Power quality in supplying welding networks in the automotive industry

Dietrich Stade, Helge Schäfer, Peter Ulrich

Preface

In many industrial sectors, electric resistance welding is a standard production process. The short pulses of current on which the welding process depends cause huge, rapid variations in the apparent power (ΔS_A).
The duration (T) of a welding pulse will be between 60 and 600 ms, and these pulses are repeated 10 to 150 times a minute, which is the repetition rate (r).
These successive sudden variations in apparent power bring about voltage changes, deviations and flicker which may cause unacceptable or troublesome interference in the power network. It often goes unnoticed that the variation in the apparent power (caused by load variation) brought about by welding machine usage is manifold (as much as three-, four-, or fivefold) in relation to the nominal capacity (rated power) when switched on for 50 % of the time. Likewise, it may be as much as 80 % of the short-circuit power. Hence remedial treatment is necessary.
The consequences (such as flicker) of undue voltage changes and deviations may be:

- an operating ban for the machine/station (for breach of compliance)
- reduced productivity of the machine
- reduced product quality (e.g. inadequate strength of welded joint)
- costly remedies of electric installation in terms of time and money
- belated installation of compensatory equipment lead to a rise of unplanned investment costs
- disruptive effects on end-user installations across downstream, upstream networks or on the same level as each other
- a disruptive influence on information and automation equipment
- fluctuations in the luminance emitted by luminaires (flicker).

There are distinctions to be made between public utility grids and industrial networks.
The amount of interference permitted to be caused by voltage changes in public utility grids is limited by their reference curve (Fig. 1), where:

medium voltage (MV): d_{Grenz} = 2 %; low voltage (LV): d_{Grenz} = 3 %
(for r < 0,01 min^{-1}: MV: $d_{max} \leq 3$ %; LV: $d_{max} \leq 6$ %)

To prevent a public low voltage grid exceeding a total flicker level of P_{st} = 1, individual network users must adhere to the following values:

short-term flicker value (10-minute value) P_{st} = 0.8 and
long-term flicker value (120-minute value) P_{lt} = 0.5.

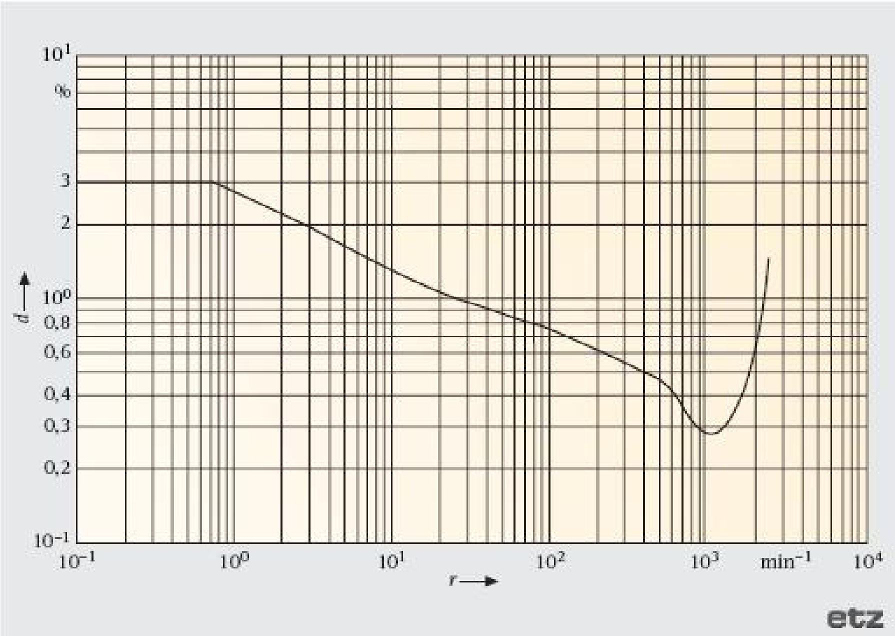

Fig. 1: Reference curve d_{ref} (r) for P_{ref} = 1 and regular, rectangular voltage changes [1]

In an industrial power system it is useful to follow the above limits at all IPCs, while, at the same time and at all costs, taking note at the planning stage of all prescribed operating features and operational requirements.

