A Comparison of Power-factor Correction on Submerged-arc Furnaces by Capacitors in Shunt and Series

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SYNOPSIS

The operating characteristics of a modern 30 MW furnace for the production of 75 per cent ferrosilicon provided with power-factor-correcting capacitors connected in shunt and series are presented in graphical form. The results are discussed, and the conclusion is reached that, according to the evidence as a whole, shunt connection is to be preferred.

INTRODUCTION

Where a maximum kVA demand forms one of the bases on which a consumer has to pay for the purchase of power to operate submerged-arc electric furnaces, it is very advantageous economically to install power-factor-correcting capacitors. In fact, this is virtually a *sine qua non* with modern large furnaces owing to the inherently low power factor of such furnaces. Power-factor decreases with increase in furnace size, both because of a decrease in resistance and, to a lesser extent, because of an increase in reactance. Thus, for an increase in furnace size from 15 MW to 30 MW, the power factor will usually decrease from more than 0,8 to less than 0,7.

The provision of capacitors, whether in shunt or in series, cannot alter the furnace power factor and thus the power liberated in the arc. These depend entirely upon the inherent reactance of the furnace system and the maximum resistance that can be successfully employed for the manufacture of a specific product. The capacitors merely correct the incoming line power on the primary side of the transformer, the degree of correction employed being dependent upon economic considerations. Owing to the large currents and low voltages on the secondary side of the transformers, it is customary to locate the capacitors on the primary side. They can theoretically be located on the secondary side of the furnace transformer by being connected across the secondary of a series transformer placed between the furnace transformer and the furnace[1]. In that case, the furnace transformer can be of smaller capacity, but the author knows of no practical application of this arrangement.

In recent years, series capacitors have replaced shunt capacitors on many of the new furnaces installed, and it is pertinent to enquire whether this change is justified. Although excellent monographs[1,2] have been written on this subject, it is still generally the case that the average manufacturer of electric-furnace products has not a very clear picture of the difference between the two types of power-factor correction. It is the object of this paper to examine the differences and to present them in a simple, easily understood graphical form.

COMPARISON OF CAPACITORS CONNECTED IN SHUNT AND SERIES

The theory of capacitors employed in shunt and series for power-factor correction has been adequately dealt with by others[1,2]. The analysis given in the Appendix has therefore been restricted to the derivation of those equations necessary for the graphical comparison of active power, corrected grid power factor, electrode-to-hearth voltage, and relative resistance, which is defined as the ratio of the total phase resistance of the furnace system to the inductive phase reactance of the furnace system, the latter being assumed to be a constant for the furnace.

These quantities are plotted against electrode current as the furnace is brought onto load on the specific transformer tapping that will give the designed load at the design point. Unless a furnace has been off-line for a relatively short period, it is more usual to bring it onto load by increases in both the electrode current and the voltage, but the graphical comparison given will still be valid.

The particular example chosen is that of a modern, large electric furnace for 75 per cent ferrosilicon, designed for optimum operation at 30 MW at a phase resistance of 1 mΩ, the inductive phase reactance being 1,15 mΩ. At this load, the electrode current will be 100 kA, the electrode-to-hearth voltage 152,4 V, and the relative resistance 0,870. The supply voltage of the line has been taken as 21,5 kV, and at the design point the grid power factor has been corrected to 0,97.

In the calculation of the electrode-to-hearth voltage, the impedance voltage drop of the transformer between no load and full load has been disregarded. Thus, the electrode-to-hearth voltage is shown as constant for shunt capacitors, whereas in practice it will slope downwards to some extent from no load to full load, in turn affecting the other parameters. However, the effect will be similar for series capacitors.

DISCUSSION

At the design point, active power, electrode-to-hearth voltage, corrected grid power factor, and relative resistance are the same for both shunt- and series-connected capacitors. The following emerges from further examination of the graphs.

With shunt capacitors, the electrode-to-hearth voltage remains constant at 152,4 V (if the drop in transformer impedance voltage is neglected) as the furnace is brought onto load, while with series capacitors this voltage rises from 103,1 V at 0 kA to 152,4 V at 100 kA, and still higher values as the current is increased further. This is an important factor when a possible breakdown of the capacitors is considered. A failure of shunt capacitors will not in any way affect the voltage steps obtainable from the transformer, and furnace operation will be completely normal except that the maximum demand will rise. A failure with series capacitors will seriously upset furnace operation, since the secondary voltages obtainable from

