Optimum dimensioning of a flicker compensator in three-phase electric-arc furnaces supply systems

Abstract

Three-phase electric arc furnaces, the design power ratings of which are in many cases above 100 MVA, primarily cause voltage fluctuations (flicker) in their high-tension feed systems, in addition to harmonics and unbalance. Static VAr compensators (SVCs) are used to smooth out these mains effects, The example of the dimensioning of an SVC is used to illustrate how effective flicker reduction can be achieved with al relatively low SVC design power rating by means of numerical process simulation and optimization of the compensator control system, saving investment costs of around € 1.8m.

Introduction

The smelting of steel is carried out worldwide in high-performance electric arc furnaces operating with either AC or DC current and at a rated power of over 100 MVA.

In the case of three-phase AC electric arc furnaces, particularly, feedback affects the high voltage supplying grid because there are uneven changes in the active net load and reactive load in the wiring of the AC system and because the physics entailed in a high current arc (the graph of current against voltage is non linear). The feedback impairs the quality of supply voltage and may disturb the operation of the whole grid. Compensators must, in many cases, be used to avoid impermissible distortion, asymmetry and rapid changes to the voltage in the network within very short periods. Their task is:

- to have ready a basic load so that variations in the supply voltage are restricted,
- to keep within permitted limits the distortion in the network voltage by means of filters and
- to make available variable, asymmetrical reactive power so as to avoid any undesired voltage changes and fluctuations (causing flicker phenomena) and any major variations in the asymmetry over time.

Compensators help to steady the electric arc, to raise the efficiency of the melting process, to lower the demand for reactive power from the supply network, to reduce electrical losses and to improve performance generally in steel production.

If the compensator needs power of more than 100 MVAr, the SVC type is, as has long been the case, an economical option. It has a mechanism to provide the necessary basic load using a filter circuit, which will also do the job of restricting voltage distortion. A thyristor-controlled reactor (TCR) is used as a choke to produce the necessary, variable, asymmetrical reactive power. The sum of the reactive power from the furnace, the TCR and the filter, whether positive or negative, corresponds, on average, to one of the ideal values prescribed for the supply network.

The compensation principle in static VAr compensators (SVCs)

The principle of reactive power compensation is illustrated in Fig. 1.

