WELDING RESEARCH

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Steady and Pulsed Direct Current Welding with a Single Converter

With a new method of firing the thyristors, steady and pulsed direct current welding with a single three-phase converter is possible

BY M. THAMODHARAN, H. P. BECK AND A. WOLF

ABSTRACT. The conventional electronically controlled power sources for steady and pulsed direct current (DC) welding are converters and transistorized power sources. In the case of steady direct current welding with a converter, a single fully or half-controlled three-phase bridge converter is commonly used. For pulsed DC welding, a single half-wave rectifier is connected in parallel with a three-phase bridge converter to produce the desired pulsed direct current with different pulse repetition frequencies and width. The three-phase bridge converter provides the background current.

These power sources produce harmonics in the AC mains, and, in the case of pulsed direct current welding, there is an unsymmetrical reaction in the mains caused by the single half-wave rectifier. In addition, the power source for pulsed DC welding is complex to operate and maintain, large in size, less efficient, relatively expensive and is associated with low dynamic response.

This investigation presents a new method of firing the thyristors, which enables steady and pulsed direct current welding with a single fully controlled bridge converter. A single fully controlled three-phase bridge converter was chosen as the power source as it contributes to reduction of reactive power with firing angles greater than a certain value. The distortions produced by the power system as a result of the new firing method can be reduced with the help of two tuned resonant line filters, if needed, although these filters add weight, size and cost to the power source. This was verified through simulation and the results are presented. Thus, some of the disadvantages associated with pulsed DC welding such as low dynamic response, low efficiency and distortions in the power system can be reduced to a minimum.

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Introduction

The latest technologies in power electronics and control systems have a tremendous impact on the development of power sources for gas metal arc (GMA) welding. These have led to the IGBT-based inverter, which is smaller, lighter, more efficient and is capable of performing a much wider range of functions besides providing high operational comfort. Nevertheless, conventional power sources like the converter, which has a very poor performance, are still being used in industry as they are robust and-less costly.

For GMAW with a converter, the steady direct current is usually obtained with a three-phase transformer and a fully controlled three-phase bridge converter — Fig. 1. The current is drawn from the AC mains, rectified and smoothed with a smoothing choke. The DC output voltage is continuously varied by varying the firing angle α of the thyristors (Ref. 1).

The power source for pulsed DC welding, which involves a periodic fast transition from a low to a high current, consists of two parallel-connected rectifiers (Fig. 2), which are a three-phase transformer with a three-phase bridge converter to generate the background current I_b and a single phase transformer with a single half-wave rectifier for the production of pulsed current I_p. The pulse width t_p is changed by altering the firing angle α of the thyristors.

The pulse frequencies that can be derived from this power source are multiples of the line frequency such as 25, 50 and 100 Hz. Both the background and pulsed current level can be changed by the firing angle and the transformation

Key Words

Three-Phase Bridge
Steady Direct Current
Pulsed Direct Current
Welding
Converter
Filter

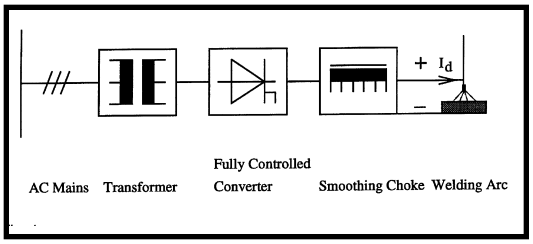

Fig. 1 — Power source for steady DC current welding (Ref. 1).

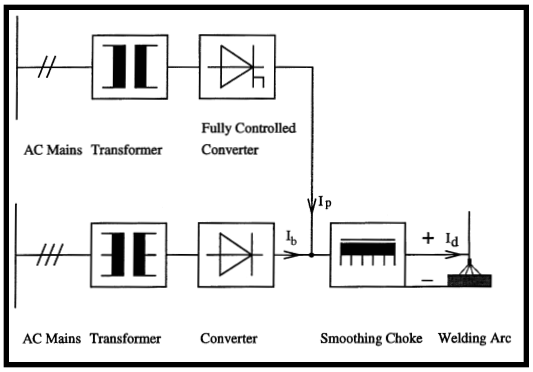

Fig. 2 — Power source for pulsed DC current welding (Ref. 1).

