AN INVESTIGATION OF VOLTAGE QUALITY IN DISTRIBUTION SYSTEMS WITH PULSED POWER LOADS - MODELING METHOD VERIFIED BY SYNCHRONOUS MEASUREMENTS

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SUMMARY
This paper presents an investigative approach of the determination of the disturbances emanated from welding devices with pulsed power and propagated within a low voltage distribution system. The metering method involving synchronous measurements both at the device’s clamps and at the substation bus is described together with measurement set-up. Synthesizing the results of measurements a mathematical model of the system elements and of the load is presented and discussed. Comments on the influence of parameters used on how the distortion is propagated within the system are given. Clarification of the interaction effect between the harmonic source and the electric power system under different load conditions is considered.

INTRODUCTION
The problem of disturbances caused by power system equipment and resulting in a non-ideal waveform of the supply voltage is as old as the power network itself. First considerations made at the end of the 19th century identified transformers and rotating machinery as the main source of the waveform distortion [1]. The development of technology over the years, especially the progress of power electronics applications, has brought about many technical conveniences the years, especially the progress of power electronics applications, has brought about many technical conveniences, but simultaneously it has created new challenges for power system operation studies. One of which is control and prediction of harmonics. Distribution systems are operating nowadays with a high content of power electronic-based equipment. The non-linear currents they draw cause self-generated interference in the supply voltage, polluting it and propagating the distortion within the system [2]. The need to understand the phenomena, especially in industrial distribution system cases is stronger then ever because the damaging effects of harmonics can no longer be ignored [3]. The proper system arrangement avoiding capacitor failure or transformer and neutral conductor overheating demand analytical methods, which require proper mathematical models to assure reliable system operation both in existing and in planned distribution systems [4].

DEVICES WITH PULSED POWER IN DISTRIBUTION SYSTEMS – LOAD CHARACTERISTICS

The study of non-linear equipment influence on the system operation becomes especially important in the case when loads with pulsed power like welding machines or electrical discharge machines are a part of the analyzed distribution system [5]. High current pulses – by welders pulses rise about 0.5A/µs with peak value about 800A (Fig.1) on the low voltage level – demanded by these devices result in stronger voltage distortion and increase the possibility of improper system operation. One should keep in mind that all the components of power system are developed to transport and distribute as much electrical power as possible through a 50 Hz (or 60 Hz) positive sequence component, and therefore, they are matched to each other and to the loads at the aforementioned fundamental frequency. In cases when single-phase supplied devices with pulsed power are working in the system the balanced conditions and this perfect match no longer exists. As a result, the distribution power system is exposed to the new operational conditions and self-generates interferences, which not only decrease the efficiency of the energy transport within it, but badly affect its immunity. The system is exposed to extremely high load unbalance and high disturbances. Nevertheless, it should withstand all those conditions. To fulfill this goal efficiently proper studies of the possible cases should be done to come up with solutions which assure the proper system operation and are economically optimal.

The studies based only on deterministic solutions are burden with errors and allow only limited choice of the proper mitigation method. The level of distortion present in distribution systems is highly dependent on the load present both down and upstream of the distribution transformer. Even the system impedance can vary changing simultaneously harmonic content in the system [6]. Therefore, every single case demands on-site measurements whose results can tune the model used and improve its exactness.

In this paper a three-step approach is proposed to study the behavior of the system. It contains a proper model design, measurements obtaining the statistical profile of the existing distortion in the studied system and the combined analysis to calculate distortion within it based on a welding device.

![Fig. 1. Waveforms of the current demanded by the welder by distinct welding power.](image-url)
MODELING AND SIMULATION METHODS FOR HARMONIC DISTORTION ASSESSMENT

In general there are two main tendencies in the modeling philosophy: studies for time domain and frequency (or harmonic) domain. Time domain simulation involving non-linear load behavior requires its mathematical description, e.g. in form of differential equations, which for most types of non-linear load are difficult to establish or unknown. The analysis in frequency domain, presented in this paper, can be built on the standard information including impedances of system elements and the characteristic (spectrum) of the current (or in some cases voltage) injected by non-linear loads. This can be easily measured. But the drawbacks here are, first of all the high errors resulting from the non-linear nature of the harmonic phenomenon itself, and the difficulties in the giving back of the interaction between harmonic source and the network.

