VOLTAGE CRITERIA IN STEEL MILL NETWORKS

The need for reactive power compensation

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ABSTRACT

This paper presents a brief examination of the need to maintain the appropriate voltage quality in an industrial network, viewed both from consumer and utility standpoints.

Of particular interest are heavy disturbing loads in conjunction with sensitive parallel-connected equipment in urban areas.

1. INTRODUCTION

Reactive power appears in every AC power system. A great many loads consume not only active but also reactive power. The electricity network itself both consumes and produces reactive power. Transmission and distribution of electric power involves reactive power losses due to the series inductance of transformers, overhead lines and underground cables. Lines and cables also generate reactive power due to their shunt capacitance. This generation of reactive power is, however, only of significance at high system voltages.

2. REACTIVE POWER AND NETWORK DISTORTION SOURCES

2.1 Reactive power fundamentals

With phasor description of voltage and current, the reactive power supplied to an AC circuit is the product of the voltage and the reactive (wattless) component being in quadrature with the voltage.

For a single-phase circuit as shown in Fig. 1 the reactive power Q is defined as

\[ Q = U_e I_e \sin \phi \]

\((U_e \& I_e \Rightarrow \text{the r.m.s. value of the signal})\)

The unit is volt-ampere reactive, \text{var}. According to IEC Publ. 27-1 the unit abbreviation is to be in lower-case letters, while other power unit abbreviations are to be in upper case letters.

![Fig. 1](image)

As it normally occurs, with non-sinusoidal-shaped signals, the AC power can be calculated using fundamental formulas \( (u \text{ and } i \text{ are the instantaneous voltage and current signals}) \):

Active power \( (W) \)

\[ P = \frac{1}{T} \int_0^T u \times i \, dt \]

Apparent power \( (VA) \)

\[ S = \left( \frac{1}{T} \int_0^T u^2 \, dt \right) \times \left( \frac{1}{T} \int_0^T i^2 \, dt \right) \]

\((T \Rightarrow \text{one cycle of the fundamental frequency})\)

Reactive power \( (\text{var}) \)

\[ Q = \sqrt{S^2 - P^2} \]

The instantaneous power, \( p(t) \), is illustrated for different loads in Fig. 2.
2.2 Typical “disturbance sources”

In the industrial network of today more and more heavy power consuming machinery is being installed, often at a weak utility source.

Most parts of the load will consume not only active power but will also have a reactive power consumption characterized by a high average value and fast variation. Many loads act as harmonic generators distorting the fundamental feeding voltage.

- Important heavy loads:
  - Electric arc furnaces
    Alternating current arc furnace (AC EAF)
    Direct current arc furnace (DC EAF)
    Ladle furnace (LF)
  - Motor drives in rolling mills
    Thyristor converters and DC drives
    AC drives with cyclo converters
  - Induction furnaces
    Mains frequency operated
    Low/high frequency operated with thyristor converter

- Other critical loads:
  - Welding machines
  - Forge hammers and rammers
  - Mains frequency motor drives with frequent switching
  - Rectifiers
  - Fluorescent lamp installations

An example of disturbing equipment in a network can be seen in Fig. 4, which shows the net influence of a 12-pulse converter (DC EAF) operation. Both voltage and current are distorted caused by thyristor firings, the current signal is close to a "staircase" format and in the voltage signal commutation sags are clearly visible. The power factor is at this instant very low.

Depending on their behaviour and power compared with the feeding system fault level, arc furnaces can be regarded as the primary disturbance sources in a network. Through the rapid speed changes in their main drives, rolling mills can disturb a nearby network due to the fluctuation in the reactive power, in particular. They are also important harmonic current generators.

In the low voltage distribution system of a plant, equipment such as rectifiers and fluorescent lamps are sources of harmonic generation and operate at a low power factor. Standard induction motors will together consume a considerable amount of reactive power, and in the case of non-constant load torque (hammers, plunge-type pumps) also generate voltage fluctuations.
3. POWER SUPPLY QUALITY (= VOLTAGE QUALITY)

3.1 Cooperation consumer ⇔ power company

The power system can be described as a generating source, a feeding network with lines and substations connecting the consumer's internal plant distribution with "the outside world". The interconnecting point between the consumer and the utility is usually designated PCC (Point of Common Coupling).

