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Field-Circuit Modelling of the Resistance Spot Welding Transformers

***Abstract**. Transformers of high frequency resistance spot welding systems are considered. The equivalent circuit of a three-winding transformer, which is obtained by replacing it with two two-winding transformers, is used. It is shown that the magnetic coupling factor for the leakage fluxes of these two-winding transformers influences on the output current. The study of the transformers includes both 2D eddy-current FEA analysis for estimation the leakage impedance and the circuit simulation, which gives the output current. The results are used to design economical welding transformers. The calculation results are confirmed experimentally.*

Streszczenie.** Zaprojektowano transformator do wsokoczestotliwościowego punktowego zgrzewania. Przeprowadzono analizę rozkładu prądów wiroychw celu uwzględnienia impedancji upływowej oraz zaproponowano schemat zastępczy transformatora trzy-uzwojeniowego otrzymanego przez zastąpienie dwóch transformatorów dwu-uzwojeniowych. **Modelowanie wysokoęstotliwościowego transform,atora do rezystancyjnego zgrzewania

Keywords: resistance spot welding, high frequency inverter, leakage inductance, three-winding transformer.
Słowa kluczowe: zgrzewanie rezystancyjne, transformator, przekształtnik

Introduction

High frequency resistance spot welding (RSW) systems are widely used due to two main advantages. The first one is reduction of size and mass of the RSW system. This advantage is obvious, especially for manual and robot welding guns. The second advantage is providing broad technological possibilities. The high frequency RSW system (fig.1) consists of an input H-bridge inverter, welding transformer and a full-wave centre tapped output rectifier that consists of diodes (D_1, D_2).

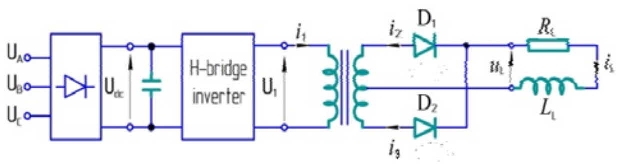


Fig.1. Schematic presentation of the discussed resistance spot welding system

An input H-bridge inverter with a modulation frequency of 1 kHz is mainly used. Increase of the modulation frequency above 1kHz is required for welding of thin sheets made of zirconium, titanium, radiation-resistant steels. The development of RSW systems with frequencies above 1 kHz sets the new problems, one of which is to provide economical high frequency welding transformers. The design of these transformers affects the load current and power consumption of RSW system because the values of their electromagnetic parameters exceed the values of the load impedance.

The specific feature of the transformer mode in RSW system is that currents can flow through the primary and one of the secondary windings (two-winding transformer) or through the primary winding and two secondary windings when the diodes are switching (three-winding transformer). Usually the currents and voltages in RSW systems are calculated only for two-winding mode of the transformer [1-4]. However the three-winding transformer electromagnetic parameters can influence on the welding current and power consumption of RSW system but there is no information about this influence.

In this regard, the aim of this work is field-circuit modelling of three-winding transformer in RSW system and the study of the influence of electromagnetic transformer parameters on the welding current and power consumption of the system. This influence should be considered when the new transformer designs are being developed. We will study RSW systems with modulation frequency from 1 kHz to 10 kHz. These frequencies are required for welding of zirconium, titanium, radiation-resistant steels parts.

RSW transformer

The basic transformer TR1, which was designed for a modulation frequency of 1 kHz, is shown in fig.2

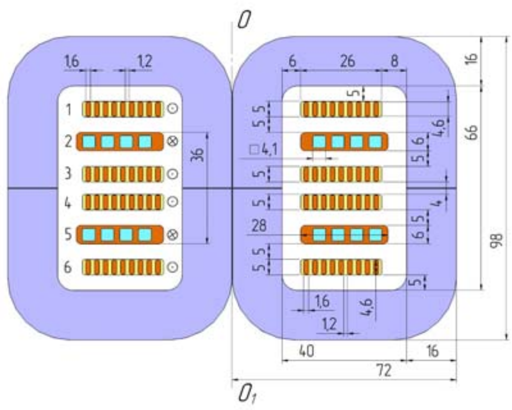


Fig.2. Design of the basic transformer TR1.

It has four copper series-connected coils of the primary winding. Each coil consists of 9 turns. Two secondary windings are connected in series and in adding. They are made of water cooled copper tubes. The average length of the coil is 0,317 m.

