Analysis of Proportional Integral and Optimized Proportional Integral Controllers for Resistance Spot Welding System (RSWS) – A Performance Perspective

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ABSTRACT: This paper is an attempt to accomplish a performance analysis of the different control techniques on spikes reduction method applied on the medium frequency transformer based DC spot welding system. Spike reduction is an important factor to be considered while spot welding systems are concerned. During normal RSWS operation, the transformer’s magnetic core can become saturated due to the unbalanced resistances of both transformer secondary windings and different characteristics of output rectifier diodes, which causes current spikes and over-current protection switch-off of the entire system. The current control technique is a piecewise linear control technique that is inspired from the DC-DC converter control algorithms to register a novel spike reduction method in the MFDC spot welding applications. Two controllers that were used for the spike reduction portion of the overall applications involve the traditional PI controller and Optimized PI controller. Care is taken such that the current control technique would maintain a reduced spikes in the primary current of the transformer while it reduces the Total Harmonic Distortion. The performance parameter that is involved in the spikes reduction technique is the THD, Percentage of current spike reduction for both techniques. Matlab/Simulink™ based simulation is carried out for the MFDC RSWS with KW and results are tabulated for the PI and Optimized PI controllers and a tradeoff analysis is carried out.

Keywords: Current Control; Welding Transformer; DC-DC Converter; Resistance Spot Welding; Particle Swarm Optimization

1. Introduction

The aim of this work is to develop and evaluate a novel method to control the magnetization level in the magnetic core of a welding transformer. It is based on fuzzy logic and requires the optimum operating values of the flux and welding current across the welding system. The magnetization level controller is a substantial component of a middle-frequency direct current (MFDC) resistance spot welding system (RSWS), where the welding current and the flux density in the welding transformer’s magnetic core are controlled by two hysteresis controllers [1].
The resistance spot welding systems described in different realizations [2]-[5], are widely used in the automotive industry. Although the alternating or direct currents (dc) can be used for welding, this work focuses on the RSWS (Fig.1) with dc welding current. The resistances of the two secondary windings R2, R3 and characteristics of the rectifier diodes, connected to these windings, can slightly differ. References [6]-[9] show that combination of these small differences can result in increased dc component in welding transformer’s magnetic core flux density. It causes increasing magnetic core saturation with high impact on the transformer’s primary current i1, where current spikes eventually appear, leading to the over-current protection switch-off of the entire system. However, the problematic current spikes can be prevented either passively [6] or actively [7]-[9].

When the current spikes are prevented actively, closed-loop control of the welding current and magnetic core flux density is required. Thus, the welding current and the magnetic core flux density must be measured. While the welding current is normally measured by the Rogowski coil [10], the magnetic core flux density can be measured by the Hall sensor or by a probe coil wound around the magnetic core. In the latter, the flux density value is obtained by analogue integration of the voltage induce in the probe coil [7]. Integration of the induced voltage can be unreliable due to the unknown integration constant in the form of remnant flux and drift in analogue electronic components. The drift can be kept under control by the use of closed-loop compensated analogue integrator [9].

An advanced, two hysteresis controllers based control of the RSWS, where current spikes are prevented actively by the closed-loop control of the welding current and flux density in the welding transformer’s magnetic core, is presented in [9]. This solution requires measuring of the welding current, while instead of measured flux density only information about magnetization level in the magnetic core is required. Some methods tested on welding transformer’s magnetic core, that can be applied for magnetization level detection are presented in [7], [8]. All these methods require Hall sensor or probe coils which make them less interesting for applications in industrial RSWS, due to the relatively high sensitivity on vibrations, mechanical stresses and high temperatures. In order to overcome these problems, an ANN based magnetic core magnetization level detector was presented previously. Its only (single) input is the measured transformer’s primary current. The ANN, based on the magnetic core magnetization level detector, is trained to recognize the waveform of the current spikes, which appear in the primary current when the magnetic core is approaching the saturated region. Upon detection of a spike, the ANN target signal makes it possible for the transformer supply voltage to change direction which also changes the magnetic flux density accordingly. This way, the system is controlled using the ANN detector and over-current protection switch-off is prevented.