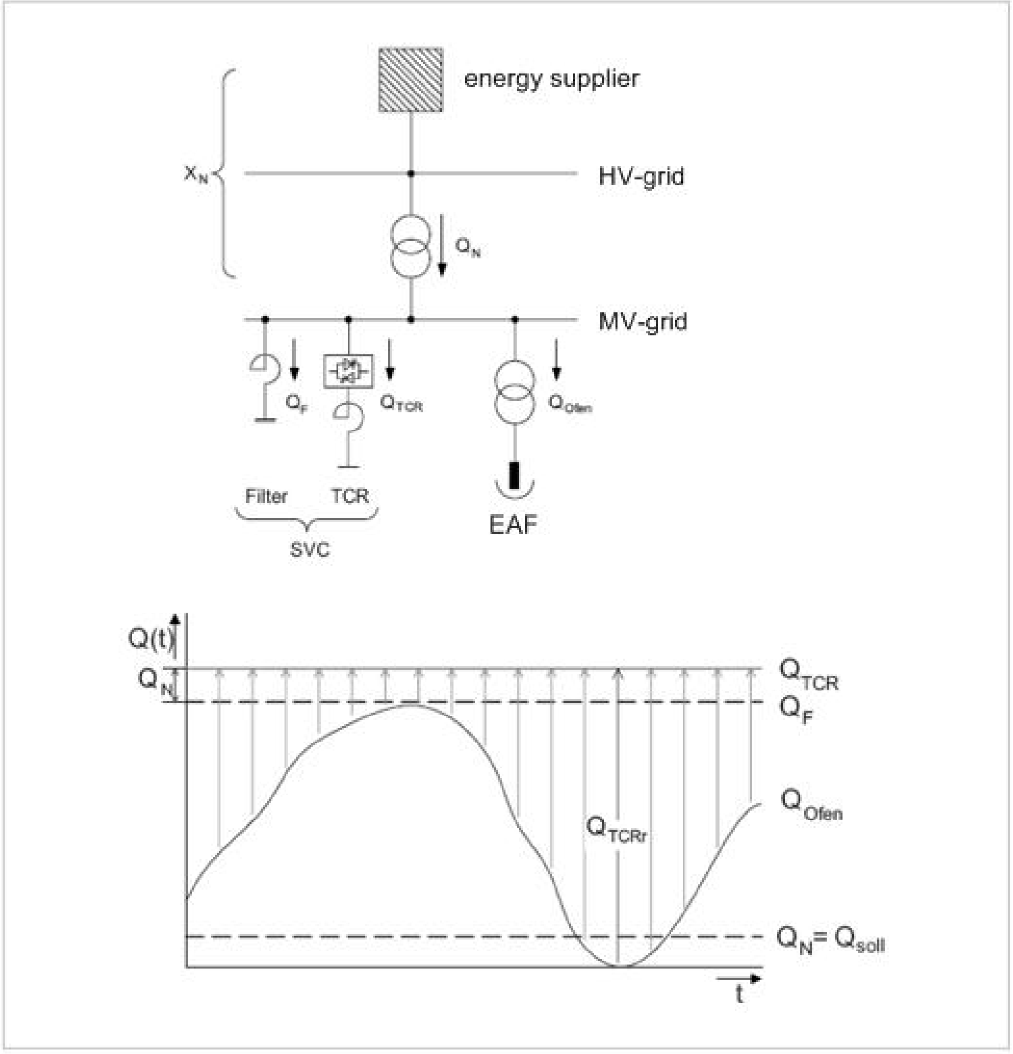


Fig. 1: Simplified mains supply system diagram and reactive load flow (indirect compensation principle)

The SVC filter circuit draws from the grid constant, capacitive reactive power and filters the harmonics of the furnace network voltage arising from the operation of the electric arc furnace. The TCR acting as a choke takes inductive reactive power in varying amounts over time from the network, with the aim of keeping constant the reactive power remaining in the particular branch of the network from the combined work of the electric arc furnace, the filter circuit and the TCR itself at an ideal figure

$$Q_{soll} = Q_N = Q_{Ofen} – Q_F + Q_{TCR}$$

The purpose of the mechanism is to ensure a constant longitudinal voltage drop and to limit any flicker, any voltage asymmetry, and the voltage fluctuations caused by the operation of the furnace to an acceptable level. The TCR as a regulation mechanism must be capable of remedying any deviations from the control values within 1 to 2 wave periods of the network.

The rated power of the TCR Q_{TCRr} will normally be set to exceed the rated power of the filter circuits by 10 % to 15 %. This will ensure that the targeted control level $Q_N = Q_{soll}$ will also be achieved for any electric arc furnaces currently out of operation and for an ideal control value of $Q_{soll} > 0$.

Computational simulation of the process facilitates optimum configuration of SVC

The computer model of the energy sources in the supply grid (the transformers, the wiring, the chokes and the condensers) necessary for the simulation of the electrical behaviour of the three-phase AC electric arc furnace plus grid plus compensator is created on the basis of known alternative circuits consisting of R, L, C and switch elements. These substitute circuits are linked together by differential equations which apply to the grid structure. A similar procedure is used for the electrical equipment of the AC arc furnaces.

The substitute elements R_{EAF} and X_{EAF} represent the sum of the leakage reactance and the resistance of the furnace transformers, the furnace chokes and the high-current circuit (see Fig. 2).