Principles of calculation

The voltage change (ΔU) which is produced by variations in apparent power (ΔS_A) is, as a good approximation, the variation in the longitudinal voltage.

Using the equations

$$\Delta S_A = \sqrt{\Delta P_A^2 + \Delta Q_A^2} \quad \textit{and}$$

$$j_A = arc \tan \frac{\Delta Q_A}{\Delta P_A}$$

the figure for relative voltage change when the load is symmetrical and three-phase comes out as:

$$d = \frac{\Delta U}{U} \cdot 100\% = \frac{\Delta S_A}{S_{kv}} \cos(\psi_k - \varphi_A) \cdot 100\%$$

S_{kv}: minimum short-circuit value at point of load variation

ψ_k : impedance angle

and for single-phase loads with a connection at L1 and L2 for the external wire to neutral wire voltage:

$$d_{L1-N} \approx \frac{\Delta S_A}{S_{kv}} \cdot \sqrt{3} \cos(\psi_k - \varphi_A + 30°) \cdot 100\%$$

$$d_{L2-N} \approx \frac{\Delta S_A}{S_{kv}} \cdot \sqrt{3} \cos(\psi_k - \varphi_A - 30°) \cdot 100\%$$

$$d_{L3-N} \approx 0$$

For rectangular (equidistant) voltage changes the permissible voltage change (d_{zul}) for an individual network user with a known repetition rate (r) is easy to determine.

Using the equation: $P = \frac{d_{Grenz}(r)}{d_{ref}(r)} \cdot 1$ in per units (p.u.) the answer is:

$$d_{zul}(r) \leq d_{Grenz}(r) = 0{,}8 \cdot d_{ref}(r)$$

to enable the short-term flicker value to be maintained as (P_{st} =0.8) and to enable the long-term flicker value to be kept at (P_{lt} = 0.5).

$$d_{zul}(r) \leq d_{Grenz}(r) = 0{,}5 \cdot d_{ref}(r)$$

If the reference curve is approximated in accordance with Fig. 1 (P_{ref} = 1) in the area covered by r = 1 min^{-1} up to r = 1000 min^{-1}, for square, equidistant voltage changes (F = 1), using mathematical analysis, then:

$$P_{ref.}^{3,2} = (d_{ref} \cdot F)^{3,2} \frac{r}{27} = 1$$

F: form factor (here F = 1)

It follows that:

$$P^{3,2} = (d \cdot F)^{3,2} \frac{r}{27}$$

and thus that:

$$P = 0.36 \cdot d \cdot F \sqrt[3,2]{r}$$

d in %; r in min^{-1}

The form factor can be looked up in Fig. 2 for the rectangular pulses produced, for example by welding machines, by referring to the pulse duration (T).
If the voltage changes of individual flicker sources (i) are low in probability of coincidence, then the sum of the flicker effect will be:

$$P_{\Sigma} = \sqrt[3,2]{\sum P_i^{3,2}} \,.$$

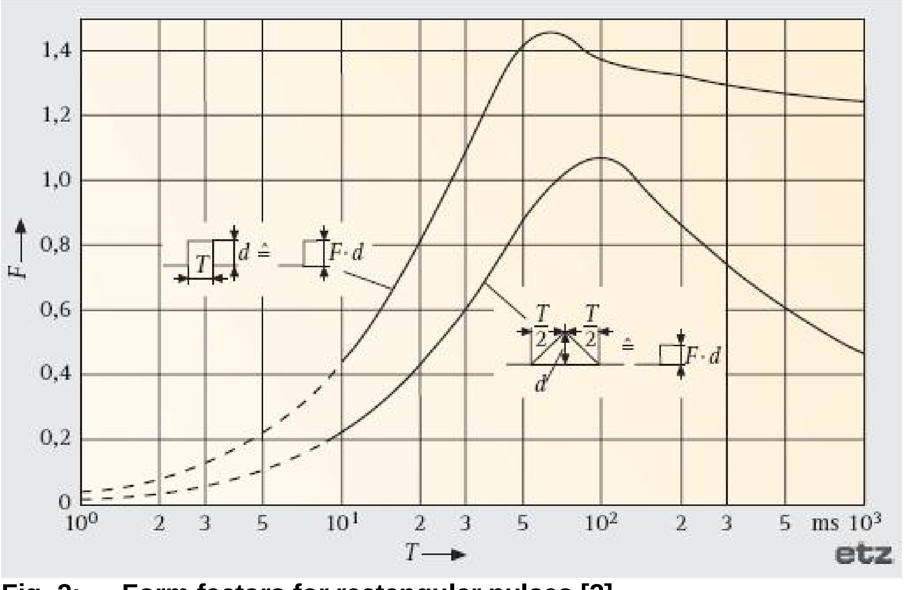

Fig. 2: Form factors for rectangular pulses [2]

Flicker disturbances in a 20-kV public grid resulting from an unregulated welding machine and how to cure them

An unregulated pressure welding machine with phase AC current operating in a company's low-voltage network may cause an unacceptable long-term flicker value in a public 20-kV grid when it is switched on.

Fluctuations in the luminance (or flickering of the light), $P_{st} > 1$, will result.

Fig. 3 is a highly simplified diagram of the grid showing the most important grid details for the 20-kV grid and the figures for the pressure welding machine (PWM).

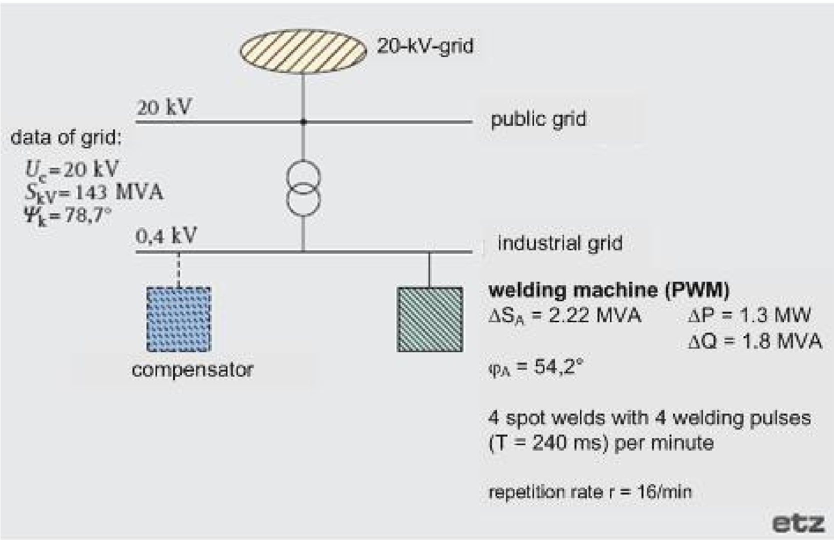

Fig. 3 simplified diagram of the grid

Flicker calculation (by mathematical analysis) leads to the following algorithm:

Relative voltage change: $$d = \frac{2.22}{143}\cos 24.5° \cdot 100\,\% = 1.4\,\%$$

Form factor (Fig. 2): T = 240 ms $\rightarrow$ F = 1.3

Long-term flicker: $$P_{lt} = 0.36 \cdot 1.4 \cdot 1.3 \cdot \sqrt[3,2]{16} = 1.56$$

Result: d = 1.4 % < d_{Grenz} = 2 % is ok, but flicker level is very high:
P_{lt} = 1.56 > $P_{lt\ Grenz}$ = 0.5

Here, the limit for human recognition of a flicker is significantly exceeded. Reduction of the flicker level by means of a compensatory system is preferable to costly changes to the grid (for example, raising of the short-circuit power S_k).

Flicker compensation

If a compensation condenser is switched on at the same time as the welding pulse starts, it will ideally be possible to eliminate the relative voltage change.
The compensatory figure for d = 0 will be $Q_C = \Delta P\left(\cos\psi_k + \tan\varphi_A\right) = 2.06\,MVAr$.

It must be said that staggered switching of the compensatory equipment either on or off (with a delay of T_V) will give two pulses. The repetition rate r will be doubled and the permissible range of the interference pulses will be determined by the length of the delay.
As the T_V is reduced, the flicker will be brought down to the permissible level.