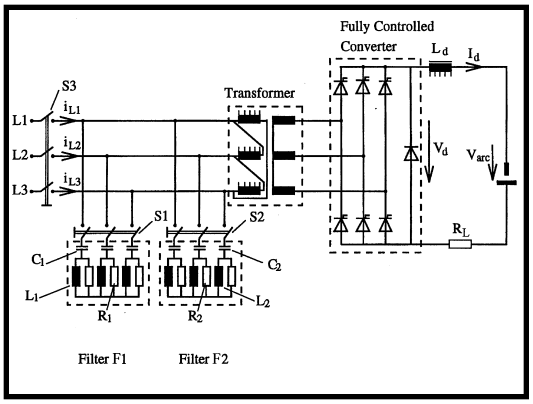

Fig. 3 — Three-phase fully controlled bridge converter with filters F1 and F2.

ratio of the transformer (Ref. 1). Some of the disadvantages associated with such a power source are unsymmetrical reaction in the AC mains caused by the single half-wave rectifier, high production cost, high power loss, low efficiency, low dynamic response and large size and weight.

This research presents a new method of firing the thyristors for a single fully controlled three-phase bridge converter for GMA welding, which enables both steady direct as well as pulsed direct current welding. The fully controlled three-phase converter was chosen as it reduces reactive power drawn from the power lines with firing angles greater than 60 deg.

Thus, some of the above-mentioned disadvantages such as high power loss, low efficiency and low dynamic response can be reduced to a minimum. The distortions in the power system produced as a result of the new firing method can be reduced with the use of two tuned resonant harmonic line filters, if needed.

The Power Source

The power source circuit is shown in Fig. 3. It consists of a three-phase BC6F-rectifier (bridge-controlled 6-pulse rectifier with a freewheel diode), a 49-kVA three-phase transformer in a delta-star connection (DY5) with primary taps, two L-C filters and a smoothing choke with tapping from 0.1 to 0.5 mH. V_{arc}, R_L, I_d and V_d represent the welding arc voltage, ohmic resistance of the welding cable, output current and output voltage, respectively.

With this circuit and a new method of firing the thyristors, it is possible to produce both steady direct current as well as pulsed direct current with multiples of the line frequency such as f_p = 25 Hz, 33 ⅓ Hz, 50 Hz, 100 Hz and 150 Hz, and with various pulse widths t_p.

The purpose of the transformer is to reduce the incoming voltage to a level that is needed for the welding process. The delta-star-connection and the BC6F-bridge converter contribute to lowering harmonic distortions and reactive power, respectively. The main advantage of the delta-star-connection of the transformer with primary taps is that it eliminates the third harmonics (150 Hz) and its multiples (Ref. 4). The taps are used to adjust the turn's ratio to more closely match the maximum output voltage to the intended load voltage. The disadvantages are its weight, size and cost. Besides these, the operator should be skilled enough to select the correct tap for a specific load.

The BC6F-bridge converter was chosen as it reduces the reactive power with firing angle α beyond 60 deg (α > 60 deg). For firing angles less than 60 deg, the DC voltage of the converter is always positive, and the freewheel diode does not come into operation. As the firing angle advances beyond this point, the load current starts to freewheel through the diode, thus cutting off the input line current and preventing the DC voltage from swinging into the negative direction. This reduces the amount of reactive power drawn from the mains, thus improving its power factor (Ref. 4). The freewheel diode plays a vital role in the limitation of the short-circuit current meant to generate the welding arc and in a faulty situation. In both these cases, the current is commutated in the freewheel diode and eases with an e-function. The circuit breaker S3 protects the converter against thermal damage and instantaneous excess current.

To further suppress the reactive power and harmonics, two series resonant shunt filters F1 and F2 tuned to different harmonic frequencies are used. The values of the inductance L_1, L_2, capacitance C_1, C_2, and resistance R_1, R_2, are determined through simulation depending on the welding method. The broad band effect of the filter given by the resistance R_1 and R_2 are obtained with the help of the ratio of the power loss in the resistance P to the reactive power of each filter Q, which was kept small (P/Q < 5%).

Simulation Results and Discussions

The welding power source was numerically simulated using the program NETASIM (Ref. 2). The models in the simulation are represented with differential, functional and logical equations. For simulation purposes, the welding arc voltage for GMA welding is given by (Ref. 3)

$$V_{arc} = 14.0\ V + 0.05 \cdot I_d(A) \qquad (1)$$

where I_d = DC current.