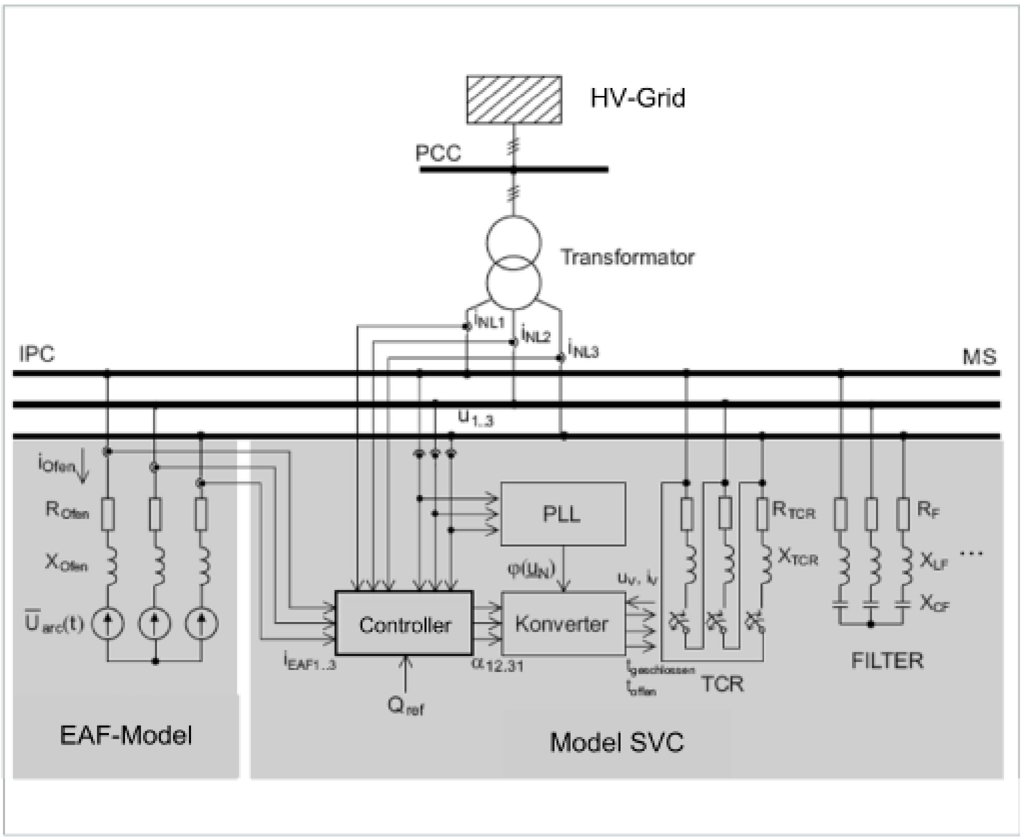


Fig. 2: Equivalent circuit diagram and calculation model

The electric arcs of the furnace are represented in the data by a voltage source which changes over time $u_{arc}(t)$ and are described during the creation of the model by a mean value $\bar{U}_{arc}(t)$ which changes over time, which may be positive or negative and which is formed in any half period of the actual electric arc voltage wave $u_{arc}(t)$. In this way the statistically probable arcing behaviour of the three-phase AC arc is simulated in dependence on its operational phase [1].

There will be a statistically probable degree of fluctuation in the electric arc voltage as a result of the electromagnetic phenomena (shift in position or change in length) in the arc. The fluctuations are stronger during the burn-in phase of every melt process because the scrap metal surface is hard and uneven and the scrap itself shifts or collapses. Since the arc voltage varies over time, there are constant adaptations going on within the furnace current. The time constants are in the upper range of µs.

To rate the SVC, electrical conditions in the supply network for this operational stage of the electric arc furnace has to be used which have been obtained from reference measurements and are available in the form of statistical distribution curves for $\bar{U}_{arc}(t)$.

In the case of the filter circuits with the different frequencies to which they are tuned, and of the TCRs of the SVC, the substitution elements R_F, X_{LF}, X_{CF}, R_{TCR} and X_{TCR} are taken into account for the calculation of the electrical network parameters (see Fig. 2). The switching behaviour of the power converter valves is simulated by ideal switches with the actual time of switching set to depend on the valve voltage u_V, the valve current i_V, the phase position of the vector depicting supply voltage $\varphi(\underline{u}_N)$, and the angles α_{12}, α_{23} and α_{31} which control the TCR.

To fulfil the purposes of the investigation, it is necessary to integrate the method of operation of the TCR control system into the calculation of the network, thus ensuring economical configuration of the compensator. This regulation instance provide a servo control through the input currents of the three-phase AC electric arc with superposed reactive power control. The method provides on the one hand a short delay in composing the control variable and on the other hand it gains a great stationary accuracy.

Differential equations are used for the discrete mathematical description of the transfer elements for the control mechanism [2].

An example of rating

The compensator of an electric furnace steelworks, composed of filters and the regulated, choked condenser, was not capable of bringing the flickering due to the operation of the electric arc furnace down to a permissible level, particularly in the 110-kV network of urban consumers (Fig. 3).

