Performance comparison between Hysteresis Controller (HC) and Proportional Integral (PI) Controller for Resistance Spot Welding System

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Abstract—The objective of this paper is to compare the saturation level control performance between Hysteresis Controller and PI controller in a middle-frequency direct current (MFDC) resistance spot welding system(RSWS). It consists of an input converter, welding transformer, and a full-wave rectifier mounted at the transformer secondary. The unequalohmic resistances of the two transformer's secondary circuits and the different characteristics of the diodes of output rectifier certainly lead to the magnetic core saturation which, consequently, causes the unwanted spikes in the transformer's primary current and over-current protection switch-off. The goal is to determine which control strategy gives better performance with respect to the magnetic core saturation. The two controllers presented such as HC and PI controllers for controlling the saturation level in the magnetic core of a welding transformer of highly nonlinear system of RSWS. The simulation study has been done in Matlab/Simulink environment shows that both controllers are capable to control the saturation level in the core of welding transformer successfully. The result shows that PI controller delivered the better response compared to HC controller. Responses are presented here with details analysis.

Keywords : Hysteresis, PI, core saturation, welding system.

I INTRODUCTION

Resistance spot welding is one of the most widely used inexpensive and efficient material joining processes in the automotive industry. This work deals with the modeling, analysis and corresponding control design of the welding current source, which represents an electromagnetical subsystem of the entire welding system. However, the technical questions of welding itself are not a subject of this work.

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 R_2, R_3 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 i_1, 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, PI controller is introduced. A dc-dc converter must provide a regulated dc output voltage under varying load and input voltage conditions. The converter component values are also changing with time, temperature, pressure, and so forth. Hence, the control of the output voltage should be performed in a closed-loop manner using principles of negative feedback. The most common closed-loop control method for PWM converter, namely, the current-mode control is presented schematically in below section. The current-mode control scheme is presented in section III. An additional inner control loop feeds back an inductor current signal, and this current signal, converted into its voltage analog, is compared to the control voltage. This modification of replacing the sawtooth waveform of the voltage-mode control scheme by a converter current signal significantly alters the dynamic behavior of the converter, which then takes on some characteristics of a current source. Among other control methods of converters, a hysteretic (or bang-bang) control is very simple for hardware implementation. However, the hysteretic control results in variable frequency operation of semiconductor switches. Generally, a constant switching frequency is preferred in power electronic circuits for easier elimination of electromagnetic interference and better utilization of magnetic components So the constant switching frequency gives better performance in the application of resistance spot welding system (RSWS). It uses the hysterisis controller. When it is used frequency cant be maintained. And the transformer saturation also happens due to the change in resistance of the RSWS.

In this paper, PI controller works well and giving better performance in terms of limiting flux density in order to limit the spikes in the primary current caused by the saturation to prevent the over current protection switch-off.

II. DYNAMIC MODEL OF THE RSWS

The RSWS, shown in Fig.1, consists of an input rectifier, an H-bridge inverter, a single phase transformer and a full-wave output rectifier [9]. The three-phase alternating current (ac) voltages u1, u2, u3, supplied from the electric grid, are rectified in the input rectifier in order to produce the direct current (dc) bus voltage. This voltage is used in the H-bridge inverter, where different switching patterns and modulation techniques can be applied, to generate ac voltage uH, required for supply of the welding transformer. The welding transformer has one primary and two secondary windings. They are marked with indices 1, 2 and 3, respectively. The currents, the number of turns, the resistance and the leakage inductances of the primary and two secondary welding transformer’s windings are denoted by i1, i2, i3, N1, N2, N3, R1, R2, R3, and Lσ1, Lσ2, Lσ3. The effects of the eddy current losses are accounted by the resistor Rfe. Rl and Ll are the resistance and inductance of the load. The output rectifier diodes D1 and D2 are connected to both transformer’s secondary coils. They generate the dc welding current il which has a dc value a few times higher than the amplitudes of ac currents i2 and i3 that appear in the transformer’s secondary coils without the rectifier diodes.

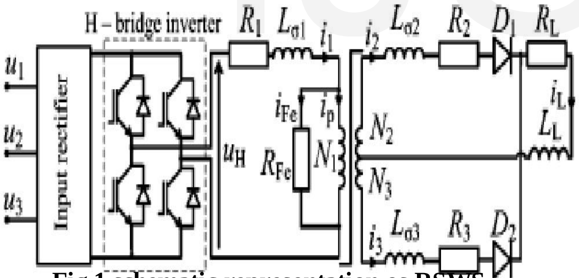


Fig.1.schematic representation os RSWS

The dynamic model of the RSWS was built based on the schematic presentation, shown in Fig.1. In this work the model is built with the programme package Matlab/Simulink based on the following set of equations (1) – (9).