The ohmic resistance of the welding cable for a maximum DC current of 600 A was calculated to be R_L = 0.93 mΩ.

Steady Direct Current Welding

For steady direct current welding, the DC voltage and current are varied continuously through the transformer's transformation ratio. Figure 4 shows the voltage and current waveforms for the transformation ratio a = 0.07. Finer output voltages are derived by changing the firing angle α given by (Ref. 4)

$$V_{d\alpha} = V_{di} \cdot \cos \alpha \qquad (2)$$

where V_{di} = maximum average DC output voltage value obtained at α = 0 deg.

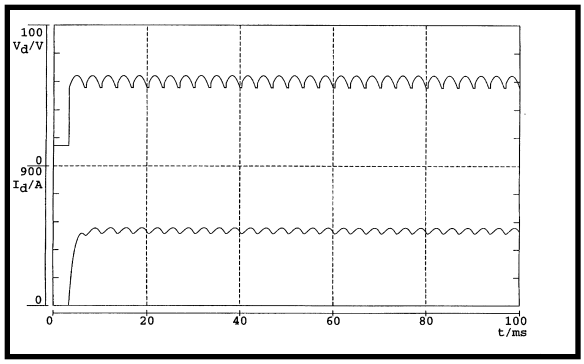

Fig. 4 — Voltage V_d and current I_d waveforms with a transformation ratio a = 0.07.

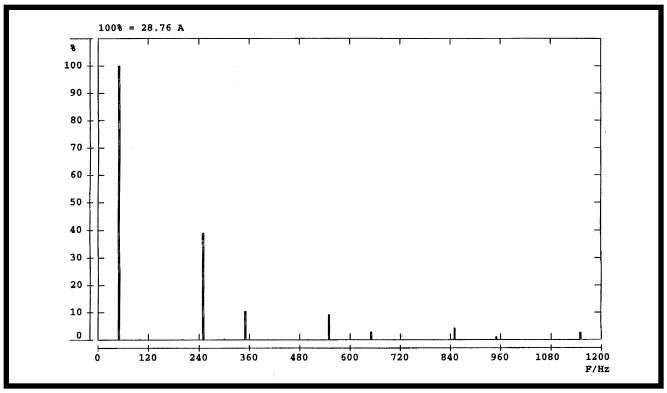

Fig. 5 — Fourier spectrum of the AC current I_{L1} (without Filter F1).

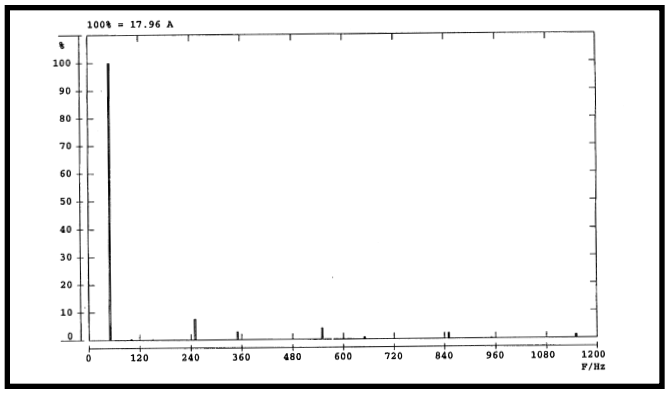

Fig. 6 — Fourier spectrum of the AC current I_{L1} (with Filter F1).

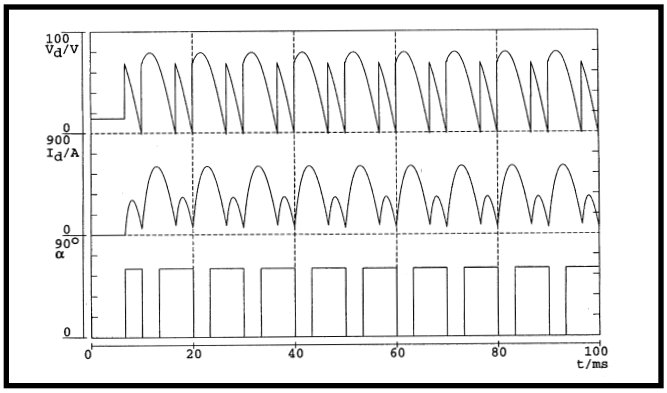

Fig. 7 — Voltage V_d and current I_d waveforms and variation of the firing angle α (pulse frequency f_p = 100 Hz, pulse width t_p = 3.3 ms).