Equivalent circuit of a three-winding transformer

In this paper we used the equivalent circuit of three-winding transformer described in [5-7]. It is given in fig.3. This circuit was successfully used for studying transformers of double-bridge rectifiers. Here's some information explaining the electromagnetic parameters in the equivalent circuit of the transformer, which is necessary for further analysis of the RSW system. First of all it differs from well-known equivalent circuit [8]. The two secondary windings of the transformer in fig.3 are not conductively coupled. All inductances in the circuit are always positive. 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). 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.

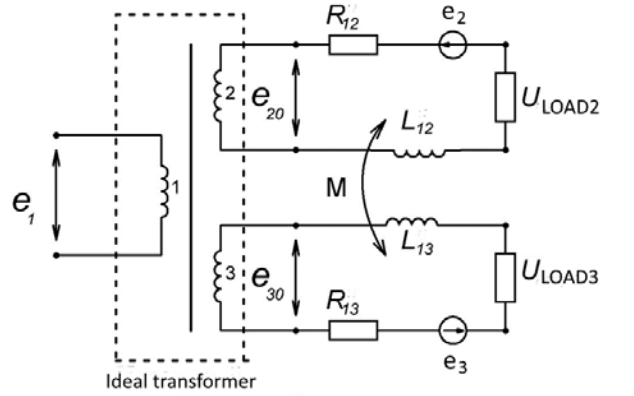


Fig.3. Equivalent circuit of a three-winding transformer

Equations of a three-winding transformer, referred to the secondary windings, for instantaneous magnitudes of currents and voltages are:

$$(1)\quad \left.\begin{aligned} e_{02} &= R_{12}i_2 + L_{12}\frac{di_2}{dt} + \frac{R_1}{k_{12}k_{13}}i_3 + M\frac{di_3}{dt} + u_{LOAD2} \\ e_{03} &= R_{13}i_3 + L_{13}\frac{di_3}{dt} + \frac{R_1}{k_{12}k_{13}}i_2 + M\frac{di_2}{dt} + u_{LOAD3} \end{aligned}\right\}$$

where i_2, i_3 are currents in windings 2 and 3, e_{02}, e_{03} are open circuit EMF in windings 2 and 3, L_{12}, R_{12} are leakage inductance and real resistance of transformer 1-2, L_{13}, R_{13} are leakage inductance and real resistance of transformer 1-3, R_1 is real resistance of winding 1, $k_{12} = w_1 / w_2$, $k_{13} = w_1 / w_3$, w_1, w_2, w_3 are turns of windings 1, 2, 3, M - the mutual inductance of the leakage fluxes of transformers 1-2 and 1-3, u_{LOAD2} is voltage on the terminals of winding 2, u_{LOAD3} is voltage on the terminals of winding 3.

An ideal three-winding transformer in fig.3 allows us to find the RMS values of primary current and voltage which are necessary for calculation of power consumption. This ideal transformer forms the open circuit voltages of the secondary windings e_{02}, e_{03}. The presence of this ideal three-winding transformer distinguishes the equivalent circuit in Fig.3 from the equivalent circuits used in [5-7]. The mutual inductance of the leakage fluxes can be found [7]:

$$(2)\qquad M = \frac{L_{12} + L_{13} - L_{23}}{2k_{12}k_{13}}$$

where L_{23} is the leakage inductance of transformer 2–3. All the leakage inductances in (2) are referred to winding 1. Due to the symmetry of the design of transformer we have $L_{12} = L_{13}$.

The degree of magnetic coupling of transformers 1-2 and 1-3 is characterized by the magnetic coupling factor for the leakage fluxes $k_M = \dfrac{M}{\sqrt{L_{12}L_{13}}}$.

The magnetic coupling factor k_M 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. We also introduced dependent sources of EMF $e_3 = \dfrac{r_1}{k_{12}k_{13}}i_2$ and $e_2 = \dfrac{r_1}{k_{12}k_{13}}i_3$. 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.

Calculation of equivalent circuit three-winding transformer parameters

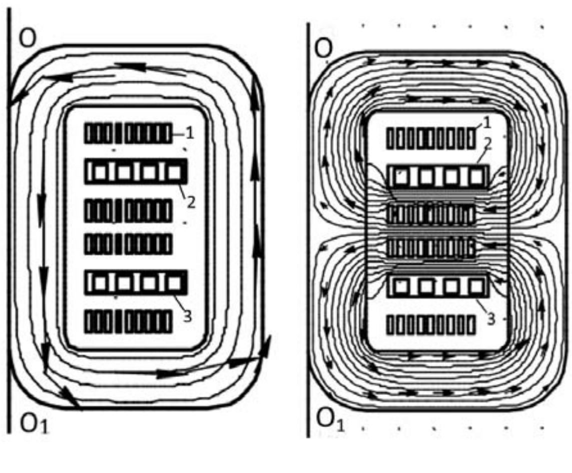
The magnetic leakage fields in transformers 1-2, 1-3 (short-circuit tests for transformers 1-2, 1-3) was modelled by the 2D FEA software QuickField [9]. From the FEA model we evaluate parameters L_{12}, R_{12}, L_{13}, R_{13} in the equivalent circuit. We made additionally FEA simulations of short-circuit field in transformer 2-3 for evaluating the magnetic leakage mutual inductance M .