2. MFDC Setup

The complete MFDC setup with the DC supply is as shown in the Figure 1. which comprises of the single phase inverter connected to the DC supply followed by the transformer with the output rectifier.

![Figure 1. MFDC setup for the Proposed Work](image)
The mathematical modeling of this MFDC setup has been exclusively detailed in the literature [12]. The circuit model as shown in the Figure 1, comprises of the DC supply U_{DC} followed by the single-phase inverter with the switches, working with 1000Hz, S_1, S_2, S_3 and S_4. The inverter output voltage with 1000Hz is supplied to the medium frequency transformer working with 1000Hz. L_{e1}, L_{e2} and L_{e3} are the leakage reactance of the three windings with one primary and two secondary windings. The transformer is a center-tapped transformer traditionally used for the rectifying circuit. N_1,N_2 and N_3 are the number of turns in the one primary and two secondary winding respectively. D_1 and D_2 are the rectifying diodes to get a DC power at the load. We avoid the repetition of the mathematical model in order to detail the proposed work for current spike reduction. The current spike occurring in the primary current of the transformer is due to the unequal impedance occurring in the two circuits L_{e2}, R_2, D_1 and L_{e3}, R_3, D_2 with R_L and L_L commonly occurring for both the circuits is unavoidable. Thus the corrective measures are incorporated that would reduce the spike in the current in the primary current of the transformer.

The literature [12] talks about the hysteresis controller that is developed to create the PWM technique that would control both the current spike and the magnetic saturation of the windings of the transformer. In order to develop the reference current for the control of the inverter for a proper PWM generation the mathematical model of the saturation transformer is used for the development of the proposed novel control for the current spike reduction.

2.1. Proposed Control Technique with Traditional Dynamic Model

By referring the circuit in Figure 1 applying KVL on the primary winding circuit we obtain the equation (1)

\[ u = R_{i_p}i_p + L_{i_p}(di_p/dt) + N_1(d\phi/dt) \quad (1) \]

Similarly implementing KVL on the secondary windings equation (2) and (3) would be got.

\[ 0 = R_{i_2}i_2 + L_{i_2}(di_2/dt) + N_2(d\phi/dt) + dp_1 + R_{i_2}i_2 + L_2(d(i_2+i_3)/dt) \quad (2) \]

and

\[ 0 = R_{i_2}i_2 + L_{i_2}(di_2/dt) + N_2(d\phi/dt) + dp_2 + R_{i_2}i_2 + L_2(d(i_2+i_3)/dt) \quad (3) \]

where \( \phi \) is the magnetic flux, \( dp_1 \) and \( dp_2 \) are the nonlinear characteristics of the output rectifier D_1 and D_2. R_L and L_L are the load resistance and the inductance. Applying KVL in the magnetic circuit with \( i_p \) as the primary winding current, \( H(B) \) is the magnetizing curve of the iron core \( \sigma \) the air gap B the iron core flux density ,the equation obtained is as shown below in (4)

\[ N_1i_p + N_2i_2 = H(B)\mu_0 + 2\delta B/\mu_0 \quad (4) \]

The welding current \( i_3 \) is the sum of the currents flowing in the secondary windings.

\[ i_3 = i_2 + i_3 \quad (5) \]

The resistance in parallel with the winding is that of the primary side core which is circumventing some of the current coming from the inverter. The inverter current contributes to both the primary winding and the resistance in parallel to the winding.

\[ i_t = i_{i_p} + i_{f_e} \quad (6) \]

The current \( i_{f_e} \) is the current flowing through the resistance as defined in (7)

\[ i_{f_e} = N_1\phi/dt/R_{f_e} \quad (7) \]

where \( R_{f_e} \) is the resistance value.

The overall flux in the core is given by the equation (8)

\[ \phi = BA_{f_e} \quad (8) \]

where \( A_{f_e} \) is the area of cross section of the core.
The magnetomotive force is defined as
\[ \theta = N_1 i_1 + N_2 i_2 - N_3 i_3 \]  
(9)
By the use of the complete modeling of the saturation transformer, which is defined in terms of the mathematical equation, is developed as a Matlab Model and used for the spike reduction.