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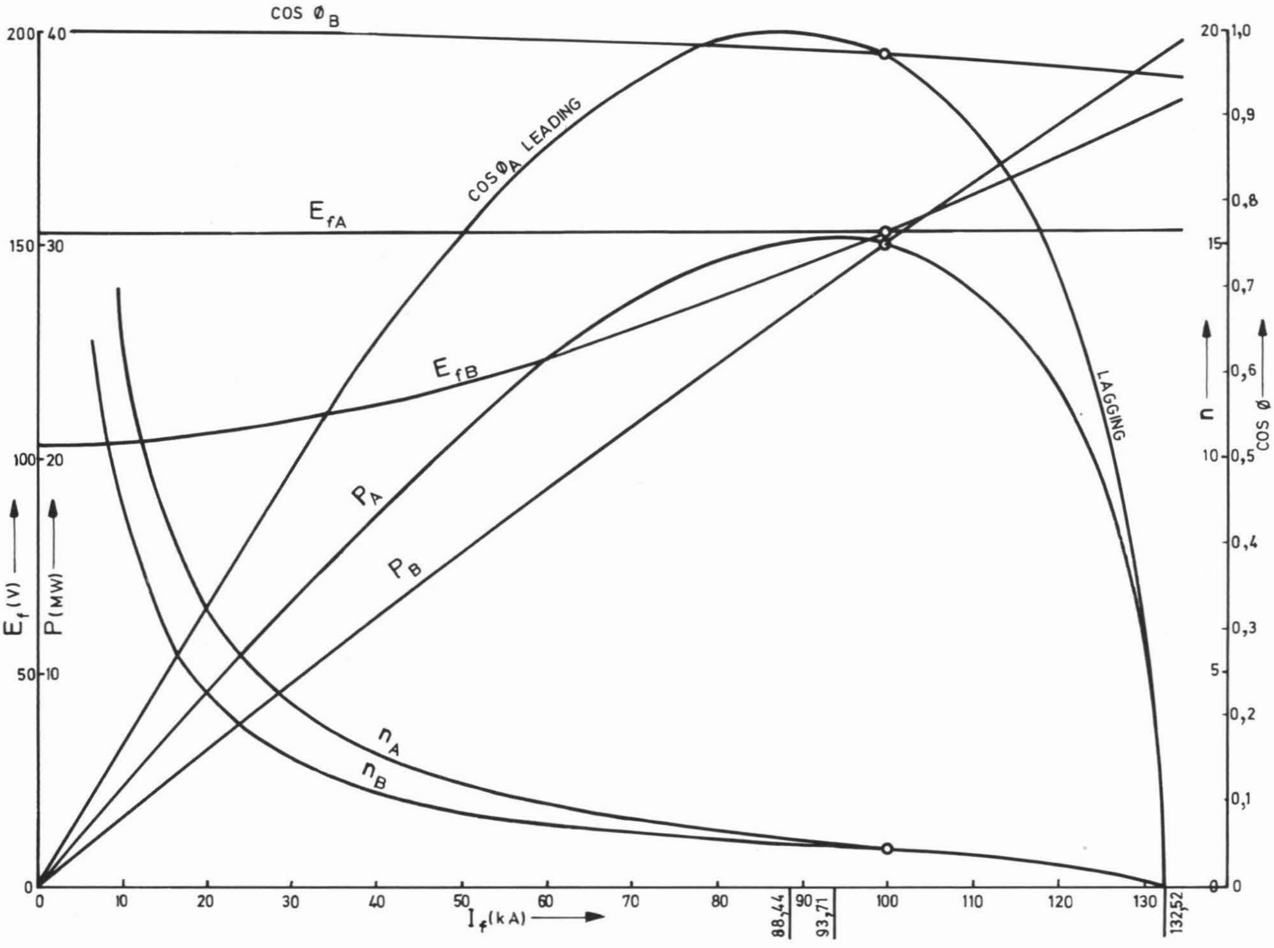

Graph, for a 30 MW furnace, of electrode current (I_f) versus grid power factor (cos ϕ_A, cos ϕ_B), furnace power P_A, (shunt), P_B (series), electrode-to-hearth voltage (E_A, E_{fB}), and relative resistance (n_A, n_B)

the transformer will be too low for the product being manufactured unless transformer tappings of a sufficiently high value are specially provided at extra cost to guard against this eventuality. It can be argued that, with modern capacitors, a break-down is unlikely: some types are now fitted with internal fuses, namely, one for each capacitor element. They are arranged to fail before the external fuse, and give the advantage that a faulty element is immediately disconnected by the element fuse without causing service interruption. The unit continues to function at slightly reduced output, and its service life remains practically unchanged. Nevertheless, the possibility of capacitor failure should be given due consideration when the choice is made between shunt and series capacitors.

