALLED COST OF CAPACITOR BANKS AS A FUNCTION OF BANK SIZE
FIGURE 5
DOLLARS / kVAR
CAPACITOR BANK SIZE [MVAR]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36

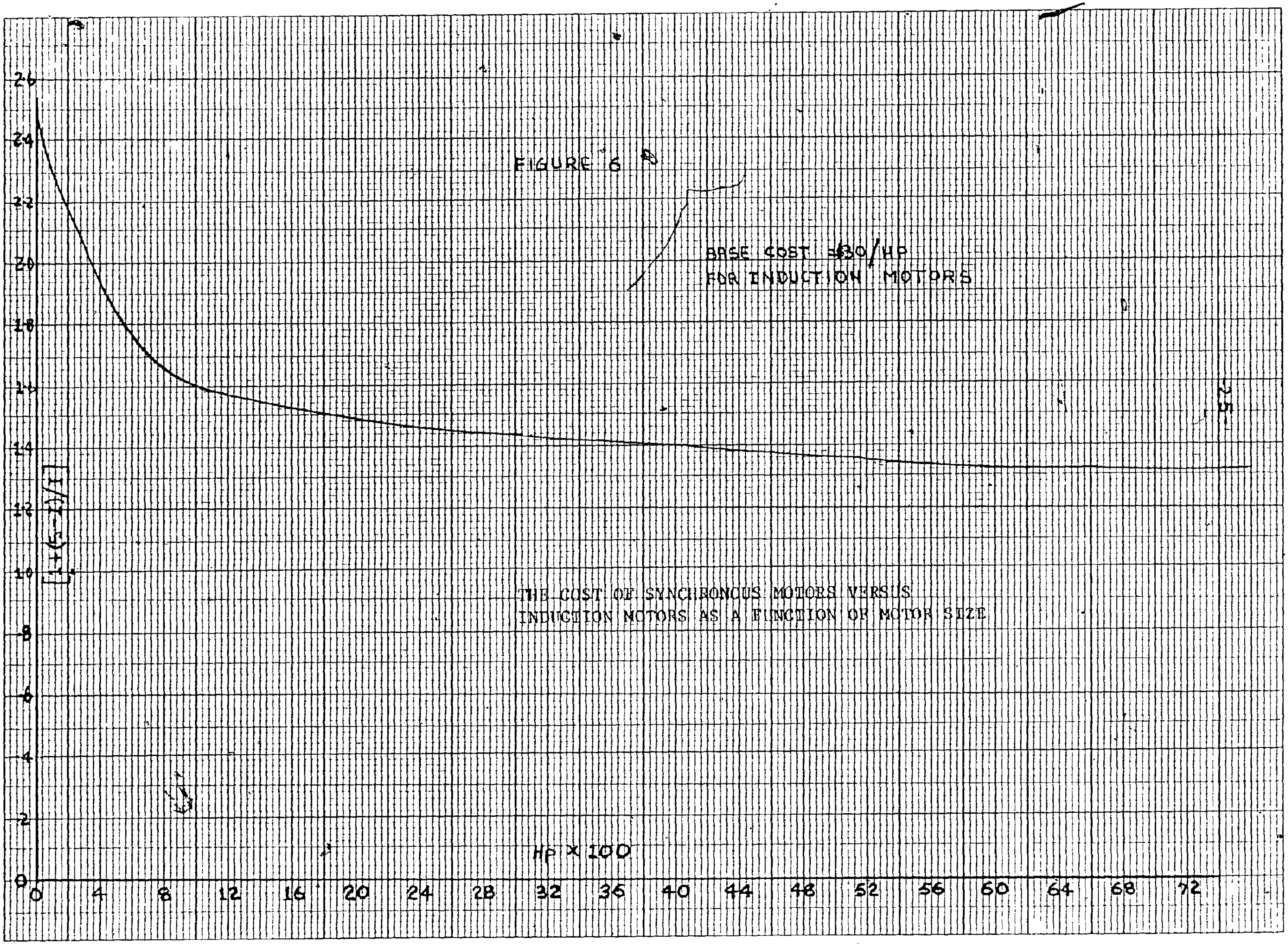


FIGURE 6
BASE COST $30/HP
FOR INDUCTION MOTORS
THE COST OF SYNCHRONOUS MOTORS VERSUS
INDUCTION MOTORS AS A FUNCTION OF MOTOR SIZE
HP X 100
[I/(I-S)+I]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
-25-

