Providing a quality electricity supply for welding machines – essential to productivity and product quality

Preface

In automotive manufacture, electric welding machines are used in many ways. To obtain consistently high quality for the welds these machines make, it is necessary to have a supply voltage of sufficient quality. Recognising this, Daimler AG integrated quite early into the company's internal quality assurance system a further system which would take account not only of the quality factors attributable to humans, machines and materials but also of the factor represented by the quality of the electrical supply. Daimler sees this as a fourth determinant, the "medium". This article gives the example of a major group of high-performance pressure welding machines which required a new electricity supply because of factory renovations, showing how the issues of high productivity and reliable weld quality during production must be raised during the planning and execution stages for the new electricity network.

Starting position and targets

In the automotive industry, one of the typical manufacturing processes is electric welding. The motor car has very many welded joints for which fully automatic welding lines are necessary. Electrical pressure welding machines (PWMs, fig. 1) with a range of power ratings are linked together in a high number of special electrical supply networks (welding networks). With these PWMs, spot-welding of steel sheet is carried out.

Fig 1. Electrical pressure welding machine in automotive manufacture

It is essential when planning the welding network to pay extreme attention to the feedback effects of the PWMs on the mains electricity supply. Various preliminary investigations carried out at reference installations [1] had earlier shown that when the short-circuit power S_k in a 525-V welding network is approx. 100 MVA, it is still possible regarding distortion and asymmetry in the supply voltage to operate unregulated, direct current PWMs up to a maximum rated power per machine of approx. $S_{50\%ED} \approx 1.8$ MVA when the machine runs for 50 % of the time and the EMI compatibility requirements in class 2 of EN 61000-2-4 are observed [2]. As no luminaires are supplied by the network for the welding, flicker is only estimated for the upstream medium voltage grid.

However, the picture is different for the assessment of the rapid voltage changes caused by the PWMs. As is well known, when such welding machines are used, a maximum load variation of $\Delta S_A = (3 \ldots 5)\ S_{50\%ED}$ [1] must be allowed for. If a welding network is supplying many unregulated PWMs, and the pulses last up to 600 ms, it can be assumed that there will be aggregation of the welding pulses from several machines. Welding machine operation thus causes deviations from the (contractually) permitted voltage U_C in the supplying network. It has been concluded from systematic quality assurance tests undertaken over a long period of time on welded joints for and with Daimler AG [3, 4] that, until there is a dip in supply voltage in a welding network to below a typical limit, no loss of quality in the weld is to be expected, as the welding current pulse does, indeed, give the necessary energy input for a good weld, i.e. for actual welding action while the pulse lasts. It is imperative to implement measures to limit the relative voltage change, i.e. the dip. This method makes it possible to eliminate the “medium” of electricity as a cause of quality loss in welding. It is here assumed, of course, that all other influences which affect the quality of the welding process, such as electrode pressure or the burn-off of welding electrodes, come within the permitted limits.

At the Daimler AG location considered in this instance, the electricity supply and automation system were redesigned for the existing infrastructure and for the three large pressure welding complexes comprising approx. 45 PWMs in all. The power of the individual PWMs varied from 1 up to a maximum of 5 MVA. The new plan had the following aims:

- considerably to improve the efficiency of the welding networks by using a rapid-response reactive current compensator,
- to provide automated clearance of each PWM to start welding only if the permitted quality parameters for the voltage supplied to the welding network would not be infringed. The welding network parameters to be monitored additionally by an upstream EEQ system.
- to ensure, by measuring the take-up of active and of reactive power by each PWM during all welding activity, that quality would be maintained for every weld but productivity would be maximised.

PWMs cause rapid changes of load ΔS_A in the feeding electrical grid

The majority of the PWMs in the welding complex operate with direct current (DC). The DC required for the welding is provided by a 6-pulse rectifier connected by means of a welding transformer to the 525-V alternating current welding network. A 3-phase thyristor bridge is used to set the right welding current I_{PSM} (Fig. 2). There is a small number of PWMs for which the DC is produced with the aid of a frequency converter with dc link and a medium frequency welding transformer (with a rectifier) connected to its output.