$$uH = R_1i_1+L\sigma_1(di_1/dt)+ N_1(d\varphi /dt) \quad (1)$$

$$0 = R_2i_2+L\sigma_2(di_2/dt)+ N_2(d\varphi/dt) + dip_1+ R_Li_L+L_L(d(i_2+ i_3)/dt) \quad (2)$$

$$0 = R_3i_3+L\sigma_3(di_3/dt)-N_3(d\varphi /dt) + dip_2+ R_Li_L+L_L(d(i_2+ i_3)/dt) \quad (3)$$

$$N_1i_p+N_2i_2- N_3i_3=H(B)l_{ic}+2\delta B/\mu_0 \quad (4)$$

$$i_L = i_2+ i_3 \quad (5)$$

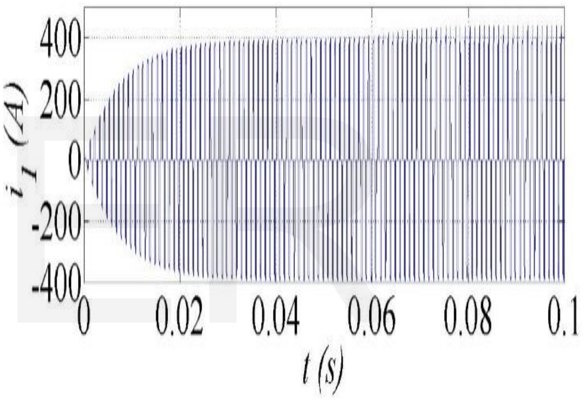
$$i1 = i_{Fe}+ i_p \quad (6)$$

$$i_{Fe} = N_1(d\varphi /dt)/R_{Fe} \quad (7)$$

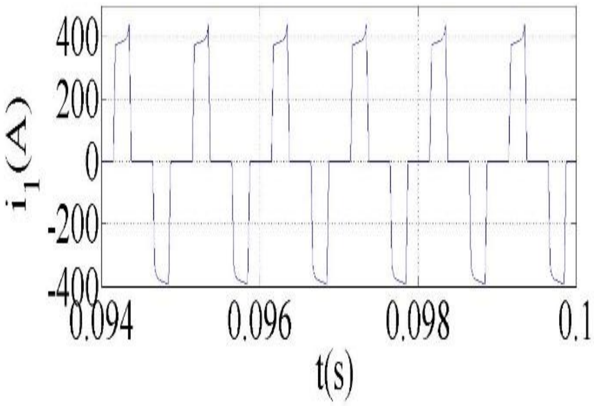
$$\varphi = BA_{Fe} \quad (8)$$

$$\theta = N_1i_1+ N_2i_2-N_3i_3 \quad (9)$$

The results of simulations, obtained by the dynamic model of the RSWS, show that small difference in resistances R2, R3 and in characteristics of the rectifier diodes D1 and D2 can cause unbalanced time behavior of the magnetic core flux and the current spikes in the primary current i1, shown in Fig.2. The a) and b) graphs in Fig. 2 show the same variables in different time scales. The current spikes appear approximately after 0.06s (Fig.2(c)). After 0.07s the current spikes become high enough to cause the over-current protection switch off of the RSWS.



(a)



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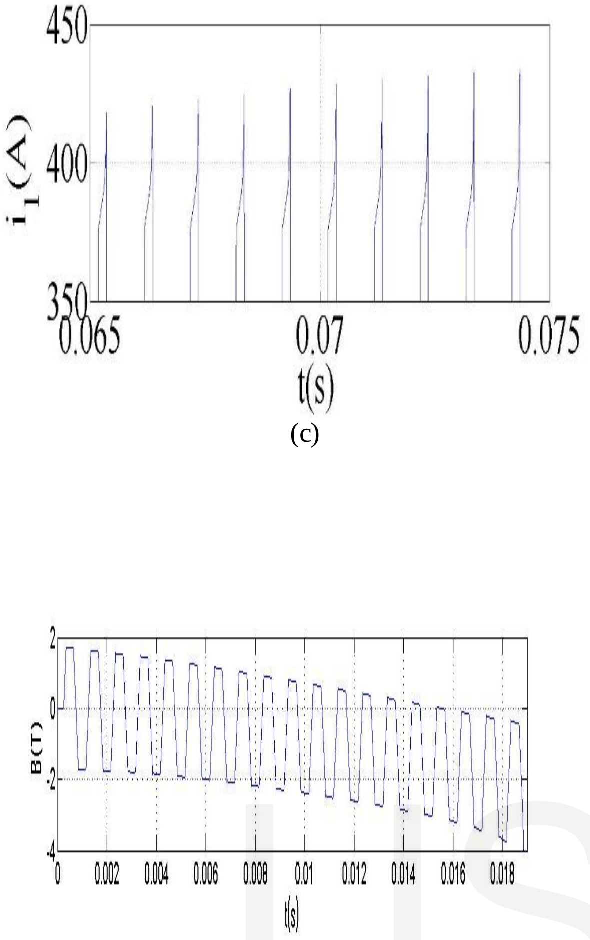


(c)

(d)

Fig. 2: (a),(b)and (c) : Time behaviour primary current i_1 (d) Flux Density

III CONTROLLER DESIGN

The current spikes in transformer primary current are the direct consequence of transformer iron core saturation caused by the offset of flux density (Figs. 3 and 5). The basic idea on how to eliminate these current spikes is, therefore, the design of advanced control, which will closed-loop control both, saturation level in the transformer iron core and the welding current.