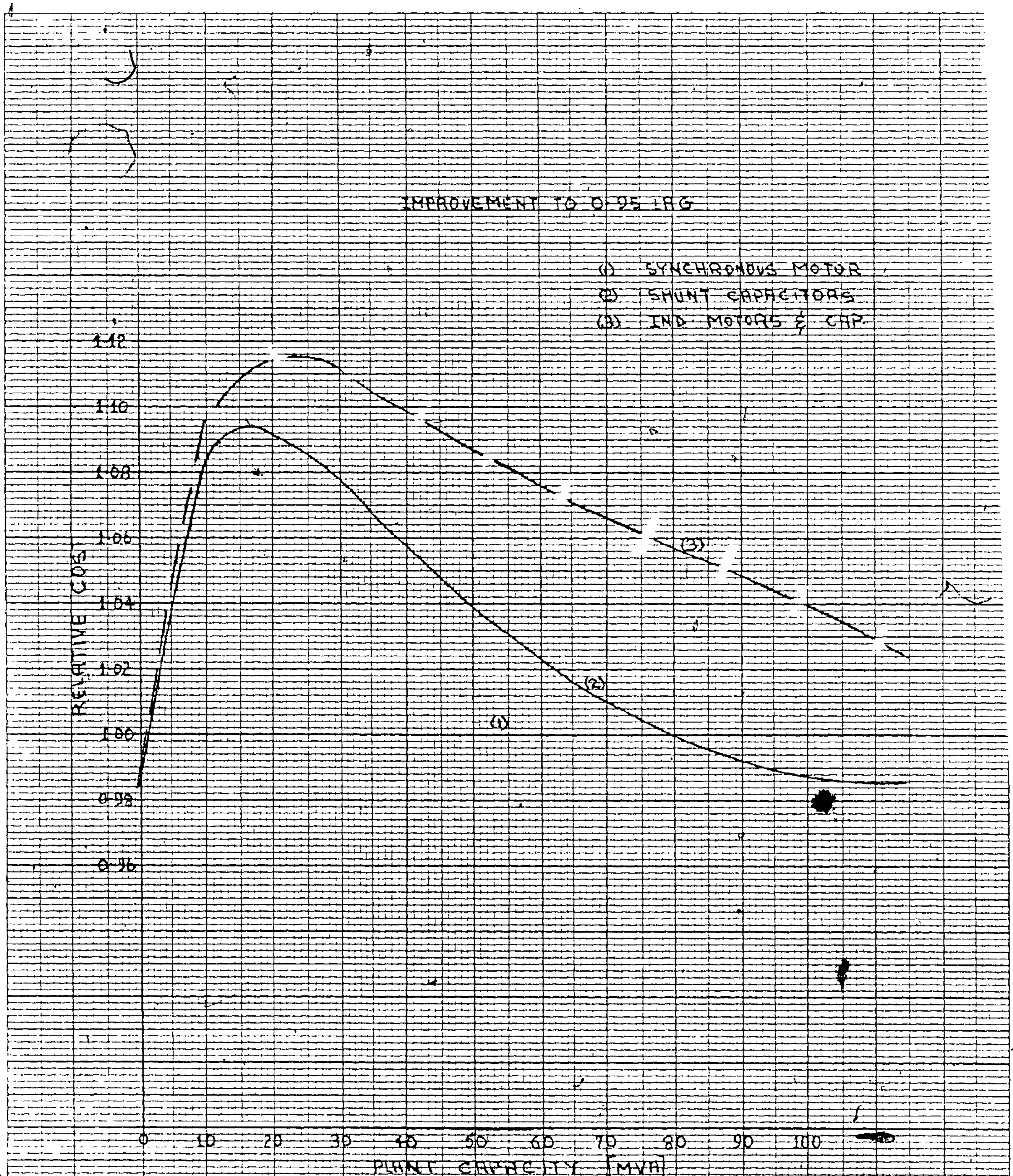

IMPROVEMENT TO 0.95 LAG
(1) SYNCHRONOUS MOTOR
(2) SHUNT CAPACITORS
(3) IND MOTORS & CAP
RELATIVE COST
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
(1)
(2)
(3)
0
10
20
30
40
50
60
70
80
90
100
PLANT CAPACITY [MVA]