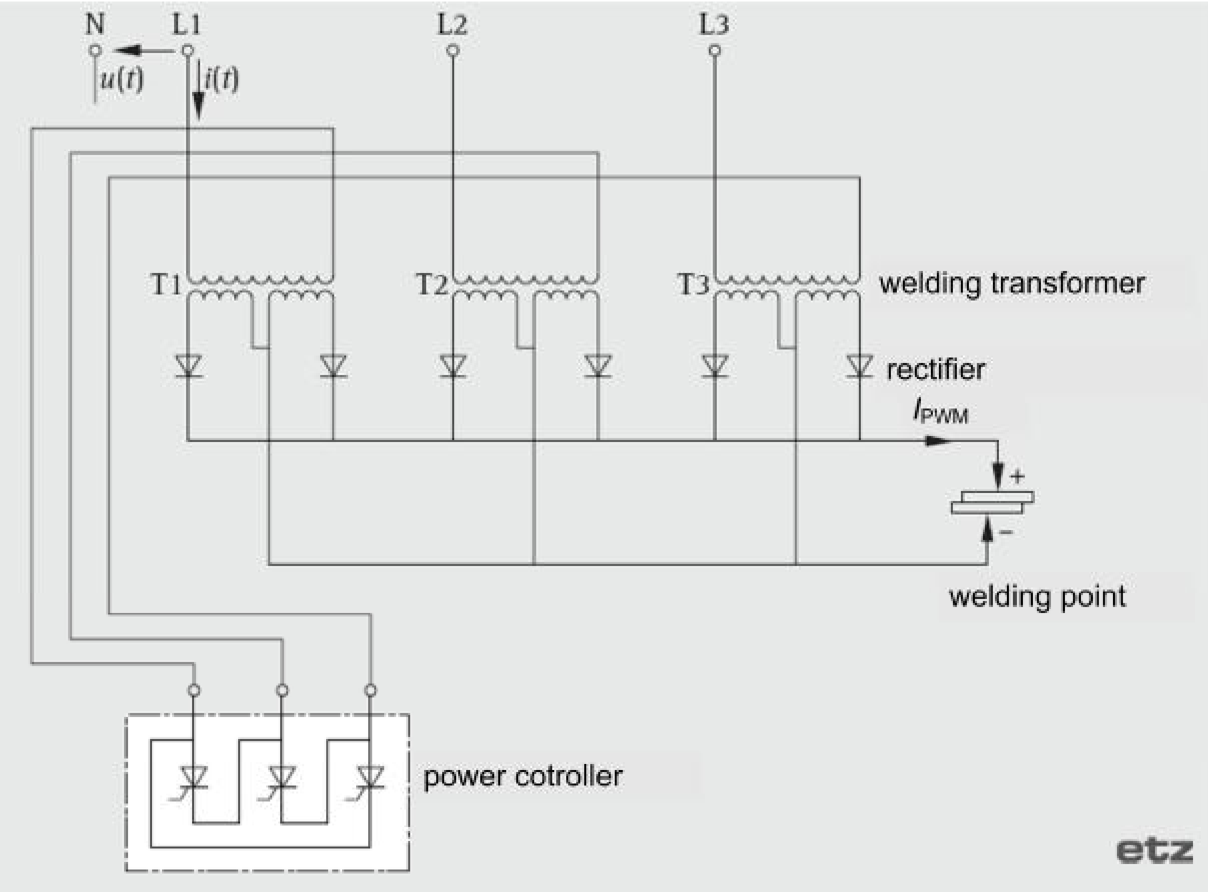

Fig 2. Frequently used basic circuit for the supply of a PWM

Fig. 3 shows the typical graph for the active input current from the grid into a PWM. The graph is formed on the basis of instantaneous values as 10-ms RMS values without any overlap.