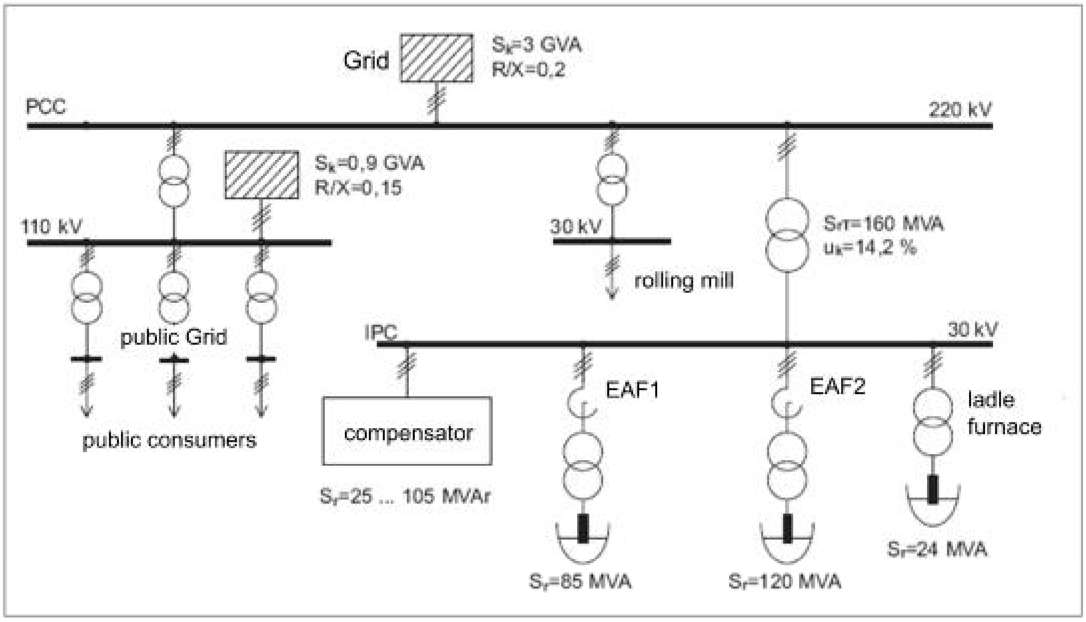


Fig. 3: Simplified overview diagram of the power supply for an iron and steel works

Measurements were taken and computer simulation were carried out for the network section shown in Fig. 3. These all confirmed that the compensation equipment in use did limit the voltage displacement at the PCC adequately, so that EN 50160 is observed, but revealed a need for measures to reduce the amount of reactive power drawn by the steelworks and to reduce flicker effectively.

Determination of the rated power of the compensator

The first thing was to measure the reactive power required over time by the electric arc furnaces in order to discover the rated power necessary for the new (SVC) compensator equipment. Fig. 4 shows an example, that of the 120-MVA furnace LBO2 during the melt and its 1-second mean values for effective and reactive power drawn. The operational conditions at the "restless" stage of the melt are marked separately.