Many countries around the world have recently started deregulating their former, often government-controlled power transmission system, and as a consequence one can observe increased so-called "wheeling" in the network. The power needed is purchased not from the nearby local utility but from a distant supplier with no direct electrical connection to the consumer's plant. This means that the power must be transmitted through the local distribution company's grid without enhancing the resources and performance for the company in question. On the contrary, this specific load may, by its vary nature, disturb the grid's power supply quality.

The different involved parties may of course have different basic interests (for instance, a reliable and low price power supply seen from the customer's point of view), but the tendency to make stricter rules and greater demands on the network quality at the PCC can be clearly observed.

Appropriate, skilled planning of the total system will become of increasing importance in the near future and four of the most common undesirable characteristic conditions which have to be avoided in the network are tabulated in Fig. 5 below.

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Fig. 5
A conventional solution in an industrial plant comprising distorting loads is to split up the network into several buses and to separate the different loads into "clean" and "distorted" systems.

Through having the step-down transformer's impedance's final series connected, in several voltage levels, up to the utility source, the influence on the surrounding power grid can be modified but the local network will still suffer from heavy voltage variations caused by the low short circuit level, which in a steel plant can be recalculated as an increased production cost, usually expressed in dollars per ton of steel.

The insertion of reactive power compensation will distinctly improve the situation.

3.2 Standards/demands

Greatly simplified, the power quality stipulations can be divided into:

- Reactive power consumption/power factor

As an example, the commonly accepted amount of reactive loading in the Swedish power grid has for many years been a maximum of 0.15 p.u. of the active load, corresponding to an average power factor of 0.99 (heavy industrial plants in Sweden are mostly connected into a 130 kV network).

Normally one does not discuss the instantaneous power load, instead integrating energy meters with maximum demand attachments are used and the maximum average value during a preset instant, say a 20-minute interval, will fix the rates and the energy costs.

Of further interest is whether a shorttime over-compensation (by fixed capacitor banks) is accepted or not. In many countries this is not permitted.

- Harmonic distortion, voltage unbalance and voltage fluctuation

Some examples of current standards and draft standards are listed below:

- IEC 555 Part 1, Part, Part 3
  "Disturbances in supply systems caused by household appliances and similar electrical equipment"

- CIGRE Working Group 36.05
  "Voltage Quality" PUBL. 36-203

- IEEE Std 519-1992
  "Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems"

- British standard P28 Sept. 1989
  "Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom"

- British standard G.5/3 Sept. 1976
  still in general worldwide use
  "Limits for harmonics in the United Kingdom Electricity System"

- British standard P.7/2 July 1970
  still in general worldwide use
  "Supply to arc furnaces"
In very condensed form, the commonly used limits are as follows:

- **Harmonic distortion**

**Harmonic Voltage Distortion** \( U_n \)

The r.m.s. amplitude of a harmonic voltage, of order \( n \), expressed as a percentage of the fundamental.

**Harmonic Current Distortion** \( I_n \)

The r.m.s. amplitude of a harmonic current, of order \( n \), expressed as a percentage of the fundamental.

**Total Harmonic Distortion** \( \text{THD} \)

Expressed as a percentage of the fundamental, and calculated using the expression:

\[
\text{THD} = \sqrt{\sum_{n=2}^{\infty} U_n^2}
\]

The standards differ in their recommendations but generally it is sufficient to use values of \( n \) up to 19 (\( n = 19/40/49 \) are in use)

Indicative values in standards are

- \( \text{THD} \) 8 % in LV-MV network (CIGRE)
- 5 % in LV-MV network (IEEE)
- 3 % in HV network (CIGRE)
- 1.5-2.5 % in HV network (IEEE)

and for an individual harmonic voltage the limitations may be 0.5 % up to 1.5 % depending on the system voltage level, and in some standards also on whether the signal represents an even or odd harmonic.

Further, also the harmonic current distortion should often be kept below a value expressed as a fraction of the connected loads fundamental current.

- **Voltage unbalance**

The unbalance is basically defined by the negative sequence unbalance factor, which is the ratio between the r.m.s. values of the negative sequence component and the positive sequence component.

\[
Un = \frac{U_{-}}{U_{+}} \times 100\%
\]

Expressed in figures, an voltage unbalance \( Un \) of 2 % is often accepted in LV-MV networks, and 1 % in an HV network.