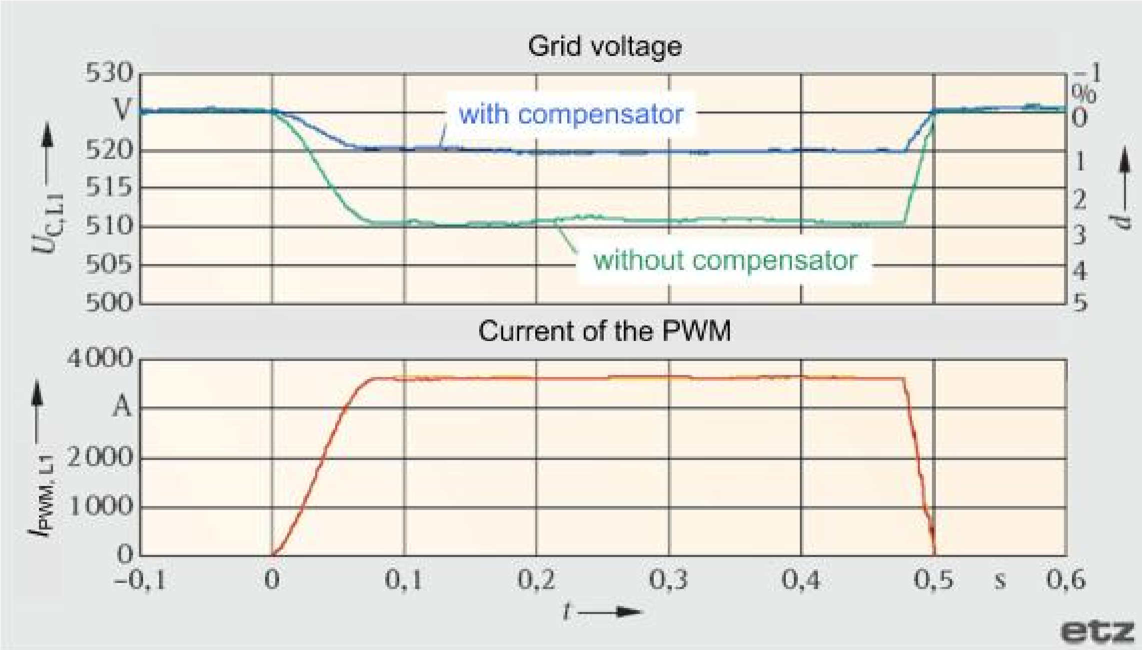

Fig. 3. Effective values of the input current and the supply voltage of a PWM during a welding pulse in line 1 with and without compensation

According to [5], it can be assumed that the change in the apparent power of the PWM to be expected for the load change caused by the PWM will be according to the following equations:

ΔS_A = (3 … 5) $S_{50\%ED}$ or (1)

ΔS_A = 0.8 S_{kM} (S_{kM}: short-circuit power of the welding machine) (2)

A displacement factor for the shift in the basic wave which describes the power relations on the grid side of a PWM has been derived from measurements taken by the author. This factor is cos φ_1 = 0.3 … 0.7 (with a mean of cos $\varphi_1 \approx 0.4$). The welding pulses last Δt_A = 0.04... 0.6 sec. When cascade welding takes place, a number of welding pulses follow one upon the other.
The rated power of the PWMs lies in a range of $S_{50\%ED}$ = 600 … 1800 kVA.

Welding network – a high-performance, low-voltage network with multiple power sources

Fig. 4 shows the basic construction of a welding network. The short-circuit power of the upstream 20-kV network is approximately 640 MVA. The mean short-circuit power to be found at connection or coupling points for the PWM is S_{kV} = 106.2 MVA and the grid impedance angle ψ_V is 76.7°, when the impedance for any input transformers and the wiring or cables is taken into account. The grid relations at the connection point for the PWM are thus characterised by the

grid impedance z_V = 0.94 %/MVA

grid reactance x_V = 0.92 %/MVA and

grid resistance r_V = 0.22 %/MVA drawn.