FIGURE 7

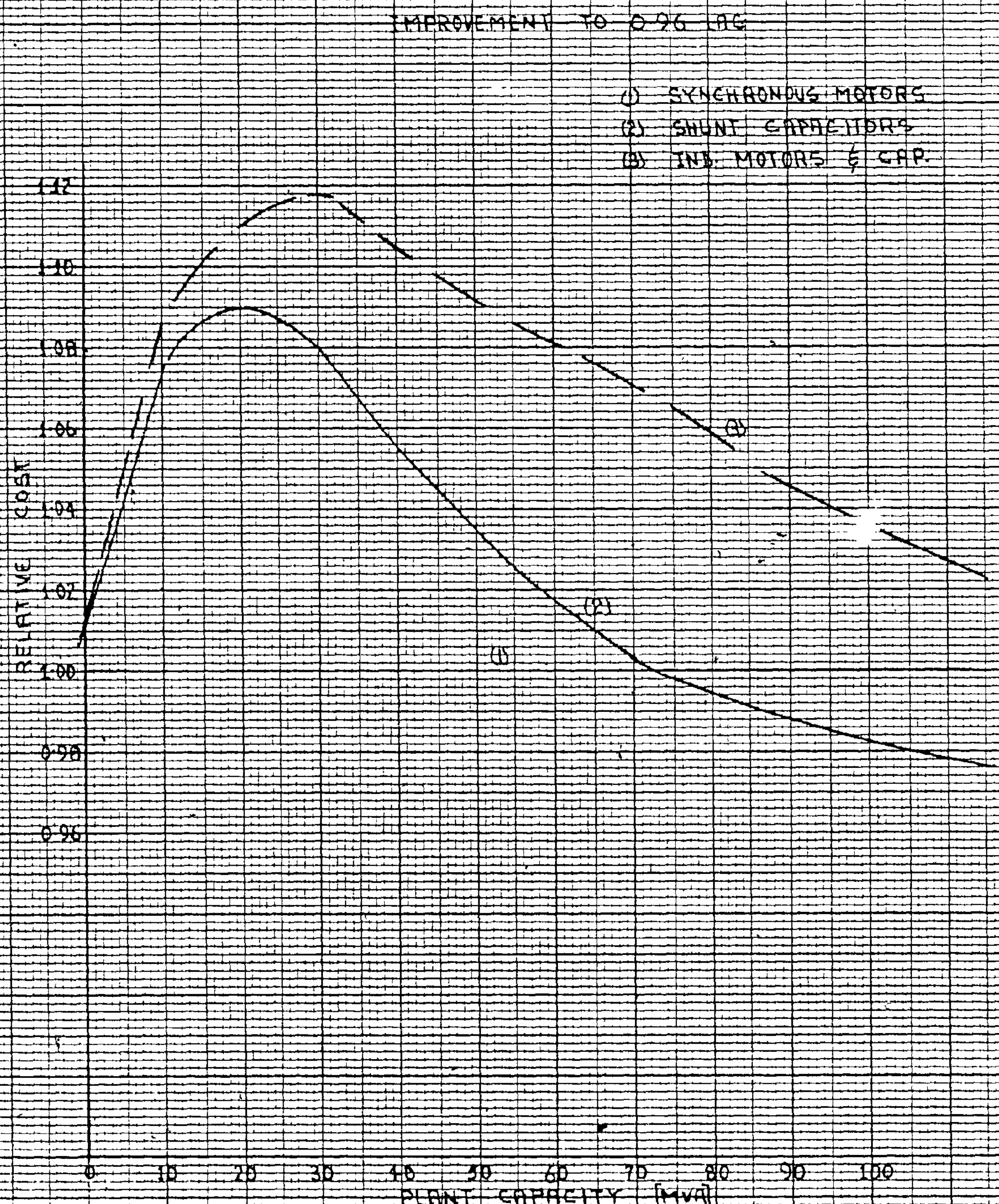

IMPROVEMENT TO 0.96 LAG
(1) SYNCHRONOUS MOTORS
(2) SHUNT CAPACITORS
(3) IND. MOTORS & CAP.
RELATIVE COST
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
(1)
(2)
(3)
0
10
20
30
40
50
60
70
80
90
100
PLANT CAPACITY [MVA]