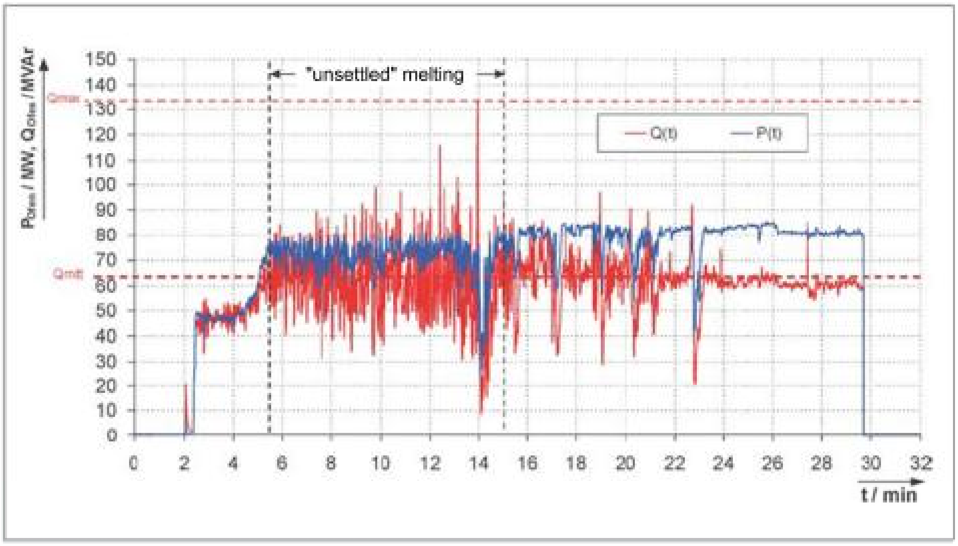
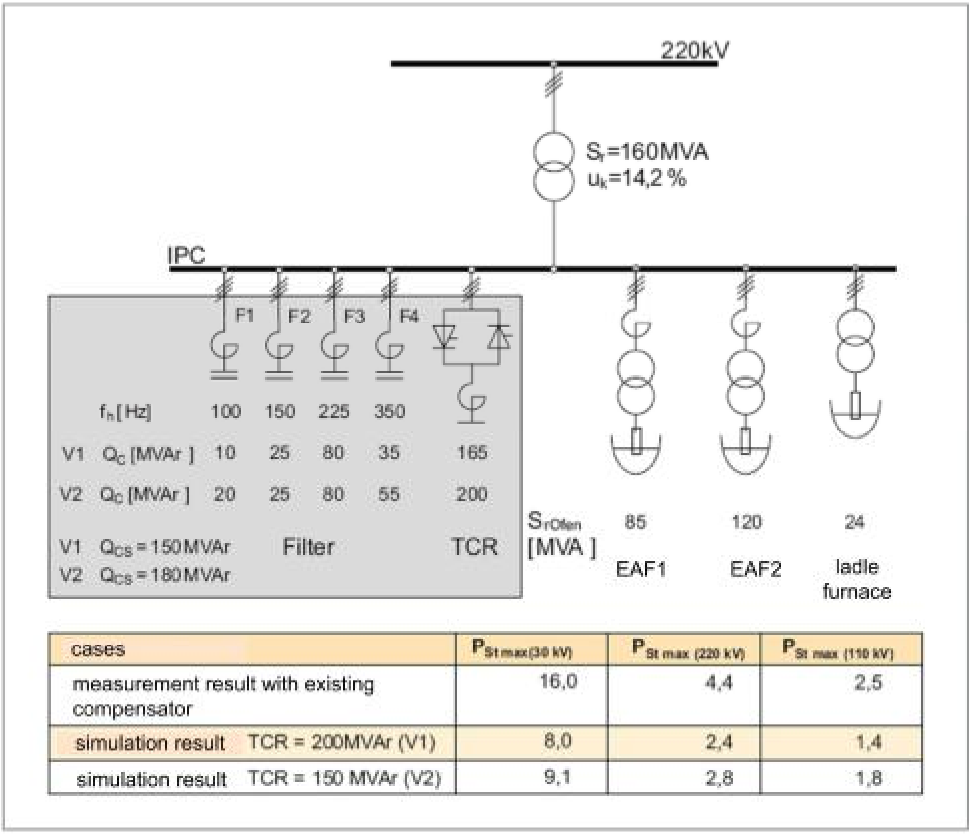


Fig. 4: Plots of the LBO2's active power and reactive load against time

The reactive power drawn fluctuates strongly. The maximum reactive power value Q_{max} exceeds twice the mean reactive power value Q_{mitt} in the course of the “restless” stage of the melt. When both of the three-phase AC electric arc furnaces are in operation at the same time under these conditions, a maximum reactive power of 180 MVAr can be drawn as part of the power supplied. For this reason, the rated power of the compensator was established as $Q_{C\Sigma}$ = 180 MVAr (shown as version V2). As maximum values always arise for only very short times where reactive power is concerned, the next smaller version of a compensator, this time with rated power of $Q_{C\Sigma}$ = 150 MVAr (version V1), was also investigated.

Two filters were added to the filter circuit (F1 and F4, see Fig. 5) and this also lessened the voltage displacement, predominantly in the range above 350 Hz. For this filter system design, the required rated power of the TCR was found to be 165 MVAr (version V1) or 200 MVAr (version V2).



