C5.1 EVALUATION OF THE CONNECTION OF A THREE-PHASE WELDING MACHINE

This example shows a study of flicker prediction based on simplified assessment methods oriented at evaluating the connection of a new fluctuating load to an existing network.

Figure C5.1 shows the diagram and data of the 15 kV supplying network. An industrial customer using a large welder (called W₁ in Figure C5.1) has requested the connection of an additional welding machine to increase production capacity. The aim of the study is to decide on the connection of this new load bearing in mind that the $P_{st}$ planning level of the utility for MV systems is 0.9.

As can be observed, the MV line feeding the disturber client is also feeding other loads (consumer 2) which are residential and office-building consumers considered as non-disturbers (i.e. as non-fluctuating loads). Consumer 1, connected at the point indicated as PCC₁, also has non-fluctuating loads.

Different flicker measurements have been performed in order to identify the background flicker levels at PCC₂ and the flicker contribution of the already operating welder 1. By these measurements, it has been observed that, when welder 1 does not operate, the background short-term flicker severity at PCC₂ is 0.30. When welder 1 is running, the flicker severity level at PCC₂ is 0.67.
The new welding machine whose connection is under study has the following characteristics:

- The power absorbed during the melting phase of the welding operation can reach 1800 kVA with a power factor of 0.85. The power absorbed during two welding periods is negligible.
- The dwell time is 1.5 s and the repetition time is 3 s; that is, welding periods last 1.5 s and are followed by 1.5 s of no load. Therefore, 20 welding operations are performed per minute, which mean 40 voltage changes per minute.

The duty cycle of both welders is around 30 minutes per hour. Therefore, this study will focus on the analysis of short-term flicker severity, $P_{st}$, as it will be a stronger requirement than $P_{lt}$.

The study is organized in the following steps:

1. Calculation of flicker severity caused at PCC$_2$ by welding machine 1.
2. Calculation of the voltage change caused at PCC$_2$ by the connection of the welding machine under study ($W_2$).
3. Estimation of the flicker severity caused at PCC$_2$ by welding machine 2.
4. Summation of the $P_{st}$ caused at PCC$_2$ by the simultaneous operation of both machines.
5. Analysis of solutions.

C5.1.1 Flicker Severity Caused at PCC$_2$ by Welding Machine 1

The $P_{st}$ level caused by the individual operation of welder 1 can be estimated by means of the measurements performed at PCC$_2$ when the welding machine is working, $P_{stPCC2\text{with}W1}$, and
when the welder is not working, $P_{st\text{PCC}_2-\text{without}W_1}$. Assuming that the disturbance created by the welder and the disturbance introduced by the background level are unrelated disturbances, a cubic summation law can be used to make this estimation:

$$P_{st1} = \sqrt[3]{P_{st\text{PCC}_2-\text{with}W_1}^3 - P_{st\text{PCC}_2-\text{without}W_1}^3} = \sqrt[3]{0.67^3 - 0.30^3} = 0.65 \quad (C5.1)$$

$P_{st1}$ is the flicker severity contribution of welder 1 to the global $P_{st}$ level at the point of connection PCC$_2$.

### C5.1.2 Voltage Change Caused by the New Welder

Before calculating the voltage change caused by the operation of the welding machine, it is necessary to determine the source impedance at the point of common coupling of this equipment. This is done by means of the following calculations:

- **Source impedance.** As indicated in Figure C5.1, the short-circuit power of the network in 66 kV is 600 MVA. Therefore, the source impedance expressed on the 15 kV side is

  $$Z_s = \frac{U_n^2}{S_{cc}} = \frac{15^2}{600} = 0.375 \Omega \quad (C5.2)$$

  A ratio of 30 will be assumed between the reactive and the resistive part of the source impedance. Therefore, the complex form of the source impedance is

  $$Z_s = 0.012 + j0.375 \Omega \quad (C5.3)$$

- **HV/MV transformer impedance.** The transformer has a rated power of 50 MVA, an inductive impedance of 10% and a resistive impedance of 0.8%. Therefore the transformer impedance is calculated as

  $$R_{T2} = \frac{\varepsilon_{Rcc} U_n^2}{S_n 100} = \frac{0.8 \cdot 15^2}{50 \cdot 100} = 0.036 \Omega \quad (C5.4)$$

  $$X_{T2} = \frac{\varepsilon_{Xcc} U_n^2}{S_n 100} = \frac{10 \cdot 15^2}{50 \cdot 100} = 0.450 \Omega \quad (C5.5)$$

  $$Z_T = 0.036 + j0.450 \Omega \quad (C5.6)$$

- **MV line impedance.** The resistance of the underground MV cable is 0.125 $\Omega$/km and the reactance is 0.104 $\Omega$/km. The length of the line is 2.5 km. Therefore, the complex impedance of this line is

  $$Z_L = 0.313 + j0.260 \Omega \quad (C5.7)$$

Therefore, the total impedance at PCC$_2$ is

$$Z_{\text{PCC}_2} = Z_s + Z_T + Z_L = 0.361 + j1.085 \Omega \quad (C5.8)$$
This value implies that a short-circuit power of approximately 200 MVA is available at PCC2. The analyzed additional welder causes power variations of 1800 kVA which represent 0.9% of this short-circuit power. This is a value high enough to require a detailed evaluation of the flicker emission levels introduced by this additional load.\footnote{At this rate of voltage variations per minute, Technical Report IEC 61000-3-7 proposes a ratio of 0.2% between the power variation of the load and the short-circuit power for approving the connection of the load to an MV system without any further analysis.}