3. Proposed Work
The Matlab model is a contribution of the [13] and thus it is reused in this work for a current control technique used in this paper. The overall block diagram of the proposed implementation would be as shown in Figure 2.

The block diagram explains how the implementation is carried for the proposed current controlled technique in order to control the spike in the transformer primary current. The \( i_2 \) and the \( i_3 \) current thus observed from the mathematical model of the saturation transformer is added and the sum of both the currents that is the magnetizing current is given to the comparator that has reference current as the another input. The error current is fed as the input to the PI controller which produces the modulation index in such a way that the magnetizing current equals the reference current. By the use of the modulation index the triangular PWM is generated to be fed to the inverter, thus controlling the spike not to cross the desired current. In order to have the performance characteristics of PI controller is replaced with Optimized PI controller by using the PSO technique is used and compared with the traditional PI controller, and the performance characteristics are analyzed.

3.1. Proportional Integral Controller
In control engineering, a PI Controller (proportional-integral controller) is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between the output and desired set-point) and the integral of that value. PI controllers consist of a proportional gain that produces an output proportional to the input error and an integration to make the study state error zero for a step change in the input.

The controller output is given by
\[ k_p \Delta + k_i \int \Delta \, dt \]  
(10)
where \( \Delta (SP – PV) \) is the error or deviation of actual measured value (PV) from the set-point (SP)
A PI controller can be modelled easily in software such as Simulink using a "flow chart" box involving laplace operators.
c = \frac{1}{\tau(1+\tau)}

(11)

Where \( G = K_p = \) proportional gain and \( G / \tau = K_i = \) integral gain.

Setting of \( G \) often tradeoff between decreasing overshoot and increasing settling time.

The integral term in PI control causes the steady state error reduce to zero which is not the case proportional only control in general.

3.2. Optimized Pi Controller Using Particle Swarm Optimization

The proportional gain \( K_p \) and the integral gain \( K_i \) of the PI controller is optimized in order to provide the lowest THD as the output, which would automatically reduce the current spike occurring in the transformer primary. The gain constants are acting as the independent variable which varies to optimize the THD of the transformer primary current.

Particle swarm optimization is a population based stochastic optimization technique stimulated by social behavior of bird flocking or fish schooling. PSO helps to solve the optimization problems. In PSO, each solution is a "bird" in the search space described as "particle". All particles have fitness values which are evaluated by the fitness function to be optimized and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles (Kennedy J, et.al., 1995). PSO is initialized with a group of random particles and then searches for optima by updating generations. In each iteration, every particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. This value is called \( P_{best} \). Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called \( g_{best} \). The \( i \)th particle is represented as \( X = (X_{i1}, X_{i2}, ..., X_{id}) \) in the \( d \)-dimensional space. The best previous position of the \( i \)th particle is recorded as represented as the following.

\[ \bar{X}_i = (\bar{X}_{i1}, \bar{X}_{i2}, ..., \bar{X}_{id}) \]

(12)

The modified velocity and position of each particle can be calculated using the current velocity and the distance from \( P_{best} \) and \( g_{best} \) as showing in the following formula.

\[ V_i = V_{i_{old}} + 2 \times \text{rand}() \times (pbestx - presentx) + 2 \times \text{rand()} \times (gbest - presentx) \]

(13)

The evolution procedure of PSO is shown in Figure 3. The Proportional Integral (PI) controllers have two parameters \( K_p \) and \( K_i \) with sampling time. The values of \( K_p \) and \( K_i \) are selected iteratively in many literatures using any of the method available for tuning it. Here the \( K_p \) and \( K_i \) is selected arbitrarily and iterated intuitively. The THD value minimization is taken as the objective and the problem becomes nonlinear due to variation of THD with respect to various \( K_p \) and \( K_i \) values. The mean value of THD is taken as the objective as shown in the below equation. The problem is defined for Shunt Active and Hybrid Filters. The PI controller equation at DC link voltage control part in Shunt Active Filter is defined as follows

\[ I_{af} = K_p \times (I_{\text{welding ref}} - I_{\text{welding}}) + K_i \times \int_{0}^{t} (I_{\text{welding ref}} - I_{\text{welding}}) \, dt \]

(14)