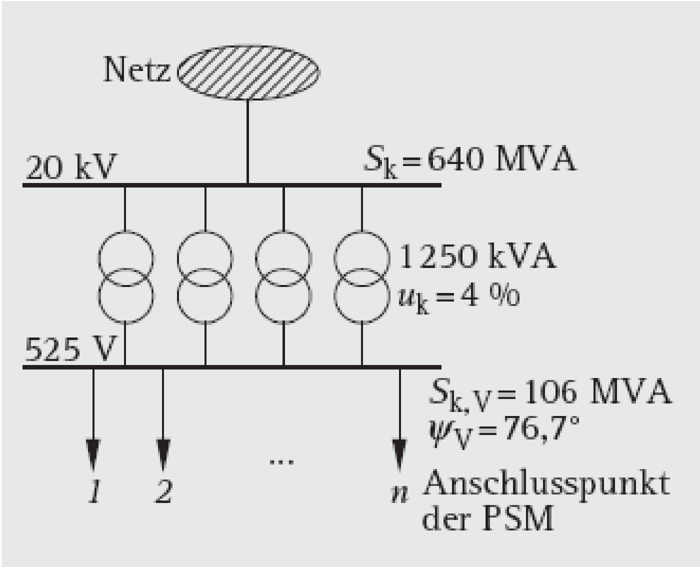

Fig 4: Simplified 525 V welding network with several PWMs

Voltage changes to be limited to 4 %

Systematic analysis of the welding process and the load changes resulting from it which was carried out on a reference plant for a similar manufacturing process provided the information that the desired productivity of the plant can be calculated if there is a change in the active load to $\Delta P_{A\,max}$ of 2.6 MW caused by two or a number of PWMs welding at the same time. To cope with this type of load, the upstream welding network must be set for a permitted voltage change of $d_{zul} \leq 4$ %, for quality maintenance purposes.

The percentage voltage change d can be calculated approximately, but with good enough accuracy, for the network situation and welding pulses from the PWMs here presented:

$$d = \Delta P_A r_V + \Delta Q_A x_V. \qquad [d]: \%; [\Delta P_A; \Delta Q_A]: MVA \qquad (3)$$

Because $r_V/x_V = \cot \psi_V$ and $\Delta Q_A/\Delta P_A = \tan \varphi_A$, an average $\cos \varphi_A$ of 0.4 is the result of equation (3) and thus the maximum permitted active load change:

$$\Delta P_{A\max\ permit} \leq \frac{d_{zul}}{x_V\left(\cot y_V + \tan j_A\right)} = \frac{4}{2.3} = 1.74\ MVA \qquad (4)$$

However, it is impossible to avoid synchronous welding on the part of a number of PWMs if productivity is to be maintained for the welding process. This requires a $\Delta P_{max} > 1.74$ MVA.

But the formula $\tan\varphi_A \cdot \tan\psi_V \geq 5 >> 1$ makes it plain that the drawing of reactive power by a rapid-response compensator from the supply grid in synchrony with the

welding pulses is not to be dispensed with. The compensator must be one which can produce capacitive reactive power without any delay.
Substitution in equation (3) produces the figure for the required capacitive power of the compensator:

$$\Delta Q_{C\max} = \Delta P_{A\max}\left(\cot\psi_V + \tan\varphi_A\right) - \frac{d_{zul}}{x_V} \qquad (5)$$

As the welding technology gives rise to the figures $P_{A\,max}$ = 2.6 MW and d_{zul} = 4 %, the maximum power required for the compensator is $\Delta Q_{C\,max}$ = 2 MVAr and this must be supplied across a range between zero and the maximum as the process demands.

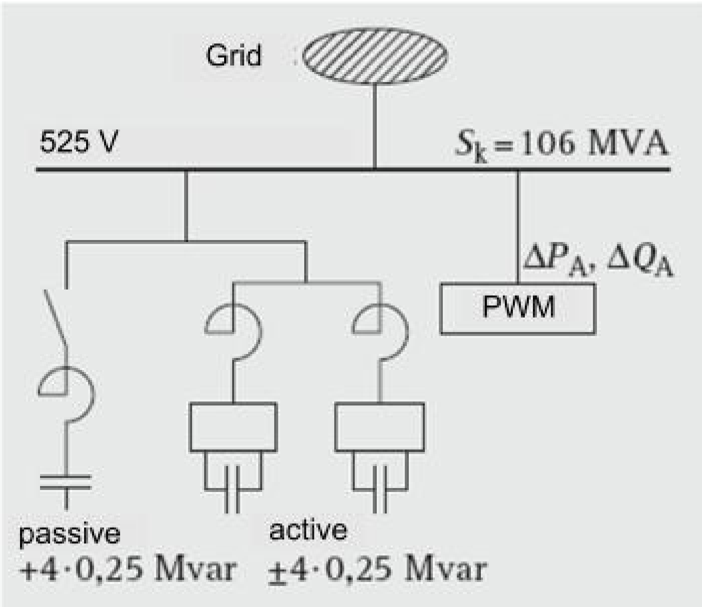

Fig 5: Basic structure of the dynamical compensator

<u>A rapid-response compensator limits the reactive power drawn from the grid</u>