Active and reactive power variations ($\Delta P$ and $\Delta Q$) caused by the additional welding machine can be calculated by making use of its known characteristics, namely the apparent power variation (1800 kVA) and the power factor (0.85). The voltage change produced by welding machine 2 at PCC2 can be calculated by applying Equation (5.12) as follows:

$$d = \frac{R_{\text{PCC}2} \cdot \Delta P + X_{\text{PCC}2} \cdot \Delta Q}{U_N^2} \times 100\%$$

$$= \frac{0.361 \cdot 1800 \cdot 10^3 \cdot 0.85 + 1.085 \cdot 1800 \cdot 10^3 \cdot 0.53}{(15 \cdot 10^3)^2} \times 100 = 0.71\%$$

(C5.9)

**C5.1.3 Estimation of the Flicker Severity Caused by Welding Machine 2**

The repetition rate of the voltage changes caused by the welding machine is, as previously indicated, 40 voltage changes per minute. Entering this value into the severity curve (Figure C5.2) for rectangular steps produces on the ordinate the voltage change $d_o \approx 0.9\%$ which leads to $P_{sto} = 1$.

\[\text{Figure C5.2 Rectangular voltage variation for } P_{st} = 1\]
Taking into account that short-term flicker severity is a linear parameter with respect to the magnitude of the voltage change that causes it, the expected $P_{st2}$ caused by the individual contribution of welder 2 for the voltage change calculated in (C5.9) is

$$P_{st2} = \frac{d}{d_o} = \frac{0.71}{0.90} = 0.79$$  \hspace{1cm} (C5.10)

The expected $P_{st}$ can also be calculated by means of the analytical approach presented in the publication IEC 61000-3-3 [1] that was discussed in Section 3.3. This method is based on calculating the flicker time, $t_f$, by means of the following expression:

$$t_f = 2.3 \ (d \cdot F)^{3.2}$$  \hspace{1cm} (C5.11)

In this case, since voltage changes are rectangular, factor $F$ is one unit. Therefore

$$t_f = 2.3 \ (0.71)^{3.2} = 0.769 \text{ s}$$  \hspace{1cm} (C5.12)

$P_{st}$ is determined by summing all the flicker times, $\Sigma t_f$, inside a 10 min time interval, $T_p$. Considering that 40 voltage changes occur per minute, i.e.

$$P_{st} = \left( \frac{\Sigma t_f}{T_p} \right)^{1/3.2} = \left( \frac{10 \cdot 40 \cdot 0.769}{600} \right)^{1/3.2} = 0.81$$  \hspace{1cm} (C5.13)

the value of $P_{st2}$ calculated by means of this method is very close to the value obtained by means of the flicker curve, although a slight difference appears between them. This difference can be understood by bearing in mind that both approaches, although providing reasonable estimates, are based on simplifications.

**C5.1.4 $P_{st}$ Caused by the Simultaneous Operation of Both Machines**

In order to obtain the total flicker severity at point PCC$_2$, the individual contribution of each disturbing load connected to this point ($P_{st1}$ and $P_{st2}$) together with the background flicker level ($P_{stPCC1\text{ without }W1}$), must be considered.

Therefore, assuming that the operation of both welders is uncorrelated, the summation law described in Section 5.3.3 can be applied with a coefficient $m = 3$. This assumption ignores the more severe flicker which would result from the coincidence of steps from different welders. In this case, since welding cycles last 3 s, this can be an acceptable assumption. Therefore, the global flicker emission at PCC$_2$ is equal to

$$P_{st} = \sqrt[3]{P_{stPCC1\text{ without }W1}^3 + P_{st1}^3 + P_{st2}^3} = \sqrt[3]{0.33^3 + 0.65^3 + 0.79^3} = 0.93$$  \hspace{1cm} (C5.14)

This value exceeds the utility planning level ($P_{st} = 0.9$) and, therefore, it is not tolerable. The connection of the additional welder machine is unacceptable, unless mitigation methods are provided.
C5.1.5 Analysis of Solutions

A possible solution is to install a compensator device to reduce flicker emission of the welders. Another possibility is to reinforce the short-circuit power at the point of connection of the welders by building a new line. Although this can be an expensive solution, the technical analysis presented next shows the improvement achieved by means of this solution.

If a new underground cable, identical to the existing one, is connected in parallel with it between PCC\(_1\) and PCC\(_2\), the short-circuit power at PCC\(_2\) is increased. The new impedance of the equivalent parallel of both lines is

\[ Z'_L = \frac{Z_L}{2} = \frac{0.313 + j0.260}{2} = 0.157 + j0.130 \ \Omega \]  

(C5.15)

Therefore, the new total impedance at PCC\(_2\) is

\[ Z_{PCC2} = Z_s + Z_T + Z'_L = 0.205 + j0.955 \ \Omega \]  

(C5.16)

The available short-circuit power at PCC\(_2\) is now 230 MVA.