Where \( I_{\text{welding}} \) is welding current at DC link, \( I_{\text{welding ref}} \) is references current, \( K_p \) is Proportional constant and \( K_i \) is Integral constant.
The Objective function is

\[
\text{Minimize} \sum_{i=0}^{n} \text{mean(THD)}
\]  \hspace{1cm} (15)

Subjected to

\[
P_1 \leq K_p \leq P_2
\]  \hspace{1cm} (16)
\[
I_1 \leq K_i \leq I_2
\]  \hspace{1cm} (17)

Here, \(P_1\) refers lower limit of \(K_p\) value, \(P_2\) refers upper limit of \(K_p\) value, \(I_1\) refers lower limit of \(K_i\) value and \(I_2\) refers upper limit of \(K_i\) value.

4. Results and Analysis

Matlab based implementation of the MFDC based RSWS is carried out with the current control technique as discussed in the previous section using the traditional PI controller and optimized PI controller with the proposed current control method. The Total Harmonic Distortion (THD) was calculated for two methods and the results were discussed. The Figure 4 shows the THD of PI controller. The Figure 5 shows the flux wave in the primary winding that shows the spike. Due to the variation in the resistance of the two secondary winding circuits the current spike in the primary winding current waveform has been introduced.

The output responses for the PI controller based MFDC RSWS with the proposed current control technique are as shown in the Figure 4, 5, 6 and 7. It is observed in the Figure 4 that the THD is 37.4% .
The flux response, which has a reduced spike, is measured in the PI controlled current controlled MFDC RSWS. The flux response is as shown in the Figure 5.

It is observed that the current spike in the primary current with the PI based proposed control technique has reduced to a significant extent, which is evident in the Figure 6.
The welding current for each control technique in the transformer has been measured and the ripple in percentage is found using the steady state region of the current in the welding current response.

It is measured by the following formula

$$\text{Ripple} = \frac{I_{hss}}{I_{lss}} \times 100$$  \hspace{1cm} (18)

where $I_{hss}$ is the high side peak current in the triangular portion of the steady state current and $I_{lss}$ is the low side peak current in the triangular portion of the steady state current.

From figure 8, it is clear that the THD value of PI-PSO has come down to 36.68% as compared to THD of PI controller in figure 4.
Similar to the equation 18, the spike current is also calculated by considering the amplitude of the spike current alone in the primary current of the transformer response.

It is observed that the current spike in the primary current with the PI-PSO based proposed control technique has reduced to a significant extent, which is evident in the Figure 10.

Summarizing all the results in a tabular format would provide a tradeoff analysis of the control techniques used in the paper and a suggestion is given among the implementation techniques which would provide a clear cut view of the future development in the control techniques. The Table 1 indicates the THD available in the primary winding current and amount of ripple current in the welding current for two control techniques in the implementation that is carried out.
Table.1 THD in Primary Current and Ripple Current

| Method | THD(%) | Current Spike Percentage (%) | Welding Current Ripple(%) (T(ms)) | Rise Time (T(s)) | Settling Time (T(ms)) |
|--------|--------|-------------------------------|----------------------------------|------------------|-----------------------|
| PI     | 37.32  | 1.25                          | 5.88                             | 19               | 30                    |
| PI-PSO | 36.68  | 0.125                         | 6.16                             | 21               | 26                    |

From the Table.1 it can be observed that the THD is high for the PI controller and low for the PI-PSO controller. The current spike ripple is the lowest in the Optimized PI or PI-PSO method. Welding current ripple measured in the proposed work showed it’s low in the PI controller. Rise time is less in PI controller where as high in PI-PSO and settling time is less in PI-PSO and high in PI controller.

5. Conclusion

The proposed work with the two controllers like the PI controller and PI-PSO controllers were implemented using Matlab/Simulink and the results were observed and tabulated. The results observed do not indicate that a particular method is dominant in all aspects. But the tradeoff analysis on the results suggest that optimized PI could act as a best method considering its overall performance of reduced THD and current spikes, while keeping in mind that PI have lesser computational complexity as compared to PI-PSO which has the best current spike reduction occurring. Although it could be concluded that the PI-PSO method would be best suited for this spike reduction implementation.

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