- **Voltage fluctuation and flicker**

Many papers on voltage fluctuations have been published over the last few years and here we simply wish to stress the difference between very low frequency fluctuation, which can be dealt with by, for instance, transformer tap-changers, and the much more irritating fluctuation with a range of some Hz. It is only the latter which should be designated “flicker”.

In IEC Publ. 868 a standard flicker instrument is described, usable in 50 and 60 Hz systems. Other types of instrument exist in the market such as the \( \Delta V10 \) meter developed in Japan and widely used in Asian countries. As all these instruments use different algorithms, there are difficulties in comparing results from measurements.

Fig. 7 shows an example of planned limits of acceptable voltage fluctuations in the Swedish national 220-400 kV power grid.

![PERMISSIBLE VOLTAGE FLUCTUATION](image)

**Fig. 7**

In the IEEE Std 519 Fig. 10.3 two curves are plotted, "border line of irritation" and "border line of visibility"; showing the flicker frequency range more in detail.
4. CORRECTIVE ACTION AND POSSIBLE IMPROVEMENTS

As discussed above, both the consumer and the power supplier suffer if the system voltage quality cannot be kept within acceptable limits.

Of importance in this connection is the reactive power consumption, which can be clearly seen in the simple phasor diagram in Fig. 8 below showing the voltage drop caused by a line impedance (the impedance may of course also represent a transformer or a cable network).

![Fig. 8](image-url)

The voltage drop is defined by

$$\Delta U = |U_1| - |U_2|$$

The equation can be approximately rewritten and expressed by

$$\Delta U = RI \cos \varphi + XI \sin \varphi$$

or

$$\Delta U = \frac{(RP + XQ)}{U_2}$$

$X$ is usually much larger than $R$ and a change in the reactive load $Q$ will create a high voltage variation on the load side if not counteracted by a reactive power shunt compensator.

A minor step change in the reactive power will cause a corresponding voltage change expressed approximately by

$$\Delta U = \frac{\Delta Q}{Ssc} \times 100 \%$$

where

- $\Delta Q$ = a change in the reactive power injection (leading or lagging)
- $Ssc$ = network short circuit capacity or “fault level”

4.1 Power factor correction with capacitors

Through shunt compensation using capacitors, that generate reactive power into the network it is possible to decrease transmission losses.

However, the power factor correcting equipment can be located differently, as illustrated in the well known Fig. 9 below.

![Fig. 9](image-url)

A Central plant compensation on the HV side
B Central plant compensation on the MV side
C Group compensation
D Individual compensation
Location of the compensating equipment "inside" the plant (B and C in the Fig. 9) will often be the recommended solution, based on combined functions of power factor correction and filtering of harmonic distortion caused by the load.

In the simple power system in Fig. 10 the possible "take out" load is limited by the stepdown transformer rating. With a normal load consisting of small induction motors the system power factor will be low, and by adjusting the power factor more power will be available ($S'_L < S_L$) and can be utilised in the plant.

4.2 Filtering

Many plant loads, from small PC units and fluorescent lamps up to the very large EAF installations are sources of harmonic generation and are normally responsible for high reactive power consumption.

By building up the capacitor banks needed for power factor correction in the form of tuned filters the network harmonic distortion can be kept to an acceptable level.

The use of tuned filters will also minimize the resonance risks between the inductive network and the capacitor.

In a low voltage distribution system with moderately fluctuating load, group compensation equipment can consist of a set of contactor switched capacitors which, with a static var controller, stepwise correct the load power consumption.

In an HV system, "fixed capacitors" operated on/off via ordinary circuit breakers are in frequent use, but in plants with rapidly fluctuating loads such units are not sufficient and a static var compensator with dynamic control should be inserted.
5. STATIC VAR COMPENSATORS (SVCs)

A thyristor-controlled static var compensator (SVC) is a static shunt reactive device, in which the reactive power generation or absorption can be varied by means of thyristor switches.

5.1 The thyristor

Some definitions.

