Mathematical model for calculation of power consumption and electromagnetic noise of resistance welding machines

L. Sakhno, O. Sakhno, S. Dubitsky*

St. Petersburg State Polytechnic University, Department of Theoretical Electroengineering,
Polytechnicheskaya 29, St. Petersburg, 190251, Russia, e-mail: lsahno2010@yandex.ru

*Tor Ltd, the vendor of QuickField FEA Software,
Moskovsky pr. 22, lit. T, St. Petersburg 190013, Russia. E-mail: simon.dubitsky@ieee.org

Abstract— Important features of resistance welding machines are substantial current pulsations in the welding circuit and a highly non-uniform power intake from the supply mains. In order to develop welders that would comply with electromagnetic noise level specifications and be compatible with the supply mains, a careful analysis of higher harmonics generated by resistance welders is therefore essential. With this end in view, a mathematical model was developed which makes it possible to calculate electromagnetic processes end to analyze harmonic composition of currents and voltages in any component of a resistance welder power source.

The model was used for the harmonic analysis of the mains current and the welding circuit in application to the inverter power unit for a steel pipe flash butt welder. The calculations yielded data which permitted selection of appropriate harmonic current suppression devices to be installed at the supply network buses and enabled quantitization of the electromagnetic noise generated by welding current harmonics.The calculated electromagnetic processes in the welding source were corroborated experimentally.

Keywords— electromagnetic compatibility, power consumption, resistance flash welding , welding machine

I. INTRODUCTION

ELECTRIC welders represent a common source of electromagnetic noise in power networks. Such noise steins from a nonlinear and asymmetric load of power net--. works with the welders in operatic::, which results in distortion of their current and voltage curves. Moreover, an abruptly non-uniform power intake from the network or a limited power scarce (Diesel-generator set) is possible in welding, and inducing voltage drops. The quality of electric power may thus be deteriorated by the electromagnetic noise. Because of this industrial welders are generally powered by special networks equipped with noise suppression devices. Voltage drops at the power source buses adversely affect welder's operation, because high-quality welds can be obtained only with a stable voltage at the welder's input. The voltage drops can also upset serviceability of the welder having an inverter power unit. The block diagram of an inverter source in fig1 consists of the three-phase bridge rectifier with the capacitor filter, the inverter, the welding transformer to which secondary windings via the single-phase two-half-period rectifier with an average point welded details are connected.

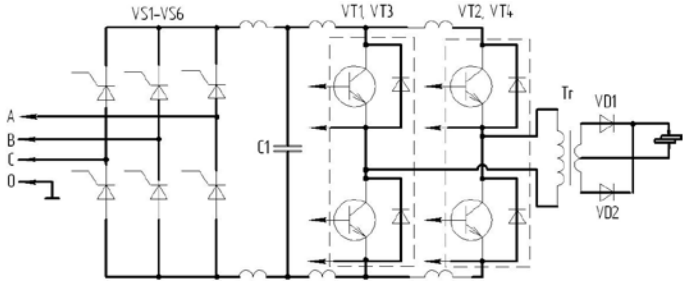

Fig. 1. Circuit diagram of the flashing butt resistance welder for steel pipes.

Hence development of new welders entails evaluation of their impact on supply mains or Diesel-generator sets and necessitates provision of their electromagnetic compatibility.

II. THE CALCULATION METHOD

The problem is generally solved by experimental investigation [1,2]. At the same time, efficient means for analysis of the noise level and electromagnetic compatibility of welders and power sources are provided by studies on the associated electromagnetic processes with the use of computer simulation making it possible to evaluate distortions of current and voltage in the power source, voltage drops and surges at the welder's power source input, to analyze operating conditions for a Diesel-generated set supplying power to the welder, to estimate flashing stability and impact of power source electric resistance on it, and to find the ways to ensure electromagnetic compatibility. Complexity of mathematical modeling stemming from a high order of the set of nonlinear differential equations that describe electromagnetic processes and necessity to develop special mathematical models corresponding to various welder configurations and their load conditions made impossible a wide application of the method to solution of the above problems. However, availability of numerous multipurpose software packages makes unnecessary development of specialized mathematical models for each configuration of the power source and substantially reduces the time needed to obtain solution. The efficiency of application of a multipurpose software package is exemplified by analysis of electromagnetic compatibility for medium-power resistance welders and shop power network.