For example the results of the parameter calculations for the transformer in Fig. 2 are given in the table for a frequency of 1 kHz and 10 kHz. All the parameters in the table are referred to the secondary windings.

Table 1. The example the results of the parameter calculations for the transformer

f [Hz]	*L_{12}=L_{13} [nH]*	*L_{23} [nH]*	*M[nГн]*	*K_M*	*R_{12}=R_{13} μOhm*
1000	86,9	256	-41	-0,47	154
10000	65,1	187	-28,4	-0,43	547

The table shows that the magnetic leakage mutual inductance M is negative. This means that leakage flux in winding 3 caused by transformer 1-2 (fig.4b) has the same direction as the main flux of this transformer (fig.4a). Magnetic fluxes in fig.4 were received by 2D FEA calculations. Due to symmetry we can consider half of the cross section of the transformer.



a) b)

Fig.4. The magnetic fluxes of the transformer 1-2
a) open circuit (main flux), b) short circuit (leakage flux)

In addition, the table shows that the skin effect significantly affects the parameters of the transformer and this effect should be taken into account in the calculation of electromagnetic processes in it.

Calculated impedances of transformers 1-2 and 1-3 for transformer in fig.2 differ from experimental ones by no more than 10%.

Circuit modelling of the high frequency RSW system

We used the Microcap [10] software for calculation of electromagnetic processes in high frequency RSW system. The model for RSW system simulation is shown in Fig. 5.

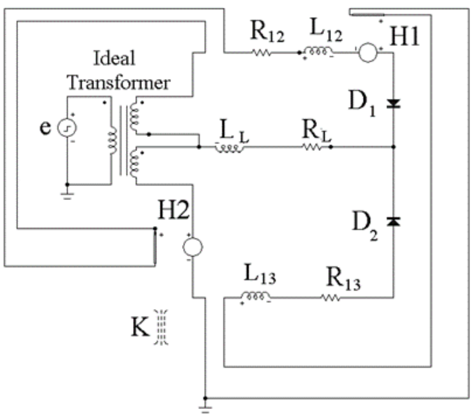


Fig.5. The model for RSW system simulation

The H-bridge invertor is modelled by pulse square voltage source e. The period of the voltage source e is $T = 1/f$ (f is a modulation frequency). The parameters of the transformer equivalent circuit are the results of the magnetic leakage fields calculation. The load of RWS system is represented by inductance $L_L = 780$ nH and real resistance $R_L = 100\ \mu Ohm$ which were measured. The results of the calculation of the welding current for RSW system with the transformer in fig.2 are confirmed by experiments.

The calculation results

We used the circuit in fig.5 for the study of the influence of the leakage inductance of transformer *1-2 (1-3)* L_{12} (L_{13}) and the magnetic coupling factor k_M on welding current and power consumption of RSW system. We have found that the welding current increases if the leakage inductance reduces (fig.6).

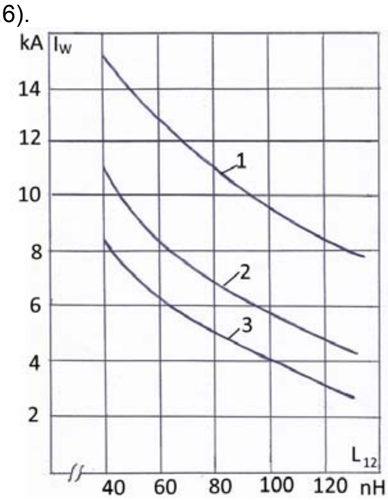


Fig.6. The influence of the leakage inductance on the RMS welding current (curve 1 corresponds to k_M=*-0.5*, curve 2 corresponds to k_M=0 , curve 3 corresponds to k_M=0.5)

Consequently, the same current can be obtained at different values of leakage inductance and different primary voltages. That means that if we want to reduce power consumption for given welding current of RSW system we should reduce the leakage inductances. We have found that the load current is greater when coupling factor is negative than when this one is positive (fig.6). This result does not depend on the value of leakage inductance. We can explain this effect by the change of the time of diode switching. The time of diodes switching is less when the coupling factor is negative. Figure 7 shows the switching time vs the leakage inductance at a frequency of 1000 Hz and different couplings (curve 1 corresponds to $k_M = 0{,}5$, curve 2 corresponds to $k_M = 0$, curve 3 corresponds to $k_M = -0{,}5$).