FIGURE 8

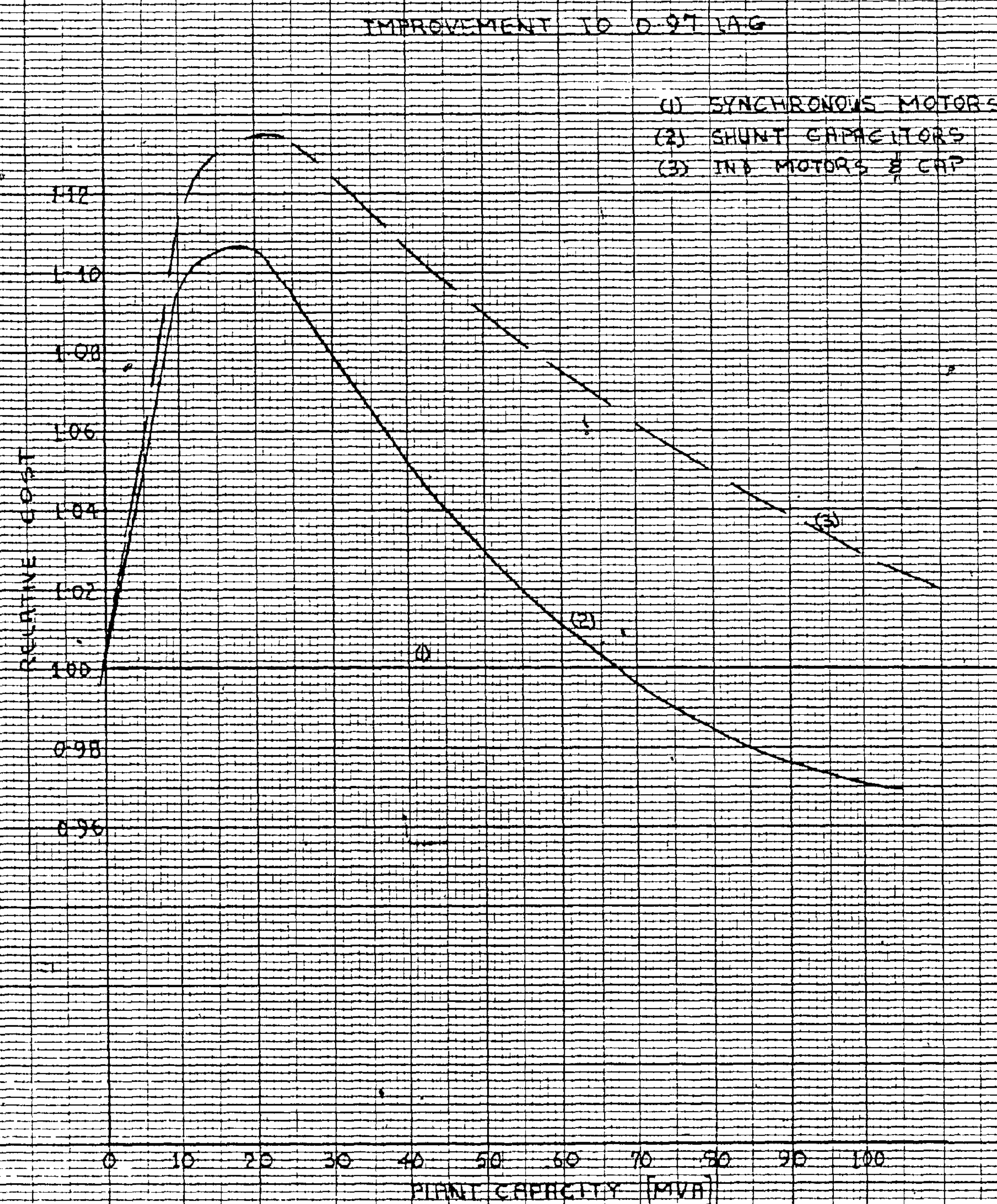