To the left of the full-load point as the furnace is brought onto load, the relative furnace resistance is always less for the same electrode current with series capacitors than it is with shunt capacitors, while the reverse is true beyond the full-load point. This follows directly from the difference in electrode-to-hearth voltages for the two cases. A lower relative resistance at the same electrode current and charge resistivity is associated with deeper electrode immersions. Thus, as a furnace with series capacitors is brought onto load, electrode immersions tend to be deeper than in a furnace with shunt capacitors. This is an advantage that can, however, be offset for shunt capacitors if the load is raised on lower voltages, as is usually done. At the full-load point, electrode immersions are equal, while, beyond this point, immersions will tend to be deeper with shunt than with series capacitors, which offers some advantage, particularly when an attempt is being made to gain immersion by an increase in electrode current.

It is further to be noted that, for the same change in current in the region of the full-load point, electrode immersions will change less with series than with shunt capacitors. With series capacitors, therefore, the practice of trying to gain on electrode immersions by a temporary increase in the electrode current will be relatively ineffective. This is also apparent from the fact that, with series capacitors, the electrode-to-hearth voltage rises with current.

It has been claimed[2], however, that the smaller change in electrode position obtained for a determined change in electrode current or active power at the full-load point, with series-capacitor compensation compared with shunt compensation, offers a great advantage from both operating and regulating technique. From the operating point of view, modern furnaces are usually provided with both current and impedance regulation. If it is desired to limit electrode movement to a minimum, the furnace with shunt capacitors can be run on constant impedance or so-called 'fixed zone' control. Thus, there need not be more wear and tear on the regulators and electrode-hoisting equipment than for series-capacitor compensation. This equipment is, in any case, robust and designed for the life of the furnace. With series capacitors, the transformer voltage steps can be chosen somewhat further apart, but the saving in cost is hardly significant.

As electrode current is increased from zero, the grid power factor for shunt capacitors alters from leading to unity to 0,97 lagging at the full-load point, and to lower values lagging beyond the full-load point. With series capacitors, the grid power factor cannot become leading and reduces from unity at zero load to 0,97 at full load, and slightly lower values beyond full load. The avoidance of a leading power factor is probably to be preferred, although in the author's experience a leading power factor, while bringing a furnace with shunt capacitors onto load, has not proved a disadvantage. Compaints about a leading power factor have never been received from the electricity-generating authority, probably because the furnace load constitutes only a fraction of the total load on the grid, and because a leading power factor is generally employed only for a relatively short time. Moreover, shunt capacitors are usually arranged in separate banks of two or three, one or more of which can be switched in at a time. Thus, if a furnace has to be operated for a long time on low load, as when a new furnace is being started up or for any other reason, capacitor correction can be employed in multiples of one-third of the total installed MV AR to suit conditions. From the electricity consumer's point of view, the elimination of a leading power factor offers no advantage. With either shunt or series capacitors, the maximum demand will not be exceeded as the furnace is brought onto load, even with a leading power factor in the shunt case, because the load is below full load.

When a furnace is brought onto load, active power is always greater with shunt than with series capacitors, as is to be expected from the higher relative resistance for shunt capacitors. This favours product output. With shunt capacitors, if the furnace has an inherent power factor of more than 0,7071 at the full-load point, power will continue to rise as current is increased beyond full load, but the rate of rise will be considerably less than in a furnace with series capacitors. On the other hand, if the full-load power factor is below 0,7071, active power will decrease with further increase in current. In a furnace with series capacitors, the power will always increase – and increase fairly rapidly – through the full-load point. It is to be noted, however, that this is obtained only at the expense of an increase in both the electrode-to-hearth voltage and the relative resistance compared with the shunt case. If the furnace can be operated at a higher voltage, the increase in voltage and power can equally well be achieved in the furnace with shunt capacitors by the operator's simply pressing a button on the control desk to operate the on-load tap changer for a higher voltage. The rising-power characteristic of series-compensated furnaces is thus of little significance, the more so when operation is to the left of the full-load point as often occurs in practice.

It should be noted particularly that, with series compensation, it is necessary to work exactly at the full-load point for optimum operation. Below this point, power falls off rapidly. This is in direct contrast to a shunt-compensated furnace, where the power varies only minimally through the full-load point. It follows that, with series capacitors, it is necessary to design the full-load point exactly, which will in general be impossible. With shunt capacitors, appreciably more latitude is allowable in the design point.