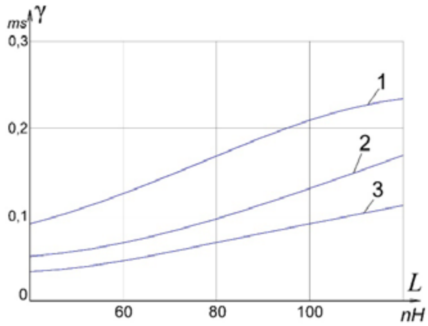


Fig.7. The switching time γ vs the leakage inductance L at a frequency of 1 kHz

The role of the diode switching time depends on the frequency. At high frequency this role is more than at low frequency. We can confirm this conclusion by figures 8 (at a frequency 1 kHz) and 9 (at a frequency 10 kHz) where we can see currents in secondary windings (red is for winding 2, blue is for winding 3). The leakage inductance is *L=80 nH* for the both figures.

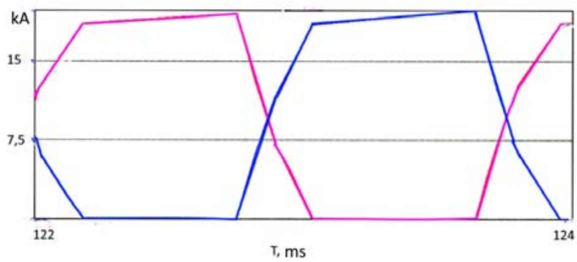


Fig.8. Currents i_2, i_3 vs time in the secondary windings at f=1 kHz

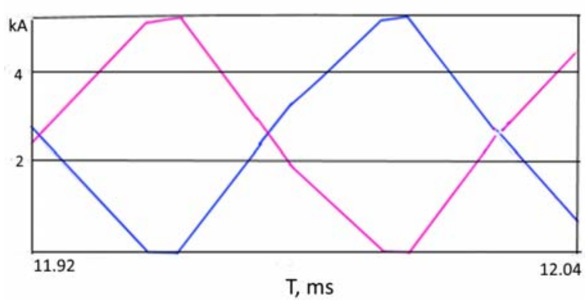


Fig.9. Currents i_2, i_3 vs time in the secondary windings at f=10 kHz

The time of switching the diodes is much more for frequency 10 kHz. Therefore, the work of the transformer in a mode where the current flows in all three windings (during switching the diodes), influences on the load current and power consumption. If the time of the diodes switching is much less than the half-period of the inverter, transformer can be considered as a two-winding one when we calculate the load current.

On the basis of the calculation results we come to a definite decision. We can reduce power consumption of RSW system if we design its transformer with reduced leakage inductance and negative coupling factor. In this connection we investigated several transformer designs for RSW system. Designs differ interleaving of primary and secondary windings and the number of primary winding coils. They have different leakage inductances and different coupling factors for the leakage flux. All options have the same number of turns of the primary winding. The best design is shown in fig.10.

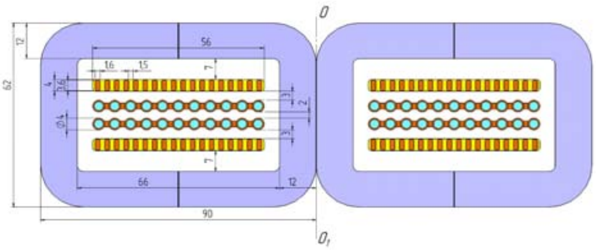


Fig.10. The new design of the transformer for RSW system

It has leakage inductances L_{12}=L_{13}=*43 nH*, coupling factor k_M=*-0.01*. The operating current of this transformer is 11 kA, a frequency of 7.5 kHz. It has 34% lower power consumption than the basic one.

Conclusions

1. An efficient equivalent circuit of RSW system was developed. It was allowed us to study the influence of electromagnetic parameters of three-winding transformer on the power consumption of these systems.
2. The most effective design of the three-winding transformer has minimal leakage inductances of transformers 1-2 , 1-3 and a negative magnetic coupling factor for the leakage fluxes.
3. On the bases of the investigations considered above the transformer with the operating current 11 kA was developed. It has 34% lower power consumption than the basic one. This result is confirmed experimentally.

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