For this method, the maximum firing angle is taken to be α = 60 deg.

The harmonics present in the nonsinusoidal alternating currents drawn by the converter for welding with DC current are determined by Fourier analysis of the current waveform and can be represented by (Ref. 10)

$$\nu = k \cdot p \pm 1 \qquad (3)$$

where k = positive integer, ν = order of the harmonic and p = pulse (p = 6 for three-phase bridge converter).

Thus, a three-phase bridge converter has 5th, 7th, 11th, 13th, 17th, 19th, etc., harmonics present in its alternating current, as shown in Fig 5. To suppress the harmonics, as well as to reduce reactive power, filter F1 was switched on during steady direct current welding. The filter was tuned to the 5th harmonic frequency (f_{r1} = 250 Hz) because of its large amplitude. The disadvantage of the filter is that it adds weight, size and cost to the power source. It should consist of an inductor and a capacitor to prevent damaging itself due to simulation by any other equipment on the power line or causing damage to other equipment connected to the same line as a result of rise in voltage. The parameter of L_1 and C_1 of the filter are calculated as follows:

Reactive power is drawn from the mains by varying the firing angle α of the thyristors. For a converter, neglecting the inductive voltage drop, the firing angle α is equal to the phase shift of the fundamental current with respect to the voltage φ. The power factor is therefore cos φ = cos α. With this relationship, the reactive power drawn from the mains can be calculated on the DC side and is given by (Ref. 4)

$$Q = U_d \cdot I_d \cdot \sin \alpha. \qquad (4)$$

With the maximum DC voltage V_{di} = 78 V, the maximum current I_d = 600 A and the maximum firing angle α = 60 deg, the maximum reactive power drawn from the main is

$$Q_{max} = 78 \text{ V} \cdot 600 \text{ A} \cdot \sin 60 \text{ deg} \qquad (5)$$

$$Q_{max} = 40.5 \text{ kVar}. \qquad (6)$$

The power factor lies at cos φ = 0.5. The filter F1 is switched on to improve the power factor to cos φ = 0.90. The reactive power after compensation is calculated with Equation 4 as

$$Q_n = 78 \text{ V} \cdot 600 \text{ A} \cdot \sin 25.8 \text{ deg} \qquad (7)$$

$$Q_n = 20.4 \text{ kVar}. \qquad (8)$$

The difference in reactive power, $Q_1 = Q_{max} - Q_n$ = 20 kVar, is supplied by the filter F1. The value of the capacitance C_1 and inductance L_1 can be determined as follows:

$$Q_1 = 3 \cdot V_{L1}^2 \cdot \omega_{50} \cdot C_1 - 3 \cdot I_{R2}^2 \cdot \omega_{50} \cdot L_1 \qquad (9)$$

with

$$L_1 = \frac{1}{\omega_r^2 \cdot C_1} \qquad (10)$$

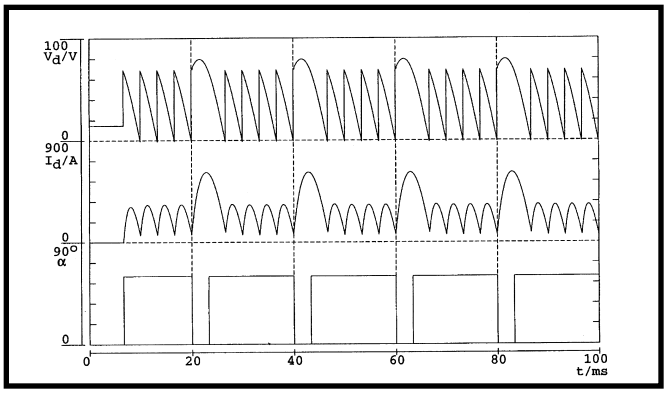

Fig. 8 — Voltage V_d and current I_d waveforms and variation of the firing angle α (pulse frequency f_p = 50 Hz, pulse width t_p = 3.3 ms).