If the question of shunt versus series capacitors is considered from a purely electrical point of view, it is said that shunt capacitors are very sensitive to harmonic currents, so that precautions have to be taken to prevent such currents overheating and consequently damaging the capacitors[2]. On the other hand, with series capacitors, the development of ferro-resonance in the transformers can give rise to the generation of excessive voltages across the capacitors by severe current surges, particularly when an unloaded transformer is switched in or when a fully loaded transformer is switched out. The use of arc gaps to protect the capacitors from over-voltage is said not to be completely satisfactory, and it has thus been proposed to replace series static capacitors with series-connected synchronous capacitors, which eliminate the phenomenon of ferro-resonance[3]. However, both types of static-capacitor connections are employed, so that it can be taken that difficulties of the type mentioned can be overcome, and there is from this point of view no overriding advantage to be gained from the choice of one type of connection rather than the other. It should nevertheless be pointed out that, with a series-capacitor installation, if it is desired to overload the transformer – which is not an unusual requirement – this will in general not be possible without exceeding the current rating of the capacitors. If such overloading of the capacitors is to be prevented, it will be necessary to install additional capacitors in parallel on each phase. In contrast, if capacitors are connected in shunt across the phases, the capacitor current and voltage always remain the same irrespective of the transformer load.

To sum up, it is concluded that there are no convincing reasons for a swing-over to series capacitors, and if the evidence is taken as a whole, shunt capacitors are to be preferred.

REFERENCES

1. FLAATHE, H.P. The use of series capacitors in conjunction with electric smelting furnaces. *Asea Pamphlet 7791E*.
2. MONDAL, A. Comparison between electric smelting furnaces provided with shunt or series capacitors. *Reunert & Lenz Engineer's Diary*, 1963.

, 1963.

3. BLELOCH, W. Compensation of reactance – submerged arc furnaces. Unpublished report, 1972.

APPENDIX

LIST OF SYMBOLS USED

Subscript A denotes magnitudes in the case of shunt capacitor compensation.

Subscript B denotes magnitudes in the case of series capacitor compensation.

a = Transformer ratio in the case of shunt compensation

$= \dfrac{\text{transf. primary phase voltage}}{\text{transf. secondary phase voltage}}$

b = Transformer ratio in the case of series compensation

$= \dfrac{\text{transf. primary phase voltage}}{\text{transf. secondary phase voltage}}$

E = Grid phase voltage

E_c = Voltage drop across series capacitor

E_f = Furnace electrode-to-hearth voltage

i = Grid phase current

I_c = Capacitor current in the case of shunt compensation

I_f = Electrode current

I_L = Inductive component of electrode current

I_R = Resistive component of electrode current

j = The operator $\sqrt{-1}$

k = The degree of compensation $= \frac{X_c}{a^2 X_L}$ or $\frac{X_c}{b^2 X_L}$

n $= \frac{R}{X_L}$, the relative phase resistance

P = Active power (P_A for shunt or P_B for series compensation)

r = Bus-bar and transformer secondary Δ phase resistance converted to equivalent Y phase resistance

R $= r + R_f$ = total phase resistance of the furnace system

R_f = Variable phase resistance of the furnace

X_c = Phase reactance of the capacitors.

X_L = Inductive phase reactance of the furnace system, assumed to be a constant for the furnace

ϕ = Phase angle of the grid

ϕ_f = Phase angle of the furnace system

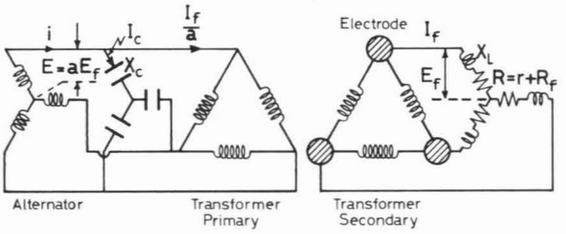

Figure 1

Simplified circuit diagram for a furnace with shunt capacitors

SHUNT CAPACITORS

Refer to Figures 1, 2, and 3.

The impedance of the furnace secondary circuit referred to the primary side of the transformer is $a^2(R + jX_L)$.