III. CALCULATION OF POWER CONSUMPTION

The power consumption of a welding machine:

$$S = U_1 I_1 \approx U_{OC2} I_2 , \qquad (1)$$

where U_1 and I_1 are primary voltage and current, I_2 is welding current, U_{OC2} is open circuit voltage of secondary winding of the welding transformer.

$$U_{OC2} = I_2 z , \quad (2)$$

where z is the full complex resistance of welding machine, I_2 is complex current.

The full complex resistance contains welder's load and a short-circuit three-winding transformer resistance.

IV. EQUIVALENT CIRCUIT OF WELDER'S LOAD

The present paper focuses on resistance flash welding which involves butting of parts preheated to a near-melting temperature. It should be noted that this technique can also be applied to other types of welding.

The welder's load is a welding circuit which represents a system of rigid and flexible curren--conducting components connecting the secondary winding of the welding transformer to the welder's electrodes between which the parts to be welded are placed. The equivalent circuit thus comprises the inductances and resistances for secondary circuit, electrodes, sections of parts, through which welding current passes, and the nonlinear components substituting the flashing zone in welding. In development of an equivalent load circuit selection of such components presents a major difficulty because of complexity of physical processes in the flashing zone. Let us consider features of the flashing process with the view to replace the flashing zone with electric circuit components. On account of a high density of current at elementary contacts between parts, they heat up and convert to liquid straps on coming in contact with each other. Changes in the volume and shape of the liquid straps are due to metal melting, movement of the strap over the surface of parts, its compression by electrodynamic forces, and liberation of vapours and gases out of the overheated metal volume. Such phenomena are responsible for abrupt changes in resistance of the flashing zone. Disintegration of liquid metal straps occurs under the influence of electrodynamic forces and metal overheating. Such disintegration is accompanied by arcing with constant voltage maintained at the flashing zone and the welding current dropping to zero. Experiments show that resistance at the flashing zone undergoes three-four-fold changes. Frequency of changes in resistance and arcing may range from 500 Hz to a few kHz, and arcing duration accounts for several tens of microseconds. With stable flashing, the welding current curve is not strictly cyclical, but, considering its recurrent nature in each cycle (both for the envelope curve and for single-pulsation currents), the welding current curve may be regarded cyclical for analysis of phenomena with an averaging interval of about 0.1 s, the cycle being equal to that of supply voltage. The flashing process generally takes tens of seconds and involves several stages. The first store can be a condition close to the welder's short-circuit or a no-load condition caused by the slopping of the metal from the flashing zone under the action of electrodynamic forces. The second stage features contact and arc occurrences, their role depending on the properties of the flashed material and the flashing condition. At the last stage, when the film of molten metal forms on the surface of welded parts, these are pressed together , which corresponds to the welder's short-circuit. This stage alsts from 0.1 to 0.8 s. The basic parameters of the flashing condition, such as equivalent contact resistance, number of connections and disconnections for the flashed butts per unit time, and voltage at the flashing zone in arcing, were found experimentally for different materials and sections of the parts being welded.

Complying with the above features of the flashing process, the equivalent circuit for the flashing zone should fit the following load conditions:

- the short-circuit condition;
- the no-load condition,
- transition from the no-load condition to the short-circuit condition, characteristic of the initial flashing stage,
- step-type changes in resistance of the flashing zone,
- cycling arcing.

Depending on the condition under consideration, the flashing zone is replaced either by a resistance or by a source of constant electromotive force (emf) and a fully controllable value (fig.2).

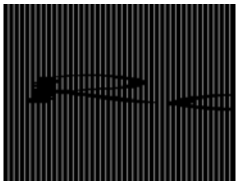

Fig. 2. Equivalent circuit of the flashing zone.

R_C - contact resistance,

U_g -arc voltage

The first of the above conditions reflects the contact occurrences at the flashing zone, and the second, the arc phenomena. When the valve is closed, the resistance or the emf source are disconnected from the welder's load; when it is opened, they are connected to the load.

V. THE EQUIVALENT CIRCUIT OF A THREE –WINDING TRANSFORMER

An example of a three –winding transformer with disk alternating windings and an armored magnetic conductor is shown in fig.3. This transformer is used in the inverter source in fig1 The primary winding consists of four series-connected coils made of wire with rectangular cross-section. The two secondary coils are made of copper tubes through which cooling water flows.