The compensator design has already been presented in [6]. Figure 5 shows the layout of the circuit. The maximum power required for the compensator is produced by several power modules. One module is a switchable, passive, choked condenser unit with 250 kVAr and an active, highly dynamic compensator unit with power of 250 kVAr (cap./ind.) based on automatic IGBTs to convert the current. The choke percentage is p = 5.6 %. In the present case, the maximum capacitive reactive power of 2 MVAr required is achieved with four modules in parallel. This makes it possible to provide capacitive reactive power across a range of 0 ... 2MVAr to the welding network as and when required. The design of the regulation mechanisms is such as to limit the reactive power taken during welding from the grid (ΔQ_N) to the value that prevents d_{max} = 4 % in the supply voltage to the welding supply network being exceeded when the average cos φ_A = 0.4 and the maximum active power $\Delta P_{A\,max}$ is being taken up, as equation (3) suggests.

$$\Delta Q_N \leq \frac{d_{\max}}{x_V} - \Delta P_{A\max} \cot y_V = 3.9\ MVAr \qquad (6)$$

This automation strategy in conjunction with a transient load response time of 40 ms or less, which is sure to maintain the structure of the control system, does not lead to any additional or undesired voltage changes at either the beginning or end of a welding pulse, as is, for example, described in [1]. This makes it possible to keep the long-term flicker values in the upstream 20-kV network well below P_{lt} = 1.5, which presents no problem at all in terms of flicker for the strip-lighting in the low voltage networks supplied exclusively by the same medium voltage network as the welding equipment. The measured values for the supply voltage (10 ms RMS value, no overlap) shown in Fig. 3 support this assertion.

Upstream intelligent system will control triggering of PWMs

For an additional PWM to be cleared for use, it must be possible to assume, from the point of view of the supply voltage to be maintained, that this, together with the use of the welding machines that have already been given clearance, will not cause deviations of more than 4 % from the supply voltage. The further PWM will therefore only be cleared for welding by an upstream control system if its reactive and active power need, which has been determined from the preceding welding activity, added to the power values for the PWMs already cleared for use, will not exceed the active and reactive power capable of being supplied by the compensator without breaching the voltage criterion (d ≤ 4 %).

The rule is:

$$\Delta P_{A\Sigma} \cdot r + \left(\Delta Q_{A\Sigma} - \Delta Q_{C\max}\right) x \leq 4\,\% \qquad (7)$$

The so-called setup mode represents a special case. This mode of operation is required when a welding machine has to be adjusted to a new welding task. At this stage, the active and reactive power currently required for the operation of the PWM is still unknown. For the quality demands on a PWM to be met as in equation (7), it is therefore necessary that a PWM in adjustment mode is only given clearance to start welding when the request message comes if no other PWM has already been cleared.