If Y_1 = admittance of furnace secondary circuit referred to the primary side, and

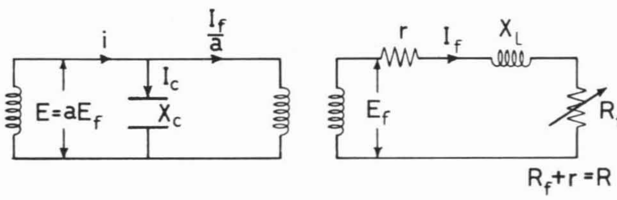

Figure 2

Equivalent phase diagram (shunt capacitors)

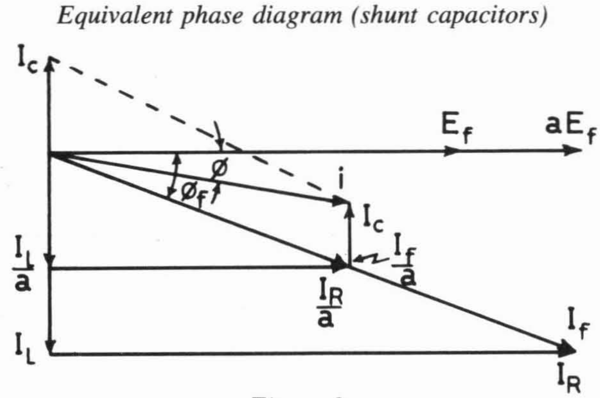

Figure 3

Current vector diagram for a furnace with shunt capacitors

Y_2 = admittance of the capacitor branch,

$$Y_1 = \frac{1}{a^2(R + jX_L)} = \frac{R - jX_L}{a^2(R^2 + X_L^2)}$$

$$Y_2 = \frac{1}{-jX_c} = \frac{j}{X_c}$$

$$i = \frac{I_f}{a} + I_c = a E_f (Y_1 + Y_2)$$

$$= (a E_f + j O)\left[\frac{R - jX_L}{a^2(R^2 + X_L^2)} + \frac{j}{X_c}\right]$$

$$= \frac{a E_f}{X_c}\left[\frac{R X_c - j X_L X_c + j a^2 (R^2 + X_L^2)}{a^2(R^2 + X_L^2)}\right]$$

$$= \frac{a E_f}{X_c}\left[\frac{R X_c}{a^2(R^2 + X_L^2)} + j\left(\frac{a^2(R^2 + X_L^2) - X_L X_c}{a^2(R^2 + X_L^2)}\right)\right]$$

$$= \frac{E_f}{k\,a\,X_L}\left[\frac{n k}{n^2+1} + j\left(\frac{n^2 + 1 - k}{n^2+1}\right)\right] \quad \ldots\ldots (1)$$

Also $E_f = I_f\sqrt{R^2 + X_L^2} = I_f X_L \sqrt{n^2+1}$, ... (2)*

$$\text{i.e.,}\quad \frac{1}{\sqrt{n^2+1}} = \frac{I_f X_L}{E_f}, \quad \ldots\ldots (3)$$

$$\text{or } n^2 + 1 = \left(\frac{F_f}{I_f X_L}\right)^2,$$

$$\text{i.e., } n = \sqrt{\left(\frac{E_f}{I_f X_L}\right)^2 - 1} \quad \ldots\ldots (4)^*$$

From (1), $\cos\phi = nk/\sqrt{n^2 k^2 + (n^2 + 1 - k)^2}$

$$= \frac{n k}{\sqrt{n^2+1}\cdot\sqrt{n^2 + (1-k)^2}} \quad \ldots\ldots (5)$$

From (3) $$= \frac{I_f X_L}{E_f} \qquad \frac{n k}{\sqrt{n^2 + (1-k)^2}} \quad \ldots\ldots (6)^*$$

k is obtained by solving (5) for k, whence

$$k = \frac{1 \pm n \tan\phi}{1 - \frac{n^2}{(n^2+1)\cos^2\phi}}$$

But from (1), $\tan\phi = \frac{n^2 + 1 - k}{n k}$ and, from the manner in which Figure 3 has been drawn, it is obvious that, for the phase-grid current to be lagging the phase-grid voltage, $\tan\phi$ must be negative, i.e., $k > n^2 + 1$. For this to be the case, it can readily be shown that the + sign must be chosen in the equation for k, so that

$$k = \frac{1 + n \tan\phi}{1 - \frac{n^2}{(n^2+1)\cos^2\phi}}$$

$$\text{i.e., } k = \frac{1 + n\sqrt{\frac{1}{\cos^2\phi} - 1}}{1 - \frac{n^2}{(n^2+1)\cos^2\phi}} \quad \ldots\ldots (7)^*$$