Both welders have a power factor of 0.85 in the welding periods. Therefore, considering (C5.9), the ratio between the voltage changes caused in this new network configuration and the previous one is

\[ \text{Ratio} = \frac{0.205 \cdot 0.85 + 0.955 \cdot 0.53}{0.361 \cdot 0.85 + 1.085 \cdot 0.53} = 0.77 \]  

(C5.17)

This result implies that in this new situation, the \(P_{st}\) level caused by the individual contribution of each welder will be decreased by a ratio of 0.77. Assuming that consumer 2 connected at PCC\(_2\) is a non-disturber consumer, the background flicker level existing at PCC\(_2\) is propagating from the upstream voltage level and, therefore, it is not modified by the addition of the new line. Therefore, the new value of flicker severity is

\[ P_{st} = \sqrt{P_{st, PCC1 - without-W1} + P_{st1}^3 + P_{st2}^3} = \sqrt{0.3^3 + (0.65 \cdot 0.77)^3 + (0.79 \cdot 0.77)^3} = 0.72 \]  

(C5.18)

The \(P_{st}\) level obtained by applying this solution is below the planning level, so this proposal is acceptable. It is important to note that this analysis is made using the assumption that the welders are the only fluctuating loads connected at the MV busbars.

An alternative approach for determining the individual emission limits of these welders could be based on calculating the quotient between their rated power and the total power of the loads directly supplied to the MV network. In such an analysis, the total flicker level acceptable at PCC\(_2\) should be shared between all the connected loads in proportion to their rated power.\(^2\) Nevertheless, in the situation analyzed in this case study, since consumer 1 and consumer 2 are non-fluctuating loads, this kind of approach would give place to very strict limits for the disturbing loads imposing flicker levels unnecessarily far below the planning limit.

\(^2\)This evaluation criterion is known as ‘Stage 2: Emission limits proportional to the agreed power of the consumer’ in the context of Technical Report IEC 61000-3-7.
levels. Therefore, under these circumstances, a more flexible method for assessment of individual limits has been applied, although it is convenient to bear in mind that future arrangements or changes in the flicker contributions of the connected customers should be carefully analyzed.  

C5.2 FLICKER MEASUREMENTS IN AN ARC FURNACE INSTALLATION

Arc furnaces are very fluctuating loads that produce stochastic flicker. The random nature of voltage fluctuations caused by arc furnaces complicates the use of simplified flicker prediction methods. A measurement campaign is a more precise way to assess flicker levels produced by this type of load.

This case study presents the $P_{lt}$ measurements that have been performed over several days in the arc furnace installation depicted in Figure C5.3. This installation is connected to a 110 kV network through a three-winding transformer whose data is indicated in Figure C5.3. The flicker measurements were performed over several days at the MV side.

Figure C5.4, Figure C5.5 and Figure C5.6 show the evolution of $P_{lt}$ at phase A, B and C, respectively, measured at the MV busbar.

Table C5.1 shows the main statistics of the $P_{lt}$ values measured at three phases over a week.

The $P_{lt}$ caused at buses upstream in a grid is reduced reciprocally to the increasing short-circuit power. According to the percent reactance values of the transformer of this installation, the available short-circuit power on the MV side, where the measurements have been carried out, is around 20 times lower than the short-circuit power available on the HV side of the transformer. Therefore, a reduction in the flicker-level emission of the

![Schematic diagram of the arc furnace installation](image)

**Figure C5.3** Schematic diagram of the arc furnace installation

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3 This evaluation criterion is known as ‘Stage 3’ in the context of Technical Report IEC 61000-3-7.
Figure C5.4  $P_{lt}$ evolution (phase A) at the MV bus of the arc furnace installation (Courtesy of Prof. Zbigniew Hanzelka)

Figure C5.5  $P_{lt}$ evolution (phase B) at the MV bus of the arc furnace installation (Courtesy of Prof. Zbigniew Hanzelka)
Figure C5.6  $P_{lt}$ evolution (phase C) at the MV bus of the arc furnace installation (Courtesy of Prof. Zbigniew Hanzelka)

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>1.901</td>
<td>2.080</td>
<td>2.064</td>
</tr>
<tr>
<td>Ave.</td>
<td>3.690</td>
<td>3.807</td>
<td>3.757</td>
</tr>
<tr>
<td>$P_{lt}$ 95 %</td>
<td>4.212</td>
<td>4.383</td>
<td>4.340</td>
</tr>
<tr>
<td>Max.</td>
<td>12.113</td>
<td>12.341</td>
<td>12.002</td>
</tr>
</tbody>
</table>

arc furnace with a ratio of 20 can be expected on the HV side with respect to the values indicated in Table C5.1. This situation leads to acceptable flicker levels in the PCC.

**BIBLIOGRAPHY**