	F1	F2	F3	F4	TCR
f_h [Hz]	100	150	225	350	
V1 Q_C [MVAr]	10	25	80	35	165
V2 Q_C [MVAr]	20	25	80	55	200

V1 Q_{CS} = 150MVAr
V2 Q_{CS} = 180MVAr

cases	$P_{St\,max (30\,kV)}$	$P_{St\,max\ (220\,kV)}$	$P_{St\,max\ (110\,kV)}$
measurement result with existing compensator	16,0	4,4	2,5
simulation result TCR = 200MVAr (V1)	8,0	2,4	1,4
simulation result TCR = 150 MVAr (V2)	9,1	2,8	1,8

Fig. 5: Results of comparative assessment of several variants

In order to prove the flicker-reducing effect of the SVC, simulation and computation based on the one-minute short-term flicker due to both furnaces being used at once for the melt at the "restless" stage were carried out. The contribution of the crucible furnace to the flicker is negligible and was therefore not taken into account for the computation.

Fig. 5 shows a comparison between the results of simulation for the versions investigated and actual measurements obtained when a TSC was used as the compensator.

The results show that the use of an SVC with Q_r = 180 MVAr will achieve the necessary flicker reduction in the 110-kV network. On the other hand it is clear that adequate flicker reduction is not yet possible with the 150-MVAr type of compensator. However, on closer analysis of the dynamic responsiveness of the 150-MVAr compensator as designed, it was seen that the windup arising under the given load in the PI regulator of the TCR was significantly impairing the electrical behaviour.

Windup arises when the range in which adaptation on the part of the control element should take place is not big enough to allow the actual value which is being regulated to reach the ideal value as set. This means that a control error will continue to be present which will result in a continuing rise in the mathematically integrated part of the regulator. In consequence, the control mechanism will have a delayed response when the polarity of the variation from the reference values changes, i.e. the control response time will be impaired. The windup effect is particularly apparent in the 150-MVAr SVC because complete compensation of the reactive power for the furnace(s) requires capacitive reactive power up to a level of 180 MVAr and the SVC is not capable of providing this.

The following diagrams show how it is possible to improve the electrical responsiveness of the less powerful compensator version (V1) by an anti-windup extension of the regulator to such an extent that flicker reduction which will meet the requirements is achieved.

Optimising control of compensator

To avoid the wind-up effect, the PI regulator (SVC) was extended by an additional mechanism.

The use of an additional limiter avoids mathematical integration of the control error (the windup effect) which arises when the range set for the compensation is not big enough fully to accommodate the necessary regulation of the furnace reactive power at certain times.

To illustrate the effectiveness of the anti-windup extension, Fig. 6 depicts a comparison of the network reactive power and how it changes over time in the branch supplying the network (on the 220-kV side) when there is a sudden change in the total reactive power of both furnaces:

- from Q_N = 120 MVAr to Q_N = 180 MVAr at $t \approx 0.1$ s (in the case of LBO1)
- from Q_N = 180 MVAr to Q_N = 120 MVAr at $t \approx 0.2$ s (in the case of LBO2)

between the picture with and the picture without an anti-windup extension of the regulator. The load variation investigated represents the "worst case scenario” for power change resulting from an overlap of the two electric arc furnaces, both operating at the “restless” stage of the melt