Finally, $P_A = 3\,I_f^{\,2}\,R = 3\,I_f^{\,2}.\,X_L\,n$ .... (8)*

and $a = \dfrac{E}{E_f}$ .... (9)*

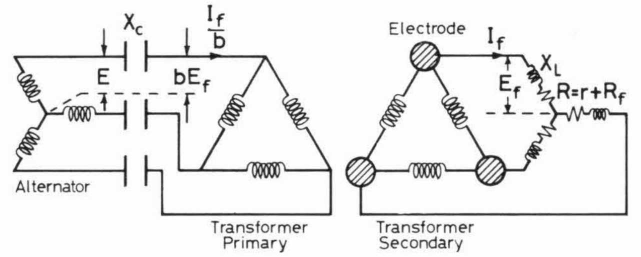

Figure 4

Simplified circuit diagram for a furnace with series capacitors

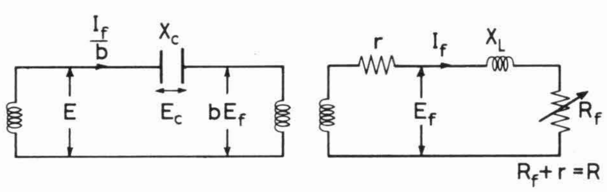

Figure 5

Equivalent phase diagram (series capacitors)

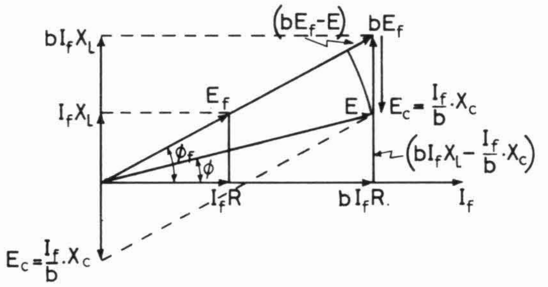

Figure 6

Voltage vector diagram for a furnace with series capacitors

SERIES CAPACITORS

Refer to Figures 4, 5, and 6.

The impedance of the furnace secondary circuit referred to the primary side of the transformer is $b^2\,(R + j\,X_L)$.

$$b\,E_f = \frac{I_f}{b}\cdot b^2\,(R + j\,X_L) = b\,I_f\,(R + j\,X_L)$$

$$E_c = \frac{I_f}{b}\,(0 - j\,X_c) = I_f\left(-j\,\frac{X_c}{b}\right).$$

Hence $$E = bE_f + E_c = I_f\left(b\,R + j\left\{b\,X_L - \frac{X_c}{b}\right\}\right)$$

$$= I_f\left(b\,R + j\left\{b\,X_L - \frac{X_c}{b}\right\}\right),$$

since $I_f = I_f + j\,0 = I_f$.

Thus, $E = I_f\,b\,X_L\{n + j\,(1-k)\}$ .... (10)

$$E = b\,I_f\,X_L\sqrt{n^2 + (1-k)^2} \quad\text{............... (11)}$$

Solving (11) for n, $n = \sqrt{\left(\dfrac{E}{b\,I_f\,X_L}\right)^2 - (1-k)^2}$ ...(12)*

From (10), $\cos\phi = \dfrac{n}{\sqrt{n^2 + (1-k)^2}}$ .... (13)

$= \dfrac{b\,I_f\,X_L\,n}{E}$ from (11) .... (14)*

k is obtained by solving (13) for k, whence

$$k = 1 \pm n\tan\phi.$$

But from (10) $\tan\phi = \dfrac{1-k}{n}$ and, from the manner in which Figure 6 has been drawn, it is obvious that, for the phase-grid current to be lagging the phase-grid voltage, $\tan\phi$ must in this case be positive, i.e., $k < 1$. Hence, the negative sign must be chosen in the equation for k

and $\quad k = 1 - n\tan\phi$

$$= 1 - n\sqrt{\frac{1}{\cos^2\phi} - 1} \quad\text{.................. (15)*}$$

Also $P_B = 3\,I_f^{\,2}\,R = 3\,I_f^{\,2}\,X_L\,n$ .... (16)*

$$E_f = I_f\sqrt{R^2 + X_L^{\,2}} = I_f\,X_L\sqrt{n^2+1}, \quad\text{...... (17)*}$$

i.e., $$I_f\,X_L = \frac{E_f}{\sqrt{n^2+1}}$$

and, by substitution of this value in (11)

$$E = \frac{b\,E_f}{\sqrt{n^2+1}}\sqrt{n^2 + (1-k)^2},$$

i.e., $$b = \frac{E\sqrt{n^2+1}}{E_f\sqrt{n^2+(1-k)^2}}$$

$$= \frac{E}{E_f}\,\frac{\cos\phi}{\cos\phi_f} \quad\text{.................. (18)*}$$

since $\cos\phi = \dfrac{n}{\sqrt{n^2+(1-k)^2}}$ and $\cos\phi_f = \dfrac{R}{\sqrt{R^2 + X_L^{\,2}}}$

$$= \frac{n}{\sqrt{n^2+1}}$$

PRACTICAL EXAMPLE

For a graphical comparison of shunt versus series capacitor compensation as applied to a particular furnace, relative resistance, grid power factor, electrode-to-hearth voltage, and active power from the above equations can be plotted against electrode current, the condition being chosen that, for a particular transformer tapping, there is equal power in the two cases at the design point of relative resistance.