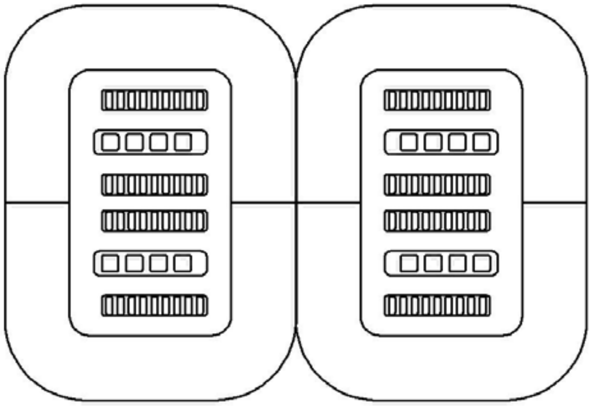

Fig.3. Design of the transformer with four primary coils

The main difference between the proposed equivalent circuit and the well-known one is that the windings not being electrically linked and always have positive inductances. Therefore, the circuit is suitable for the standard simulation program (P-Spice). It is very important that the circuit parameters have the clear physical sense and can be easily evaluated by FEA.

This circuit is based on replacing the three-winding transformer with two transformers: one with windings *1, 2* and the second with windings *1, 3* (further denoted as transformers *1-2* and *1-3*) [3]. The mutual impact of transformers *1-2* and *1-3* is modelled as a change of EMF on the terminals of their secondary windings by magnetic leakage fields. The degree of magnetic coupling of these transformers is characterized by the magnetic coupling factor for the leakage fluxes $k=\dfrac{M}{\sqrt{L_{12}L_{13}}}$ (L_{12} and L_{13} - the leakage inductances of the transformers 1-2 and 1-3 referred to their secondary sides, M - the mutual inductance of the leakage fluxes).

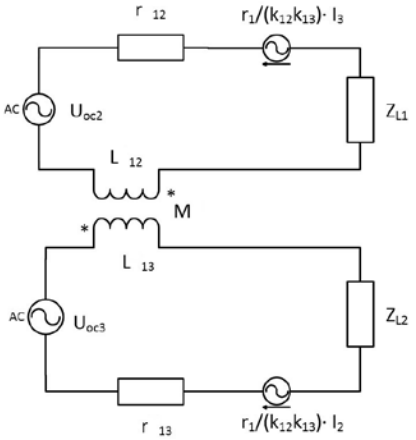

Fig.3. Equivalent circuit of three –winding transformer

The magnetic coupling factor k is convenient for the analysis of the transformer design influence on the power consumption. If $M > 0$ the direction of the leakage flux in winding 3 caused by transformer 1-2, is opposite to the direction of the main magnetic flux in this winding. If $M < 0$ the leakage flux and the main flux in winding 3 have the same direction. Similarly, if $M > 0$ the direction of the leakage flux in winding 2 caused by transformer 1-3 is opposite to the direction of the main magnetic flux in this winding. If $M < 0$ the leakage flux and the main flux have the same direction. In the equivalent circuit in fig. 2 r_{12}, r_{13} are resistances of transformers 1-2 and 1-3 referred to the secondary side, z_{L1}, z_{L2} are secondary load impedances. We also introduce dependent sources of EMF $\dfrac{r_1}{k_{12}k_{13}}I_2$ and $\dfrac{r_1}{k_{12}k_{13}}I_3$ (r_1 is an active resistance of the primary winding). They take into account the change of the voltage at the terminals of the winding 3 and 2 due to a primary winding voltage drop of the transformer 1-3 and 1-2. The magnetic leakage fields in transformers 1-2, 1-3 (short-circuit tests for transformers 1-2, 1-3) was modelled by 2D FEA software QuickField [5]. From the FEA model we evaluate parameters L_{12}, r_{12}, L_{13}, r_{13} in the equivalent circuit. For evaluating the magnetic leakage mutual inductance M we made the FEA simulation of another short-circuit field in transformer 2-3 [2]. Calculation of electromagnetic processes in the scheme in fig.1 is made using the Microcap [4] software. The mathematical model was developed to analyze electromagnetic compatibility for welders, the load of which was given above. The model makes it possible to calculate electromagnetic processes and to analyze the harmonic composition of currents and voltages in any component of resistance welders having various circuit configurations and wide power and frequency ranges.