“A thyristor is defined as a semiconductor device with a bistable characteristic, comprising three or four pn-junctions. It can be switched from the off-state to the on-state or vice versa in one or two directions”

The SVC equipment uses the reverse blocking type triode thyristor with the graphical symbol:

Fig. 13

Two examples of typical thyristor data:

U\textsubscript{DRM} & U\textsubscript{RRM} 6500 V  I\textsubscript{TRSM} 2820 A  
(thyristor type YST 45-28 P65)

U\textsubscript{DRM} & U\textsubscript{RRM} 5200 V  I\textsubscript{TRSM} 5250 A  
(thyristor type YST 60-23 P52)

Index:

D = blocking  
R = reverse blocking  
T = on/forward  
S = transient  
M = maximum

SVCs

Two types of thyristor controlled element are used in SVCs

- **TCR** Thyristor Controlled Reactor
- **TSC** Thyristor Switched Capacitor

The latter type is normally not used in SVCs for industrial applications today, but many older installations still exist.

5.2 Thyristor Controlled Reactor

Fig. 14 shows the basic diagram of a TCR.

Fig. 14

An SVC consisting of a TCR and a set of filters (FCs) forms a high speed dynamic reactive power controller with continuous variable reactive power generation. By use of phase wise power control, unbalance in the compensated load phase power is corrected.

Fig. 15
5.3 Features with a dynamic device

In load cases with comparative stable operation the power factor correction equipment can easily be composed of a set of capacitor banks. Larger loads and loads with fluctuations in reactive power such as arc furnaces and main drives in rolling mills are rarely capable of correction by fixed capacitance, and over-compensation in no load conditions especially, is a serious problem. It should also be noted that insertion of a capacitor bank by itself will only move the system voltage up to a higher level and will not stabilise the voltage when the load varies.

By using the dynamic type of power factor correction device these disadvantages are largely avoided. Fig. 16 displays one result from a field measurement. Plotting the furnace bus variation with and without the dynamic compensator in use, one readily notices the positive influence of the SVC. A more stable voltage means that more power is available for process needs with EAFs.

The difference between the no-load voltage and the voltage at the intended operating load point is illustrated in Fig. 17. The bus voltage with only a power factor correction capacitor in operation is very high; well above the standard ANSI 10 % limit. However with the furnace in operation, the busbar voltage has dipped significantly below the comparable voltage level maintained by insertion of an SVC. As a result, operation with an SVC, maintaining a more modest no-load voltage, will increase the active power input to the furnace in this case by approximate 15 %.

The SVC ability of decrease the flicker content at PCC has been described in several papers. In practice, it is difficult to make comparable measurements in a plant with a highly fluctuating load such as an EAF. Without the SVC the bus voltage level will drop as described above and the EAF’s active power as well as the power factor will change. In Fig. 18, a cooling pump was mistakenly stopped and thereby the SVC tripped in a situation with relative low load condition in a multifurnace (two EAF’s and an LF) installation. Before the SVC was restarted, it can be seen that the disturbing influence expressed as the "vf" voltage fluctuation in percent per minute is attenuated down to about half the value of operation without SVC.

(The signal "vf" represents the total r.m.s. value of signals of frequencies between 1 to 30 Hz amplitude-modulated to the fundamental "carrier" frequency as per the previously used British ERA flicker measurement method).
6. FIELD MEASUREMENTS

With reference to the CIGRE paper Publ. 36-203 one must be aware that measurements regarding voltage quality generally are long duration measurements followed by statistical calculations necessitating the use of computers before an accurate judgement of the quality can be made.

For statistical handling IEC recommends different time intervals, starting with:

- very short time interval (Tvs): 3 s
- short interval (Tsh): 10 min
  and then the longer intervals
- one day interval (Td): 24 hours
- one week interval (Twh): 7 days

At the end of the observation time (say a 24-hour period) the 95 % cumulative probability value is generally to be retained and compared to the compatibility level.

Fig. 19 illustrates one such measurement over a 24-hour period.

7. SUMMARY

By installing reactive compensation on large loads, a number of gains will be achieved, technical as well as economical:

- An improved power handling capability
- A decrease of network losses
- Suppression of harmonics
- Improved bus and system voltage control
- Lower specific costs of electricity
  (more favourable power tariffs)

References

[2] SVC for voltage stabilization and harmonic suppression in ladle furnace rolling mill ABB Pamphlet A02-0132 E
[3] Static Var Compensation of AC and DC furnaces in joint operation ABB Pamphlet A02-0143 E