Consider a modern large electric furnace for the production of 75 per cent ferrosilicon designed to give optimum operation at 30 MW, the total phase resistance at this load being 1 mΩ, and the furnace having an inductive phase reactance of 1,15 mΩ.

At this load, therefore,

Furnace power factor

$$\cos\phi_f = \frac{R}{\sqrt{R^2 + X_L{}^2}} = \frac{1}{\sqrt{1+(1{,}15)^2}} = 0{,}6562$$

Electrode current

$$I_f = \sqrt{\frac{30 \times 10^3}{3 \times 1}} = 100 \text{ kA} \quad (P = 3\, I_f{}^2 R)$$

Electrode-to-hearth voltage

$$= \frac{30 \times 10^3}{3 \times 100 \times 0{,}6562}$$

$$= 152{,}4 \text{ V} \quad (P = 3\, E_f\, I_f \cos\phi_f)$$

n at the design point

$$= \frac{\mathrm{R}}{X_L} = \frac{1}{1{,}15} = 0{,}8696.$$

Table 1

Summary of equations required for a comparison of shunt and series compensation

Units: Milliohms, volts, kiloamperes, and megawatts

QUANTITY	SHUNT CAPACITORS	SERIES CAPACITORS
n	$\sqrt{\left(\frac{E_f}{I_f X_L}\right)^2 - 1}$	$\sqrt{\left(\frac{E}{b\, I_f X_L}\right)^2 - (1-k)^2}$
$\cos\phi$	$\frac{I_f X_L}{E_f} \quad \frac{n\, k}{\sqrt{n^2 + (1-k)^2}}$	$\frac{b\, I_f X_L\, n}{E}$
k	$\frac{1 + n\sqrt{\frac{1}{\cos^2\phi} - 1}}{1 - \frac{n^2}{(n^2+1)\cos^2\phi}}$	$1 - n\sqrt{\frac{1}{\cos^2\phi} - 1}$
Transf. ratio	$\frac{E}{E_f}$	$\frac{E}{E_f}\ \frac{\cos\phi}{\cos\phi_f}$
E_f (volts)	$I_f X_L \sqrt{n^2+1}$	$I_f X_L \sqrt{n^2+1}$
P (MW)	$3\, I_f{}^2 X_L\, n\, 10^{-3}$	$3\, I_f{}^2 X_L\, n\, 10^{-3}$

Table 2

Values of the quantities in Table 1

	SHUNT CAPACITORS				SERIES CAPACITORS			
	$a = 81{,}45$, $k_A = 2{,}24553$				$b = 120{,}40$, $k_B = 0{,}78207$			
I_f(kA)	n_A	$\cos\phi_A$	E_{fA}(V)	P_A (MW)	n_B	$\cos\phi_B$	E_{fB}(V)	P_B (MW)
0	∞	Nil	152,4	Nil	∞	1,000	103,1	Nil
10	13,21	0,169		4,56	8,962	1,000	103,7	3,09
20	6,550	0,333		9,04	4,477	0,999	105,5	6,18
40	3,159	0,631		17,44	2,231	0,995	112,5	12,31
60	1,969	0,859		24,46	1,478	0,989	123,1	18,36
80	1,321	0,986		29,16	1,099	0,981	136,7	24,27
87,60					1,000	0,977	142,5	26,47
88,44	1,116	1,000		30,11	0,990	0,977	143,1	26,71
93,71	1,000	0,994		30,30				
100	0,870	0,970		30,00	0,870	0,970	152,4	30,00
110	0,672	0,885		28,05	0,785	0,964	160,8	32,78
120	0,469	0,716		23,28	0,715	0,957	169,6	35,50
130	0,198	0,346		11,54	0,654	0,949	178,7	38,15
132,52	Nil	Nil	↓	Nil	0,640	0,947	181,0	38,80

The values in Table 2 are plotted in the graph.

Assume that the line supply voltage = 21 500 V and that, at the design point, it is desired to correct the grid power factor to cos $\phi = 0{,}97$.

The values of the quantities in Table 1 can now be calculated, and are given in Table 2.