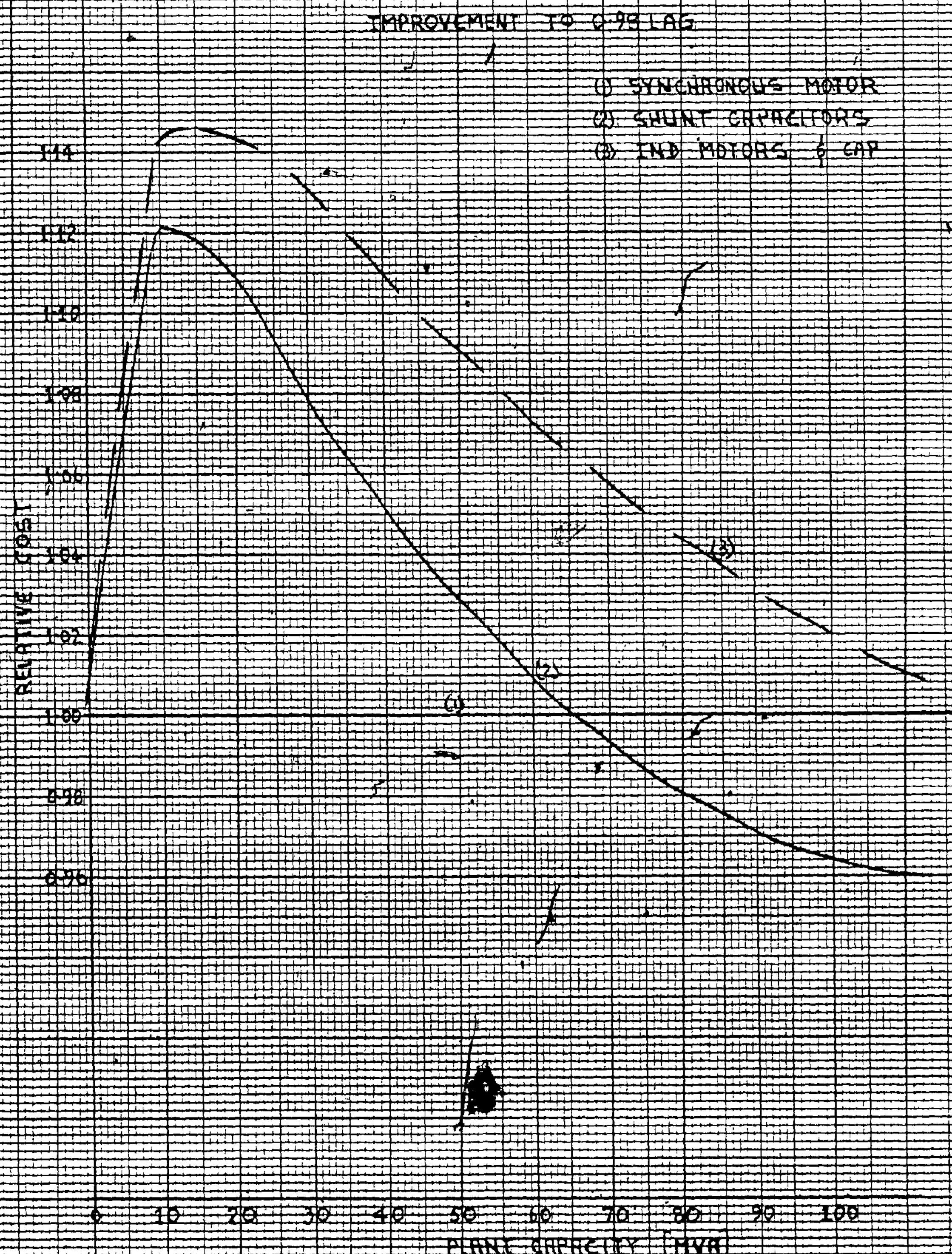