$P_{lt} \leq P_{Grenz} = 0.5$ requires a form factor of:

$F \leq \frac{0.5}{0.36 \cdot 1.4 \cdot \sqrt[3,2]{32}} = 0.34$ and this is reached at $T_V \leq 7$ ms (see Fig. 2).

The effect is achieved with a compensation system with thyristors as this is able to cope with fast and frequent switching. The moment for switching the thyristors is decided by the current measurement or by direct control from an external trigger, e.g. on the welding machine.

How to ensure voltage quality in the case of a number of unregulated welding machines

In a known case, when the welding shop of an automotive manufacturer which contained a number of welding machines with various power usage was relocated, there was a reduction of the short-circuit power in the 20-kV network supply down to approx. 60 % of the original. The power supply to the welding shop is now provided by a 20-kV network internal to the company supplying three equal 525-V low voltage networks with rated power of 7.5 MVA which are exclusively used for the operation of unregulated welding machines with three-phase AC current (see Fig. 4).
It was necessary to select a suitable compensation plan and to organise the relevant equipment.

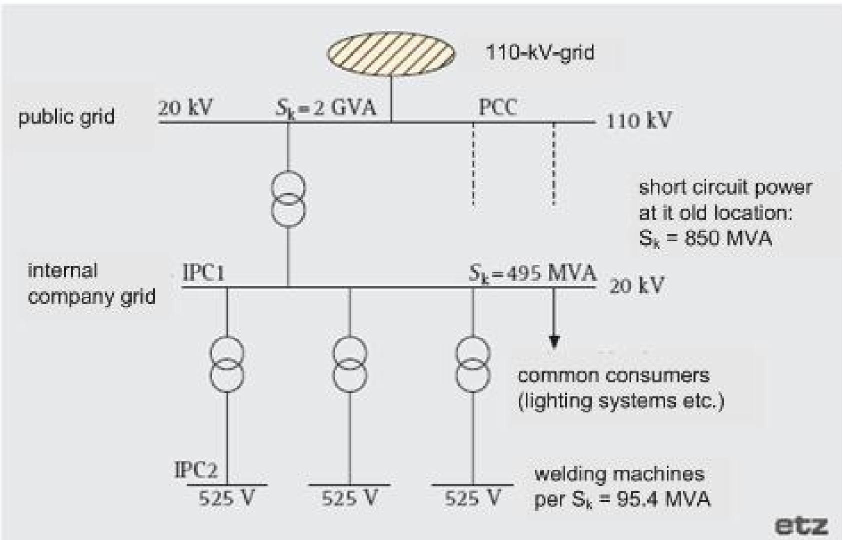

Fig. 4: Highly simplified grid diagram for the network supplying power to the welding machines

In all three welding networks (Fig. 4) there are two heavy-duty pressure welding machines which may affect voltage by as much as 8 % when welding at high power. In addition, there are about twenty small and medium-sized pressure welding machines in each of the network sections. The 20-kV network is also used to supply other departments within the company. Among other things, a number of lights are connected to the three network elements.

The following picture, different from that in the first case shown above, has developed in respect of maintenance of voltage quality:

- The in-company electricity supply is coupled to the public grid on the 110-kV side (as a PCC). This is the point at which the requirements listed above ($d \leq 2$ %; $P_{lt} \leq 0.5$) have be guaranteed, quite simply in this case because of the high short-circuit power in the 110-kV grid.
- It is adequate for the in-company 20-kV network (at IPC1) to limit the voltage changes to 2 %, thus avoiding interference with production equipment. A figure of 1.5 p.u. for the P_{lt} can be tolerated, as this does not exceed the recognisability level in the downstream low-voltage networks with neon striplights used for illumination.
- Maintenance of the flicker level is irrelevant for the 525-V welding networks themselves (at IPC2). The size of the permissible dip in the voltage depends on the associated lowering of the welding power for the unregulated welding machines so there is no loss of weld quality.
  In the case cited, it was found that the permissible voltage drop was d = 6 % (i.e. 94 % of the agreed supply voltage is maintained). Individual compensation was not used in any of the welding machines, even in the largest, because, as shown in the first exemplary case, it is not possible to limit the voltage drop in this situation.