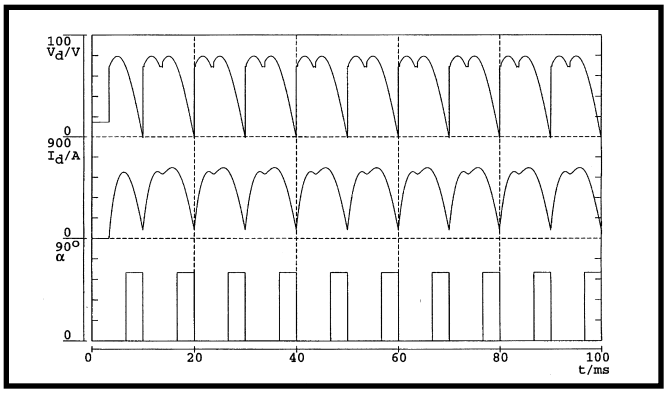

Fig. 9 — Voltage V_d and current I_d waveforms and variation of the firing angle α (pulse frequency f_p = 100 Hz, pulse width t_p = 6.6 ms).

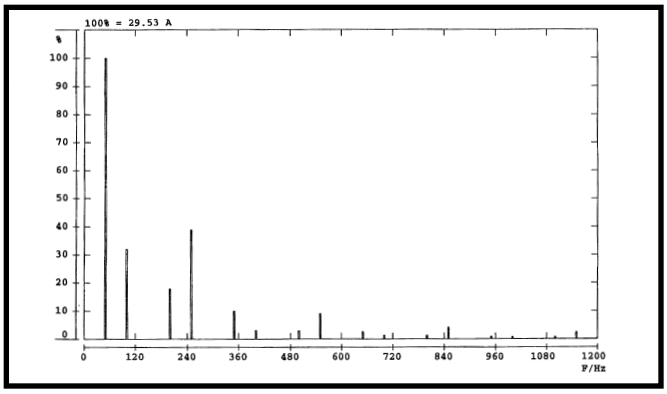

Fig. 10 — Fourier spectrum of the AC current I_{L1} (without Filter F2).

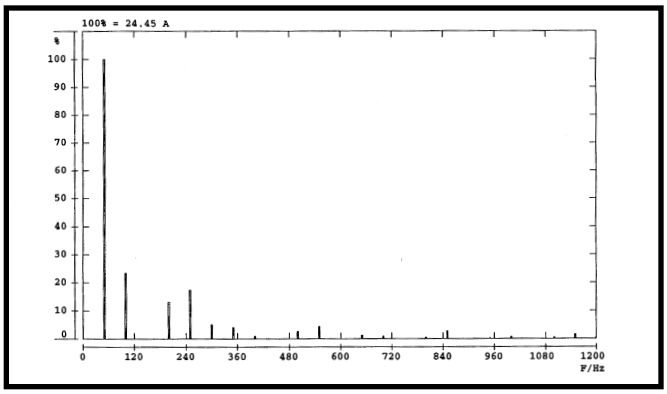

Fig. 11 — Fourier spectrum of the AC current I_{L1} (with Filter F2).

where V_{L1} = voltage across filter F1 = 230 V, ω_{50} = natural frequency = $2 \cdot \pi \cdot 50$ Hz, I_{R2} = current across the inductance L_1 = 31.25 A (from simulation), ω_r = angular frequency of the 5th harmonics = $2 \cdot \pi \cdot 250$ Hz.

Substituting Equation 10 into 9 and using the values above results in

$$C_1 = 0.42\text{mF} \quad (11)$$

$$L_1 = 0.96\text{mH}. \quad (12)$$

The resistance R_1, which determines the broad band filter effect, was determined, with the help of the ratio ((P/Q)< 5%), to be 7 Ω.

It has been observed that with the use of filter F1, the power factor can be increased and the overall harmonics can be reduced by 50%, as shown in Fig. 6. The firing angle lies at α = 60 deg.

Pulsed Direct Current Welding

There are several advantages of pulsed direct current welding. They include the ability to weld thin and thick metals with reduced spatter in all positions, its spray-like transfer, minimal distortion, its potential for lowering fume emissions, ability to fine-tune arc wave form and energy savings.