In this paper a heuristic approach is proposed accomplished by using a phase domain nodal admittance matrix technique where the model parameters (impedances) are tuned by the results obtained from synchronous measurements. The nodal admittance matrix of the system elements is built based on information of the system elements and loads. At first the fundamental frequency load flow solution is obtained involving iterative Newton-Raphson method [7].

Then, around this working point, a direct solution is obtained, i.e. equation (1) is solved at every frequency h of interest:

\[
\begin{bmatrix}
Y_h & U_h \\
U_h & I_h
\end{bmatrix} = \begin{bmatrix}
U_h \\
I_h
\end{bmatrix}.
\]  

(1)

The elements of the nodal admittance matrix are represented as frequency dependent impedances (admittances). The model used in calculations (Fig.2) utilizes equations proposed in [6]. The utility system is represented by its impedance (2):

\[
Z_{k,h} = j \cdot \frac{U_n^2}{S_k} \cdot h
\]  

(2)

and the middle-voltage cables are modeled (3, 4):

\[
Z_{k,h} = R_k \cdot \sqrt{3} \cdot h + jX_{k,h} \cdot h
\]  

\[
Y_{k,h} = j \cdot 10 \cdot \pi \cdot h \cdot C_{k,h} \cdot h.
\]  

(3)

(4)

The impedance of the low voltage cables, especially of the cable which supplies the welder, is modeled according to the (3). The cable capacitances are omitted. For the study of the low frequency conducted disturbances (i.e. within a frequency range 50Hz–9kHz) this assumption can be made without a big influence on the modeling exactness [6]. The transformer model is based on the assumption that its X/R ratio is constant over the studied frequency range (5).

\[
Z_{k,h} = (X_{1,h} / R_{1,h}) \cdot \text{const} \cdot h = \text{var}
\]  

(5)

Such a formulated nodal admittance matrix is used to solve (1) in the studied case, i.e. the \( Y \) matrix consists of the harmonic spectrum of the welder current according to the data obtained from direct measurements. Introducing no other non-linear devices to the modeled system the information of the distortion introduced by the single machine to the system can be obtained. Measurements and simulations of the welder current spectrum and the resulting voltage distortion on both ends of the supply cable are the subject of considerations in this paper.

ASSESSING POWER QUALITY INFORMATION BY SYNCHRONOUS MEASUREMENTS – SETUP

To determine the influence of pulsed power devices on the voltage quality drop in a distribution system an industrial resistance welder was installed in the laboratory room in one of the university buildings. This single-phase device with the maximal power of 100 kVA was supplied from the building substation via a separate low voltage cable with the length about 100 m, so that the installation of the metering system was possible both at the device’s clamps and the substation without any other load hanging on that cable.

The substation is a part of the university distribution system, a diagram representing the middle voltage network and its simplification used for the model is presented in Fig.2. At first, long-term measurements of the quasi-stationary harmonics at the building substation were made to evaluate the harmonic “noise” in the supply voltage. Fig. 3 presents the daily profile of the THD factor for voltage and its main harmonics at the building substation were made to evaluate the harmonic “noise” in the supply voltage. Fig. 3 presents the daily profile of the THD factor for voltage and its main component the 5th harmonic (3rd being small) over a day in one of the phases at the bus A. The profile was statistically achieved obeying the standard [8], i.e. 0.95 quantile were formed for every data set established during this quasi-stationary harmonic measurements. Over the sets of measurements a daily profile was created.
Then the synchronous measurement were arranged (Fig.4). Four–channel oscilloscopes LeCroy AL584 and LeCroy 9314A were installed on both ends of the cable which supplied the welder. The one at the device’s clamps and the second at substation A (Fig.4). The input channels were provided with signals coming from voltage differential probes Tektronix P5200 or Agilent N2772A and from a current probe (Tektronix A621 or Tektronix A6302). Synchronous triggering was realized through the trigger function on the current flank. The voltage signals were collected according to Fig.4. This additionally enables one to measure the influence of the welder on the voltage at other, far buses in the system (bus B).

The binary data recorded on both oscilloscopes over 100 ms were converted into ASCII files which then were used to calculate the quantities at each measuring point using Matlab’s program involving FFT.