VI. AN EXAMPLE OF APPLICATION OF MATHIMATICAL MODEL FOR ANALYSIS OF ELECTROMAGNETIC NOISE GENERATED BY MEDIUM-POWER RESISTANCE WELDER

The above mathematical model is used to calculate electromagnetic processes in the thyristor inverter welding source for a flashing butt resistance welder which is intended for large-diameter steel gas and oil pipeline construction.

This source has no single-phase two-half-period rectifier The welder's power is supplied from the mains transformer having the rated power 650 kVA, the secondary linear voltage 380 V, and the length of current-carrying wires from the welder to the transformer about 100 m.

The source is rated at 250 kVA, the inverter frequency ranges from 50 Hz to 100 Hz, and the rectifies voltage is 400-430 V. The capacitance of the capacitor bank varies from 25,000 to 75,000 uF. The principal object such calculations is to analyze the effect of medium-power flashing butt welders on most common shop networks.

Calculation of electromagnetic processes were carried out for different flashing stages modeled by the above equivalent circuit for the flashing zone.

Proceeding from the above calculations effective values for network current, voltage and power consumed in a variety of flashing stages were obtained.

In flashing, total power consumption from the mains varies by a factor of 3.2.

Calculations show that, in all flashing stages, deviations of effective values for phase currents in the mains account for 17% with 30,000 uF filter capacitance, or 10% with 75,000 uF filter capacitance. Momentary voltage surges caused by bariations in the welder's load condition amount to 60 V. The coefficient of voltage distortions constitutes 16% for 50,000 uF filter bank capacitance and 15% for 75,000 uF filter bank capacitance.

The results of calculations were correlated with experimental data. Electrical characteristics of the welding process were recorded by mirror-galvanometer oscillographs, ammeters, voltmeters, and wattmeters. Shunts were used as sensors in oscillograph recording. A correlation between calculated and measured data demonstrated the capability of tne mathematical model to find with a practical accuracy effective values for currents and voltages in different components of power sources and welder's circuits, and pulsations of power consumption in the welding processes.

The present analysis permits conclusion that power supply to the flashing butt welders through the converters of three-phase mains voltage to single-phase square-wave voltage can provide a uniform loading of mains phases. Such power supply smoothes pulsations in the mains currents and voltages, but does not actually reduce the nonuniformity of power consumption in various flashing stages.

VII. CONCLUSION

The present paper reports a mathematical model for analysis of electromagnetic noise generated by flash resistance welders and their power sources. The model permits estimation of load asymmetry for power source phases, nonuniformity of power consumption in welding, harmonic composition of currents and voltages in any circuit component, and voltage drops at welder's power source input.

For the flashing zone of welded parts an equivalent circuit is suggested obtained from analysis of experimental curves for currents and voltages reflecting their principal physical processes.

The calculated parameters of electromagnetic processes were corroborated by experimental data obtained for the inverter power source of steel pipe flash butt welders.

The mathematical model provides a broad spectrum of possibilities for studies on electromagnetic compatibility of various welders and power sources.

REFERENCES

[1] S.I. Kuchuk-Yatsenko et al., Resist ance Butt Welding of Pipelines, " "N&ukova Dumka", Kiev, 1986 , 205 p.

[2] B.E. Paton, V.K. Lebedev. Electrical Equipment for Resistance Voiding, "Mashinostroyeniye", Hoscow, i960, 440 p.

[3] L.I. Sakhno. On equivalent circuit of a three-winding transformer. *Elektrichestvo*, No 8, 2003, p.25-33.

[4] Claycomb J. R. Applied Electromagnetics Using QuickField and MATLAB. – *Laxmi Publications, Ltd*., 2010.

[5] A. Vladimirescu The SPICE Book, *John Wiley & Sons*, Inc., First Edition, 1994W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.

L.Sakhno graduated from the Electromecanical Faculty of the Leningrad Polytechnical Institute (LPI) in 1974 In 2006 she received the degree of Doct. Techn. Sci from the LPI. Her thesis dealt with the analysis and development of theoretical methods for calculation of welding transformers. She is a professor at St. Petersburg State Polytechnic University, Department of Theoretical Electroengineering.

O.Sakhno graduated from the Electromecanical Faculty of the Leningrad Polytechnical Institute (LPI) in 1974 In 1983 she received the degree of Cand.. Techn. Sci from the LPI. Her thesis dealt with the analysis and development of theoretical methods for calculation of electric network electromagnetic processes. She is a lecturer at St. Petersburg State Polytechnic University,, Department of Mathematics.