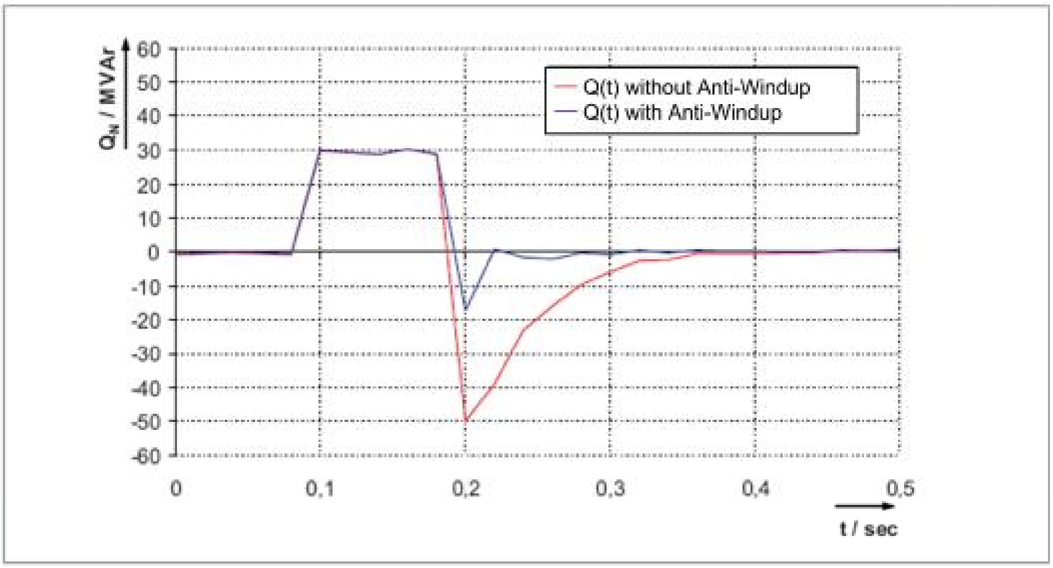


Fig. 6: Plot of supply reactive load against time (simulation result)

Fig. 7 shows the effective voltage values in the 110-kV grid for an urban area and how they change over time, firstly without and then with anti-windup extension of the PI regulator. The modifications as described improve the dynamic behaviour of the compensator to such an extent that flickering can be reduced in the 110-kV grid to P_{stmax} = 1.5 which corresponds to a (10 min) short-term flicker value of P_{st} = 0.8. The steelworks is still certain to function reliably. Also on a reliable basis, flickering is limited to permissible values in the downstream low-voltage networks serving the public. The compensation effect produced by the 150-MVAr SVC thus corresponds to that offered by 180-MVAr versions without anti-windup extension (cf. Fig. 7).

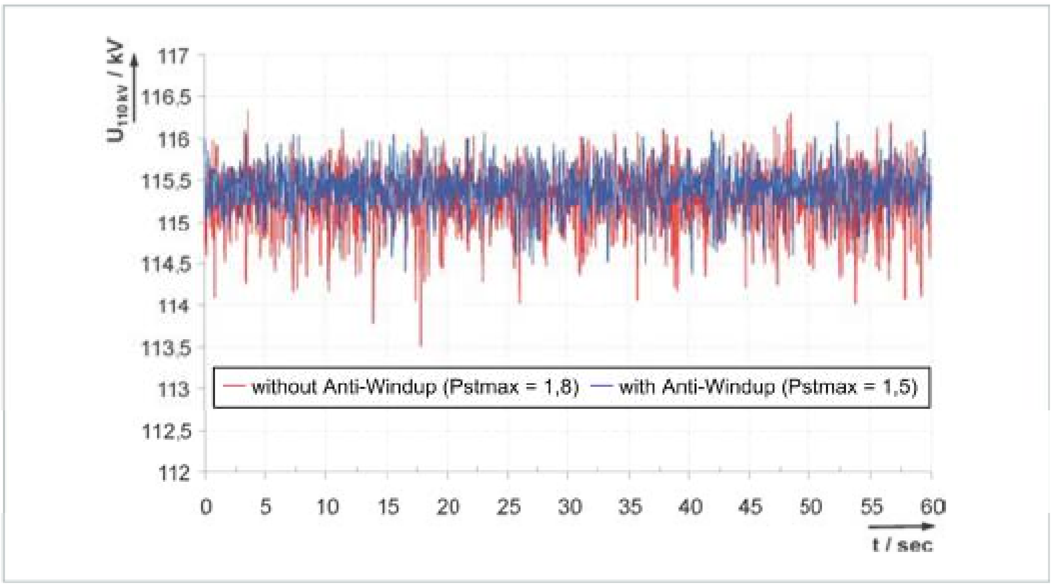


Fig. 7: Plot of supply voltage r.m.s. value in the 110kV system (see Figure 3)

On the basis of the investigations here presented, the SVC with Q_r = 150 MVAr can be considered the most technically and economically viable compensatory solution for the steelworks network. Using this type of compensator instead of the 180-MVAr type offers potential savings in investment costs to an amount of € 1.8 million.

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