**VOLTAGE QUALITY STUDY – COMPARISON SIMULATIONS AND MEASUREMENTS**

**Measurement**

The disturbances introduced by the welding device vary in accordance to changes in the welding power and influence the voltage quality at the substation bus. Fig.5 presents the 3rd and 5th harmonic level measured at the device’s clamps (point a in Fig.4) and at the station (point A in Fig.4) as a function of the device’s welding power. The 3rd harmonic damping along the cable is nearly constant over the whole power range, but the 5th damping varies. This is because of the interaction between the 5th harmonic component present in the supply voltage (Fig.3) and the component introduced by the welder. Due to the phase differences between them (harmonic cancellation effect) the damping has irregular values and is the main error source in the described model.

It is interesting to see that the maximum distortion introduced by this machine into the supply voltage (Fig.5, 6) lies near the point of 40-50% of the machine’s nominal welding power and consists mainly of the 3rd harmonic (Fig.5, 6).

**Simulations**

The simulations described here were made under the assumption, that there is no harmonic noise present in this system. In other words, the supply voltage was assumed to be clear to receive its reaction only on that device. Furthermore, the differences between simulation and the real case can be obtained to clarify the influence of the background distortion. Keeping in mind that in the voltage supplying the welder the biggest harmonic was the 5th (Fig.3) the fact of the slight difference between measured and simulated curve can be explained (Fig.6). The welder introduces more 5th component in the range of 50-70 % of nominal welding power. The difference between simulation and measurements is in this range bigger than for other power values. Again, the cancellation effect, not considered in the model, is responsible for these erroneous results.

For the way: system-station-cable-load (U-S-A-a in Fig.4) several cases were simulated to obtain the sensitivity of the solution to the model parameter changes. Also the influence of the ration power of device to short-circuit power at the substation A was examined.
The harmonic voltage transported upstream (calculated at bus B, Fig.4) is within a range 0.12...0.25% THD (with the main 5th component – the propagation of the triple harmonic orders through Dyn transformers was blocked). During measurements the effect of the welder on the voltage distortion at substations was blocked (Fig.6). The harmonic voltage emanated from the welder device comes mainly from the triple harmonics. Therefore, its propagation over the system this one has the biggest values, standing alone for the THD over the substations.

In the real system the short-circuit power to device power ratio is close to 100. Therefore, the distortion present at the station is not critical (Fig.6). The harmonic voltage transported upstream (calculated at bus B, Fig.4) is within a range 0.12...0.25% THD (with the main 5th component – the propagation of the triple harmonic orders through Dyn transformers was blocked). During measurements the effect of the welder on the voltage distortion at substations was not observable due to background "noise" – in this case around 2.5 % THD with the 5th harmonic as the main component (Fig.3).

The problem with the upstream propagation can arise when the short-circuit power to load ratio decreases. This happens when the short-circuit power at substations decreases (smaller transformer) or the number of the load increases (many welders). The increase of the short circuit power (Tr1 and Tr2 in parallel) causes reduction in the distortion over the system (Fig.7). The variation of the supply cable length has considerable influence only on the THD at the clamps (Fig.7). The inclusion of the skin effect in the low voltage cable model only minimally changes the results compared to the cases of length variation and short-circuit power modification.

CONCLUSIONS

The quality of electrical power has been the subject of many studies over the years. However, the studies of the non-linear equipment influence on system operation become very interesting when loads with pulsed power are a major part of the analyzed distribution system. In this paper the development process of the near system model for the study of distortion introduced by a welding device was proposed. Summarizing, the proper model development should concentrate on the precise short – circuit data assessment: starting from supply cable length, through middle voltage supply network parameters and ending with a correctly assumed short-circuit power at the PCC.

In the case presented the modeling process was assisted by synchronous measurements which help to tune the length of the low voltage supply cable. This can be difficult to obtain, especially in building installations and industrial systems since the route of the supply cables is not always well known. The source of error in the developed model is the background noise which is difficult to include within the model. The daily curve (Fig.3) helps to understand the phenomena in a real system (Fig.6). Here, a heuristic approach based on statistical data is proposed to discuss the influence of the distortion, which is present in the supply voltage before the welder starts working. The influence of the background harmonic content was reduced to the 5th harmonic, because in the studied system this one has the biggest values, standing alone for the THD over the substations.

The distortion emanated from the welder device comes mainly from the triple harmonics. Therefore, its propagation is blocked by the delta-star-ground step–down transformers. However, careful attention should be paid to the ground (neutral) cable which can be easily overheated in the case of multiple devices. In any case its diameter should be reduced (compared to the phase cable diameter). A closer study of the case of multiple devices and the influence of unbalance on the distortion propagation will be the subject of future considerations.

REFERENCES