The method of firing the thyristors for producing various pulsed direct current I_p, background currents I_b, pulse frequencies I_p and pulse width t_p was based on the dynamic study of the three-phase bridge converter (Ref. 5). It has been observed that an instant change in firing angle α of a commonly used digital or analog firing circuit of the thyristors, as shown in Refs. 4, 8 and 9, leads to an instant change in the DC voltage and current. For example, rapid decrease of the firing angle α rapidly increases the output voltage and current and vice versa. Since the BC6F converter operates with firing angles from α = 0 deg to α = 60 deg, the base current is fixed at any of these angles by means of the transformer tapping. The pulsed current, which can be varied between α = 0 deg and the firing angle set for the base current, is then superimposed on the base current by instantly changing the firing angle. This enables the periodic production of the above-mentioned four welding parameters. The desired pulsed direct current level, usually set at three to five times the background current, is possible (Ref. 7). It should be mentioned here that the pulse height and width could not be varied continuously and the pulse frequency is dependent only on the line frequency.

Figures 7 and 8 show the output voltage, current and firing angle α for the pulse frequency f_P of 100 Hz and 50 Hz, respectively. The firing angle α lies between α = 0 deg and α = 60 deg. The pulse width t_P can be varied as well. Figure 9 shows an example of a wider pulse.

Pulsed welding with different pulse frequencies generates different harmonics on the AC side. Each harmonic of the DC voltage is represented by (Ref.7)

$$f_P = 6 \cdot n \cdot f \quad (13)$$

where n = an integer 1,2,3.... and f = mains frequency (50 Hz).

This harmonic is accompanied by two adjacent frequencies on the AC side (Ref. 7), as indicated by Equation 3. The Fourier analysis of the AC current can further verify this. For example, welding with a pulse frequency of 150 Hz produces harmonics of 100 and 200 Hz in the alternating current.

To reduce the harmonics produced by pulsed welding, filter F2, with a power of 10 kvar, tuned to the 2nd harmonic frequency (f_{r2} = 100 Hz), was switched on. This is due to the fact that this harmonic frequency is generated with almost all pulse frequencies. Lower order harmonics were neglected, as it is very difficult to design a filter to eliminate them. The capacitance C_2 and inductance L_2 were calculated with Equations 9 and 10 by replacing L_1 with L_2, C_1 with C_2, I_{R2} with I_{R4}, and with the following values:

V_{L1} = voltage across the filter F2 = 230 V, ω_{50} = natural frequency = $2\cdot\pi\cdot50$ Hz, I_{R4} = current across the inductance L_2 = 18.3 A (from simulation), ω_r = angular frequency of the 2nd harmonics = $2\cdot\pi\cdot100$ Hz.

Thus,

$$C_2 = 0.26\text{mF} \quad (14)$$

and

$$L_2 = 9.61\text{mH}. \quad (15)$$

The Resistance R_2, with a value of 30 Ω, plays the same role as R_1 in Filter F1. Figures 10 and 11 show the Fourier analysis of the AC current without and with the use of filter F2, respectively, during pulsed current welding with pulse frequency f_p = 50 Hz and pulse width t_p = 3.3 ms. It clearly indicates that the harmonics are reduced to approximately 30%. The main objective of filter F2 with a smaller power is to reduce the harmonics in the mains and to avoid overcompensation of the reactive power. Overcompensation nevertheless occurs as the firing angle approaches $\alpha = 0$ deg during pulsed direct current production.

Conclusions

It was shown with simulation that it is possible, with a new method of firing the thyristors, to generate both steady direct as well as pulsed direct current with a single fully controlled bridge converter. The optional use of passive filters can compensate the reactive power and reduce the harmonics to a certain extent, but they add weight, size and cost to the power source. Nevertheless, some of the disadvantages associated with the conventional bridge converter power source are reduced to a minimum. The use of an active filter instead of the passive filter F2 during pulse welding could prevent overcompensation and reduce harmonics and reactive power more effectively.

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EVALUATION OF SEISMIC RESPONSE DATA FOR PIPING

by Gerry C. Slagis

Experimental data from 14 test programs on dynamic response of piping are reviewed and evaluated. All tests demonstrate the conservatism of the Section III Level D stress limits for seismic loads on piping.

These data are useful for quantifying the amount of conservatism in the Level D stress limits. But, additional evaluation of the data is necessary to establish test margins and trends. Analyses are also required to extrapolate test data to all possible piping configurations, geometries, fabrication details and pressure loadings. It appears that the EPRI systems tests are more severe than the component tests for the fatigue failure mode.

To evaluate test data for comparison to code limits, the appropriate approach is to determine the elastic test response and relate the input load level to the elastically predicted response. This is the method used in the report to compare test data.

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