DISCUSSION

Mr S.G. King:*

I fully agree with Mr Meintjes' conclusion that shunt capacitors seem to be better than series ones. Is there anything to be said for a compromise between the two – some series capacitors to enable the voltage to rise from a certain figure to the agreed full load figure, and then a set of shunt capacitors on the other side (which may know nothing about what is going on in the series side) to give the straight-line characteristic, so that one gets the best of both methods?

Mr Meintjes:

I have not given this combination any thought. However, I still wonder if there is any advantage to be gained by having, say, half the capacitors in series, except for not having a leading power factor when starting up.

Mr P. van Oers†:

Before presenting this contribution, I wish to express my sincere thanks to Mr Meintjes, and the organizers of INFACON 74, because series and shunt capacitor secrets exist no more.

With large loads, shunt capacitors require circuit-breakers to switch them in gradually, to avoid a leading power factor being drawn from the supply.

It is well known that the supply authorities do not want a leading power factor, because it gives rise to an incorrect recording of the energy consumed.

The loss in capacitors has two implications: maximum demand, and production.

If the preset maximum demand is not to be exceeded, a loss of production is the result, because the maximum demand is based on the corrective kVA with shunt capacitors.

When production is a prerequisite, the penalty is a higher maximum demand bill, if the higher maximum demand is allowed by Escom. This higher maximum demand is restricted further by the permissible overload of transformers, secondary busbars, and electrodes, whichever is the least.

The time the shunt capacitors are out of order is also a very important factor, because the operator can choose between the price to be paid for maximum demand and loss of production.

The following example will highlight this.

If, at a normal full load without shunt capacitors, the loss in production is x rand per hour and the cost of the increased maximum demand on overload in order to maintain production is y rand, then the time in hours y/x is the period in which the cost of production loss is less than the increased maximum demand costs.

This can be made attractive to the producer, if he is insured against loss of shunt capacitors, by means of a reduced premium or a bonus to the maintenance or repair department of the company involved.

In general, however, it is in the interest of the producers to ensure against loss in capacitors by using shunt capacitors, and furnace transformers and ancillary gears that can sustain the overload.

The question arises here, of course, of why the furnace is not normally overloaded; but this can be due to:

(1) limit of the authorized maximum demand of the Electricity Supply Commission,
(2) management policy, and
(3) overload not being continuous.

A weak spot in the shunt-capacitor circuit is the breaker, because of the nature of the furnace operation, which is continuous. The on-load switching demands a robust switch and continuous service. Either a standby unit or a unit requiring a minimum of maintenance is necessary. The shunt capacitors, because they are switched in under load, are subject to ferro-resonance, and in this connection unwanted harmonics arise. These harmonics can be suppressed with a filter reactor, or with harmonic choke that can be so designed as to suppress any series of harmonic voltages. Of special interest here is the fifth harmonic, which is generated in an electric arc and can disturb television receivers, so I have heard.

Series capacitors give an entirely different picture, because, besides correcting the power factor, they give an increase in the supply voltage. Subsequently, the loss in series capacitors can result only in loss of production. It is in the interest of the producer to insure against loss of production.

The rest of my contribution to Mr Meintjes' paper may seem like a repetition of what has already been said, but I shall repeat it because I know the work that is involved in preparing a paper of this kind. An added excuse for this is remarks from Mr King about the confusion in 1962, when a paper was presented by Mr C.J. Coetzee and there was subsequent discussion about the merits of capacitors in shunt and in series by Mr Mondal.

Ferro-resonance arises also when the transformer is energized via the series capacitors. The initial inrush of magnetizing current contains a series of harmonics, one of which may be of the appropriate frequency to cause resonance, and damage can be done to transformers and capacitors. Protection, however, is normally provided by means of a spark gap. This spark gap must break down at some voltage low enough to avoid risk of damage to the series capacitors.

A more modern method is a circuit breaker, which closes and short-circuits the capacitor bank.

An inspection of the spark gap will highlight furnace operation practice, because, if the transformer is switched in without bringing the tap changer to the lowest voltage, the spark gap will definitely operate.

In general, shunt capacitors are used to improve the power factor by supplying leading reactive power, and series capacitors are used to improve voltage regulation and the power factor. Expressed differently, shunt capacitors reduce the current by reducing the reactive load; series capacitors reduce the current by increasing the voltage, and, according to Mr Meintjes' paper, it does not alter the arc power, whichever system is used.

Arc power is conducted through a vapour path of such a high temperature as to be conductive and allow a current to flow. Also, maximum arc power is released when the arc resistance equals the rest of the system's reactance, as is well known.

I do not know if it is possible to obtain some capacitance from the furnace slags at the electrode tips, but it might be another field of investigation for somebody interested in this.

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