IMPROVEMENT TO 0.97 LAG
(1) SYNCHRONOUS MOTORS
(2) SHUNT CAPACITORS
(3) IND MOTORS & CAP
RELATIVE COST
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
(1)
(2)
(3)
0
10
20
30
40
50
60
70
80
90
100
PLANT CAPACITY [MVA]

FIGURE 9



IMPROVEMENT TO 0.98 LAG
(1) SYNCHRONOUS MOTOR
(2) SHUNT CAPACITORS
(3) IND MOTORS & CAP
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
RELATIVE COST
(1)
(2)
(3)
0
10
20
30
40
50
60
70
80
90
100
PLANT CAPACITY [MVA]

FIGURE 10

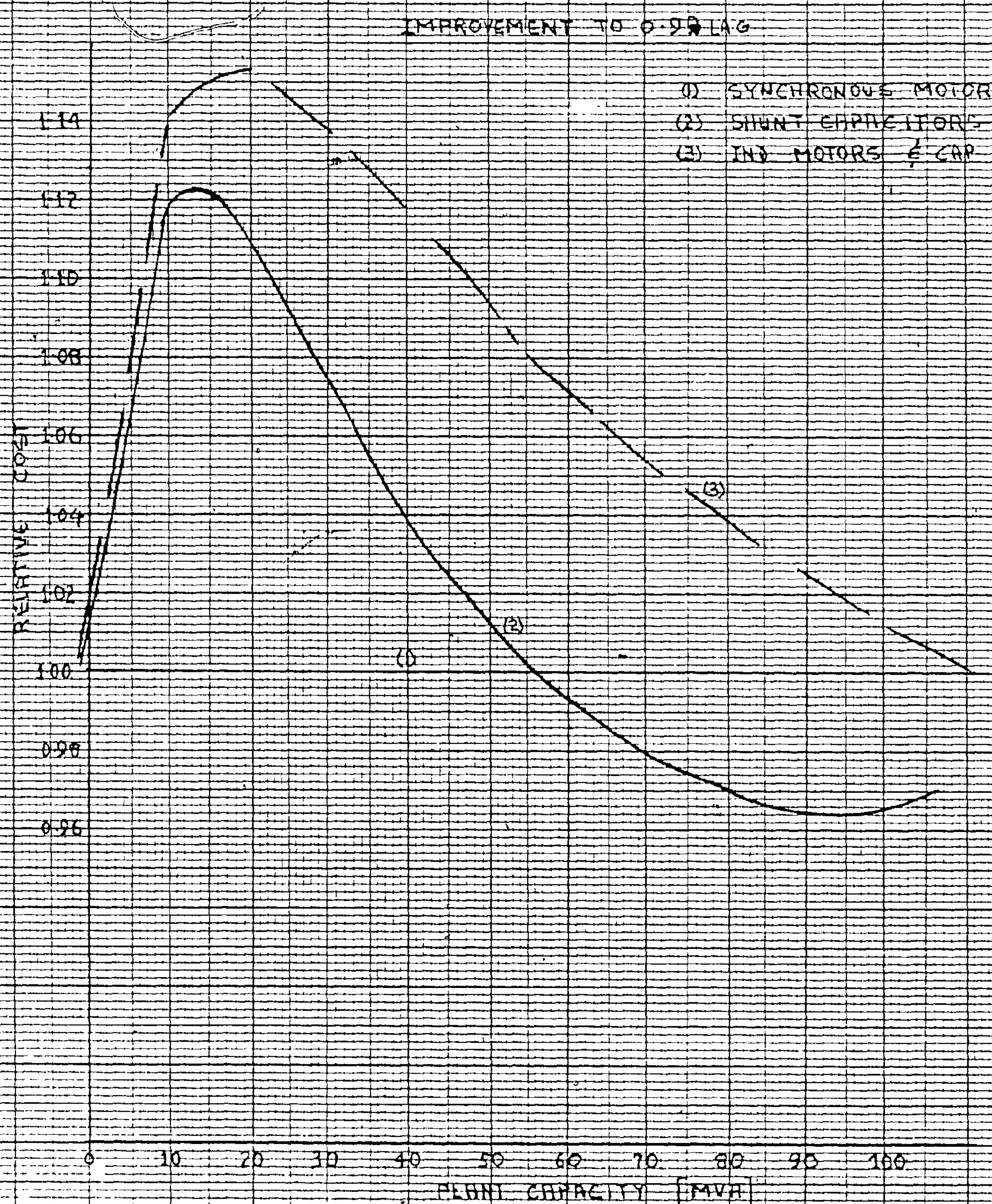

IMPROVEMENT TO 0.99 LAG
(1) SYNCHRONOUS MOTOR
(2) SHUNT CAPACITORS
(3) IND MOTORS & CAP
RELATIVE COST
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
(1)
(2)
(3)
0
10
20
30
40
50
60
70
80
90
100
PLANT CAPACITY [MVA]