Remedy

An intelligent limiting system for the grid or network which gives the signal for a welding machine or cascade of welding machines to start up will ensure that the voltage drop in the low-voltage network affected is partially reduced in such a way that there will always be power at least 94 % of the contractual voltage serving each welding operation. This limiting method must be used in conjunction with a rapid-response reactive power compensation system, in the form of an IGBT-converter for the output current with DC link. In the present case, the compensatory power was set to enable maximum productivity in the welding complex if the limiting value of d = - 6 % is applied. The alternative, unacceptable network restrictions which would have impacted on production were thus not necessary (see Fig. 5).

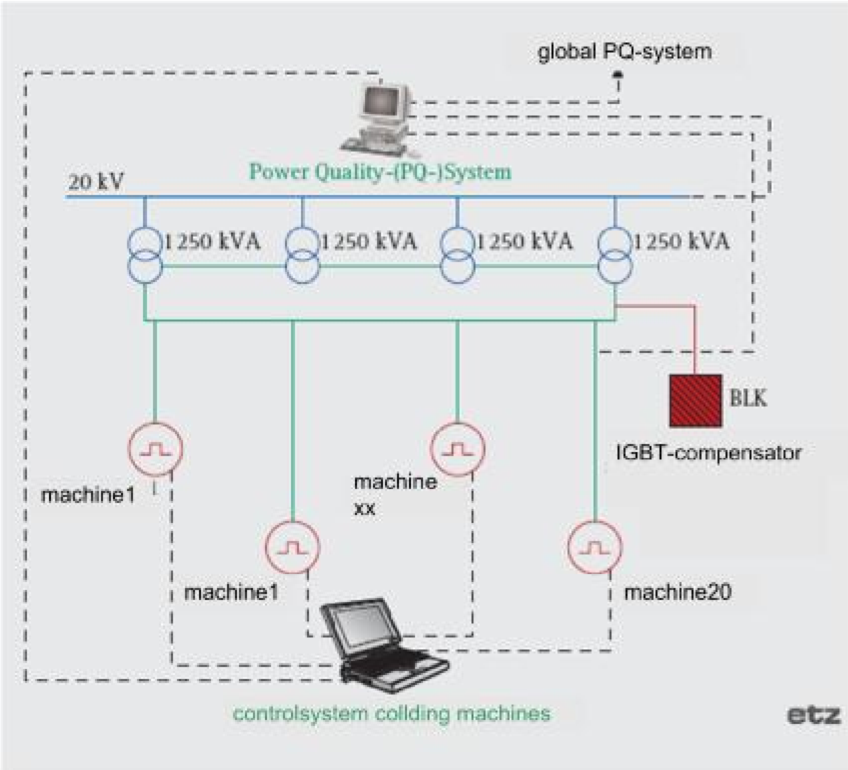

Fig. 5: Structure of system, simplified

The method reduces the compensatory power required to about 25 % of that which would be needed for individual compensation of welding machines. As such, it offers significant savings on investment costs while providing full assurance that productivity requirements are met.

In the same case, it was also necessary to check the flicker situation in the 20-kV network. For this purpose, a worst case scenario was taken in which the two largest welding machines in each element of the LV network, which normally work asynchronously, were to cause a voltage drop in each part of the LV network of at most 6 % when working in conjunction with the compensatory equipment. The calculations and values applied to this case for working out P_{lt} were :

- T = 500 ms (F = 1.3 for rectangular pulses as in Fig. 2)
- d_{NS} = 6 %
- r = 8

The flicker value which results from the aggregated flicker of the three networks for the medium-voltage network (at IPC1) is thus:

$$P_{lt(IPC1)} = 0.36 \cdot 1.3 \cdot 6 \cdot \frac{95.4}{495} \sqrt[3,2]{8} \cdot \sqrt[3,2]{3} = 1.5\,.$$

There is no disturbing effect for the works in general from a long-term flicker value of P_{lt} = 1.5 in the lighting (fluorescent strips).

Bibliography

[1] DIN EN60868-0 (VDE 0846 Part 0): 1994-8 ; Berlin-Offenbach
[2] Grundsätze für die Beurteilung von Netzrückwirkungen
3. revised edition 1992, published by the Vereinigung Deutscher Elektrizitätswerke – VDEW – e. V.