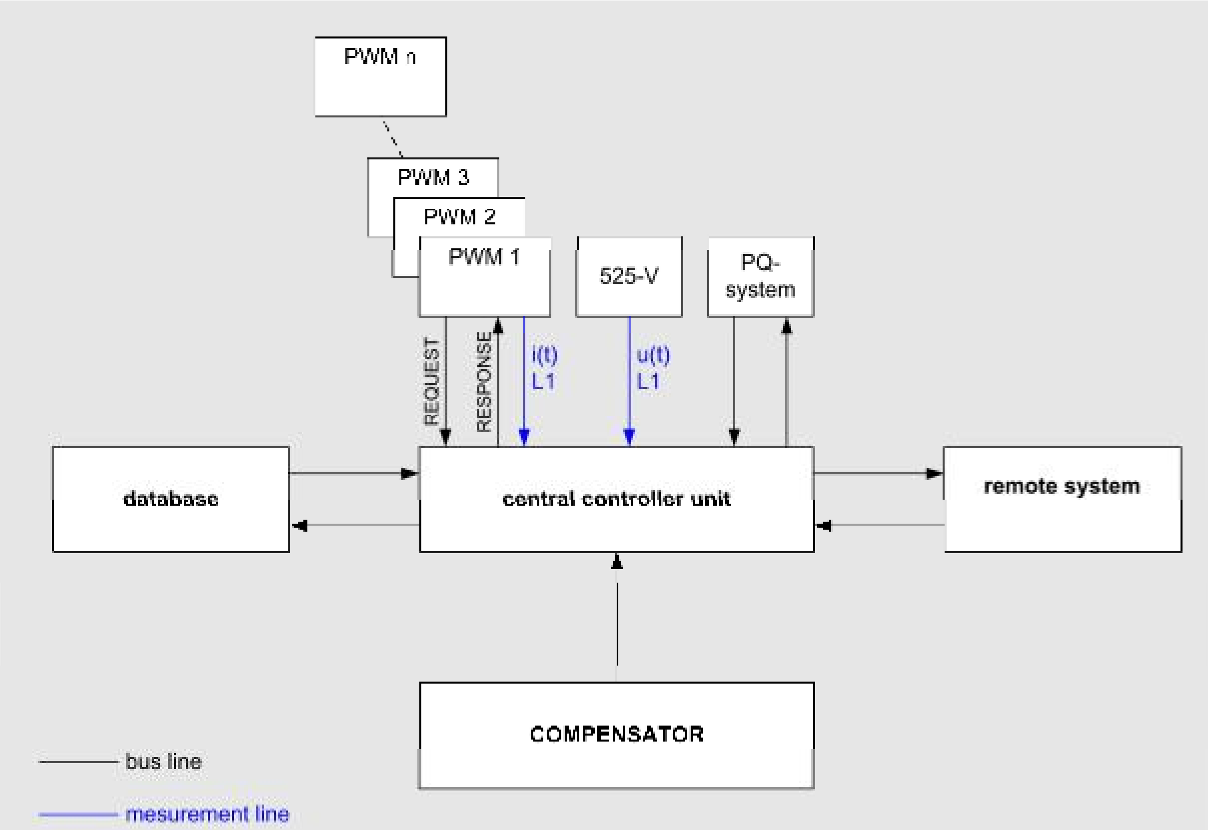

Fig 6: Communication and evaluation of measurement data of the central controller unit

For the calculation of the active and reactive power needs of a PWM, measurements are taken of the instantaneous values for the mains voltage u(t) and of the current for each PWM i(t) in L1 (see Fig. 6). Using these measured values, the active power

$$\Delta P_A^* = \frac{3}{n} \sum_{\upsilon=1}^{n} u_{\upsilon L1} \cdot i_{\upsilon L1} \qquad (8)$$

can be worked out from n instantaneous values per grid wave period of 20 ms and the apparent power

$$\Delta S_A^* \approx 3 \cdot U_{L1} \cdot I_{L1} \qquad (9)$$

can be worked out from the active values for mains voltage U_{L1} and for current used to power a PWM I_{L1} (as 20-ms RMS values [with a $\frac{20}{n}$ ms overlap]). The reactive power of the PWM can thus be calculated with sufficient accuracy from

$$\Delta Q_A^* \approx \sqrt{\Delta S_A^{*\,2} - \Delta P_A^{*\,2}} \qquad (10)$$

since the proportion of reactive power in the apparent power ΔS_A^* due to asymmetry and distortion is tiny in comparison with the proportion due to displacement.

Besides monitoring the power limit for all welding machines in simultaneous use, as earlier described, the control system also enables priorities to be allocated to individual PWMs (such as the clearance for welding or the prioritisation of cascade welds) so as to make most efficient use of the welding network and thus meet productivity demands. A control panel will enable the necessary parameters to be set and visualised. Additionally, the central control unit of the control system is integrated into a company's EEQ measuring and monitoring system which is able (among other things) to give a signal if there are any disturbances in the supply network likely to affect the voltage change in the welding network.

Active and reactive power taken up by a PWM supplies the criteria for improved quality management

The considerations thus far have indicated that it is possible to control voltage changes in a welding network so well that any breaches of the limiting values which would result in unacceptable loss of quality in the welds can be excluded.

The systematic evaluation of a number of measurement results which were obtained on the principles of equations (8) to (10) for a variety of PWMs and other tools used for welding tasks has shown that where the machine suffers a change in the electrode pressure, or wear on the electrode caps, thus losing welding quality after many welds, this will revealed in the active and reactive power consumption of the PWM.