FIGURE 11

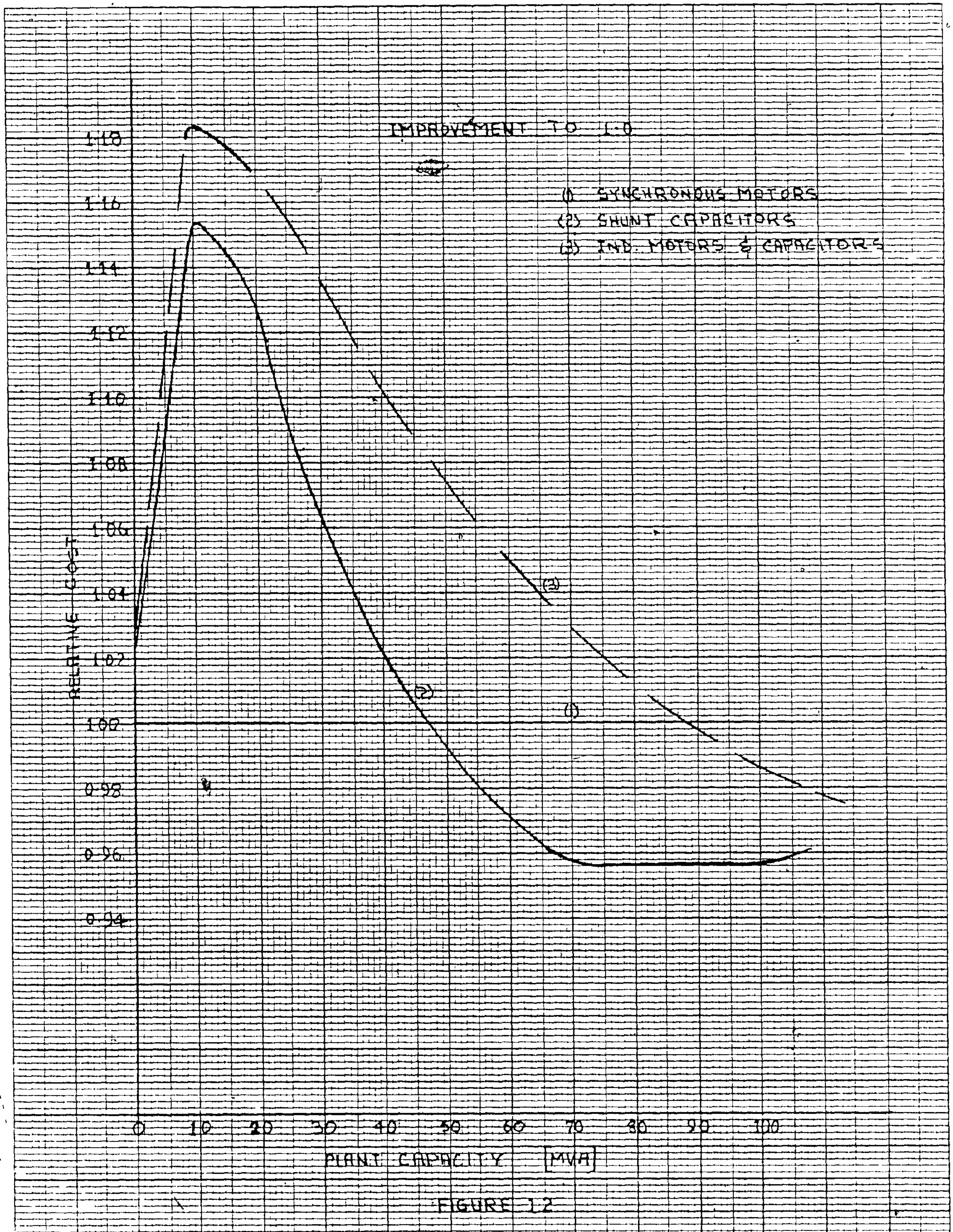

IMPROVEMENT TO 1.0
(1) SYNCHRONOUS MOTORS
(2) SHUNT CAPACITORS
(3) IND. MOTORS & CAPACITORS
RELATIVE COST
1.18
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
(3)
(2)
(1)
0
10
20
30
40
50
60
70
80
90
100
PLANT CAPACITY [MVA]

FIGURE 12

V CONCLUSION

The plots presented in this report are intended to be used for comparison purposes only, since, any dollar values given will not necessarily be accurate. This is because of the several costs that have not been included.

The relative costs of the various options, as presented, are considered to be more instructive, and indications are that the ratios are accurate. Additionally, as long as the relative costs of the equipment considered remain the same, then these curves will be valid. From the plots presented, it may be observed that the use of over-excited synchronous motors presents the lowest cost option over most of the range considered, but the shunt capacitor option tends to be lower in cost, for the high capacity plants.

These figures therefore, tend to indicate that synchronous motors are the most economical sources of reactive power, however, as was previously stated, a thorough technical analysis must be performed, before selecting this option.

Curves were not presented for either the synchronous capacitor option, or the static controlled capacitors option, since it is felt that synchronous capacitors are uneconomical, and sufficient information is not available to allow a proper assessment of the costs involved in using static controlled capacitors.

V CONCLUSION cont'd.

It should be pointed out that preliminary reports indicate that static controlled capacitors are quite reliable, and competitively priced. This option requires further investigation.

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