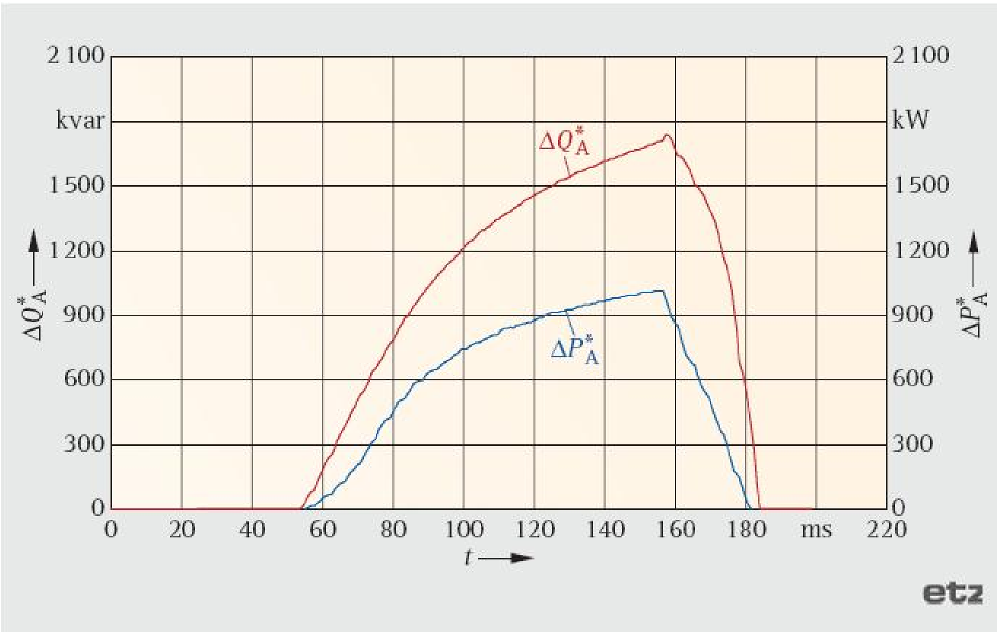

Fig. 7: active and reactive power course of a welding pulse in line 1

For this purpose, the number $z = \frac{n}{20} \cdot \Delta t_A$ are entered into a graph. This number will be based on the ΔQ_A* and ΔP_A* values from equations (8) and (10) as shown in Fig. 7, and obtained during a first welding pulse (Δt_A in ms) from a specific PWM which has carried out a particular welding task to the prescribed level of quality. It will be entered in squares of 1 x 1 power units on a ΔQ_A*-ΔP_A* grid, which has been scaled with twenty grid units for both the minimum and maximum values. The number of ΔQ_A* plotted against ΔP_A* values for each grid square z_{RE} is then stored in a database and serves as a measure of the period

$$\Delta t_A^* = z_{RE} \cdot \frac{20}{n} \quad \text{(in ms)}$$

in which (within the duration of one single pulse) a defined range of active and reactive power was maintained. The graph of ΔQ_A* plotted in this manner against ΔP_A* on the basis of a high number of individual welds is used as a benchmark for welds of acceptable quality. From the investigations it is clear that each ensuing weld which is evaluated in the same manner and has no grid square in which the number of z_{RE} revealed in the benchmark graph is exceeded, will be a weld of the correct quality. The benchmark parameters can be adapted if an ensuing weld brings about a check on its quality and this check does not give rise to any complaint. In this case, the relevant grid squares will be overwritten in the database with the higher number of ΔQ_A* versus ΔP_A*-values.

Fig. 8a is an example of a benchmark set by 375 welds at the correct level of quality. The number of ΔQ_A*values plotted against ΔP_A* values has been highlighted in Fig. 8.

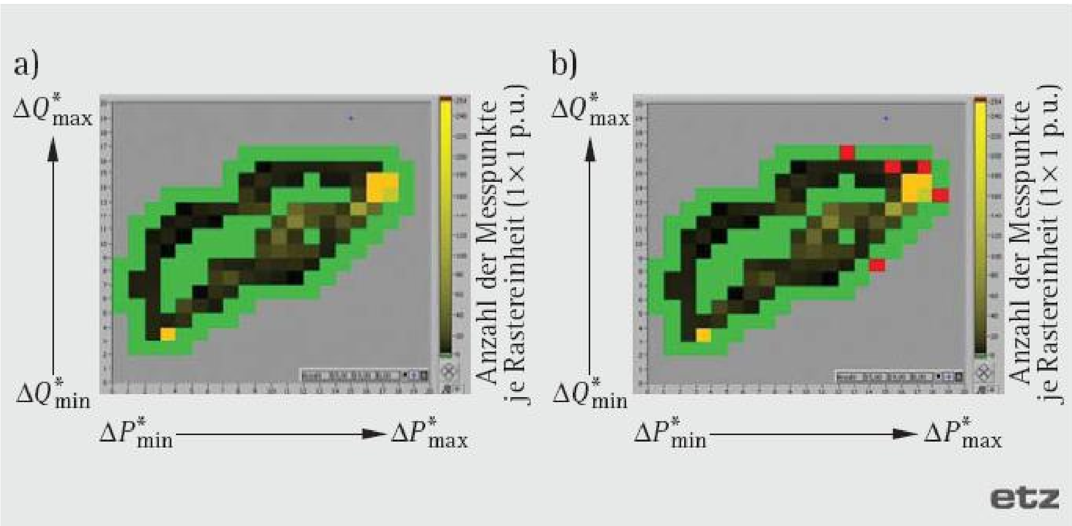

Fig. 8: a) Benchmark (counts of welding points: 347), b) deviation of measurement points during welding process

In a further welding action, the number of ΔQ_A* versus ΔP_A* values as shown in the benchmark is exceeded (see Fig. 8b), which breaches the benchmark conditions and was caused by a low-quality weld.

In summary, the new quality assurance system is thus demonstrated to be capable of:

- recognising any impermissible deviations from the supply voltage to the welding network
- detecting any changes in either the welding pulse duration or the welding current
- recording any defects in electrode pressure or any deficiencies in the physical characteristics of the electrodes with high reliability
- but, unfortunately, not (yet) of signalling as potential causes of reduced product quality any change in the features of the materials (any surface contamination, coating, material thickness) or any change to tolerances at the tool setting stage.

Prospects

By systematic, computer-aided monitoring of predefined values limiting nominal quality parameters for the supply voltage to a particular section of a manufacturing process, it is shown that electrical conformity and product quality can be maintained at a high rate of productivity. The example on which the assertion is based is that of a welding complex at Daimler AG where car bodywork elements are produced. In this situation the electricity supply was kept stable, reliable and in conformity with outside demands by the form of support described. The method succeeded in improving even upon the already well-tried Daimler AG quality assurance system.

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Authors:

Prof. Dr.-Ing. habil. Dietrich Stade (Professor D. Stade)
Dipl.-Ing. Ulrich, Peter (P. Ulrich, Graduate Engineer)

Postal contact: H. Kleinknecht GmbH & Co. KG
Weimarer Straße 1 b
98693 Ilmenau, Germany

Tel.: 03677 / 46969-0
Fax: 03677 / 46969-10
Email: vertrieb@kleinknecht.de
http://www.kleinknecht.de

Dipl.-Ing. Suck, Bruno (B. Suck, Graduate Engineer)

Postal contact: Daimler AG
FP/TGA Department; HPC B857
71059 Sindelfingen

Tel.: +49 7031-90 3053
Fax: +49 7031-90 82726
Email: bruno.suck@daimler.com
http://www.daimler.com

<u>Symbols</u>

$\cos \varphi_1$	Displacement factor (phase shift in basic wave)
d (d_{zul})	Voltage change (permissible)
i	Current (instantaneous value)
I_{L1}	Current (effective value, phase 1)
I_{PSM}	Welding current
n	Index, number
p	Degree of detuning (with choke), percentage figure
P_{lt}	Long-term flicker value
ΔP_A (ΔP_A^*)	Change in active power (* approximate value) at the connection point
$\Delta P^*_{A\Sigma}$	Change in active power for PWMs welding at the same time (approximate value)
ΔQ_A (ΔQ_A^*)	Change in reactive power (* approximate value) at the connection point
$\Delta Q^*_{A\Sigma}$	Change in reactive power for PWMs welding at the same time (approximate value)
ΔQ_N	Reactive power of grid/network
r_V	Grid/network resistance at coupling point (%/MVA value)
$S_{50\%ED}$	Nominal power if operated for 50 % of the time
ΔS_A (ΔS_A^*)	Change in load (change in apparent power)
S_{kM}	Short-circuit power of a welding machine
S_{kV}	Short-circuit power at coupling point
Δt_A	Duration of a welding pulse
Δt^*	Time period
u	Voltage (instantaneous value)
U_{L1}	Voltage (effective value, phase 1)
U_C	Contractually agreed supply voltage
x_V	Grid/network reactance at coupling point (%/MVA value)
z_{RE}	Number of ΔQ_A^* values plotted against ΔP_A^* values per grid square
φ_A	Angle of load change
ψ	Grid/network impedance angle at coupling point