A dc-dc converter must provide a regulated dc output voltage under varying load and input voltage conditions. The converter component values are also changing with time, temperature, pressure, and so forth. Hence, the control of the output voltage should be performed in a closed-loop manner using principles of negative feedback. The most common closed-loop control method for PWM converters, namely, the current-mode control, are presented schematically in Fig.5.

(a) Hysteresis Controller :

Reference currents are generated by DC to AC converters using a current control technique such as a hysteresis control. The hysteresis band is used to control load currents and determine switching signals for inverters gates, George & Agarwal (2007) Suitable stability, fast response, high accuracy, simple operation, inherent current peak limitation and load parameters variation independency make the hysteresis current control as one of the best current control methods of voltage source inverters. In this approach the current error, (difference between the reference and inverter currents) is controlled in hypothetical control band surrounding reference current.

When the load current exceeds the upper band, the comparator output activated so the output voltage is changed in such a way to decrease the load current and keep it between the bands and deactivated at lower limit. Switching frequency varies with respect to distance between upper and lower band. The other parameters like inverter-network inductance and DC link voltage affect significantly on the switching frequency**.** inverter can be controlled in unipolar or bipolar PWM method.In this approach the current error, (difference between the reference and inverter currents) is controlled in hypothetical control band surrounding reference current as shown in Figure 3.

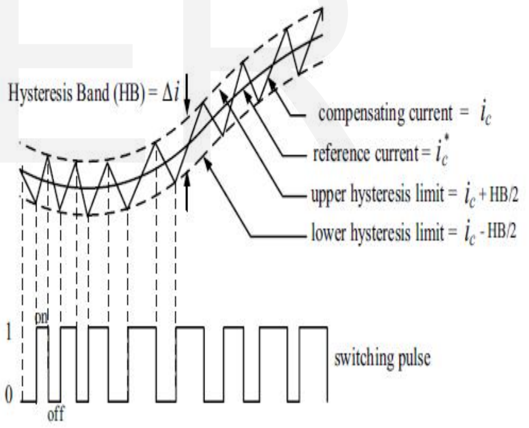


Fig.3 : Basic concept of Hysteresis Control

In hysteresis current control based on unipolar PWM, there are two upper bands and lower bands in order to change the slop of inverter output current based on their level voltages, +Vo, 0 and -Vo. The idea is to keep the current within the main area but the second upper and lower bands are to change the voltage level in order to increase or decrease the di,/dt of inverter output current.

ΔI cannot be very small as the noisy signal changes the switching time due to instantaneous comparison

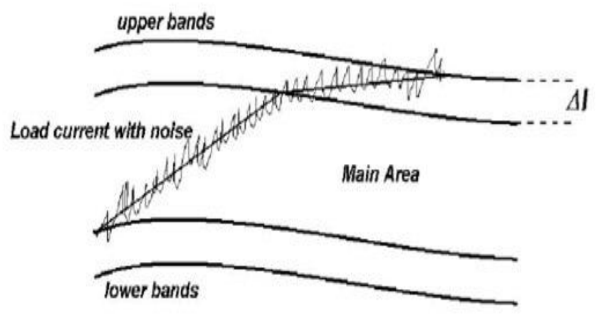


Fig.4 : Noisy Load Current with lower and upper bands.

between the load and the reference currents and increases the switching losses and it cannot be big as the total harmonic distortion may be increased.

(b) *PI 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

$$k_p\Delta + k_I \int \Delta \, dt \qquad (1)$$

where Δ is the error or deviation of actual measured value (PV) from the set-point (SP).

$$\Delta = SP - PV. \qquad (2)$$

A PI controller can be modelled easily in software such as Simulink using a "flow chart" box involving Laplace operators:

$$c = \frac{G(1+\tau s)}{\tau s} \qquad (3)$$

Where,G = K_P = proportional gain and G / τ = K_I = integral gain.

Setting a value for G is often a tradeoff between decreasing overshoot and increasing settling time. The integral term in a PI controller causes the steady-state error to reduce to zero, which is not the case for proportional only control in general.

The current-mode control scheme is presented in Fig.1 An additional inner control loop feeds back an inductor current signal, and this current signal, converted into its voltage analog, is compared to the control voltage. This modification of replacing the sawtooth waveform of the voltage-mode control scheme by a converter current signal significantly alters the dynamic behavior of the converter, which then takes on some characteristics of a current source.

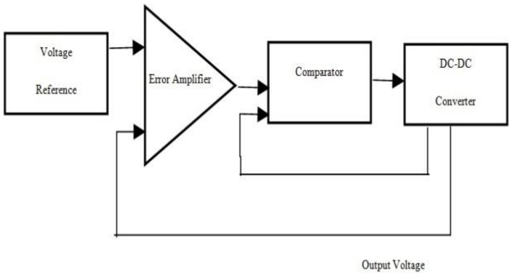


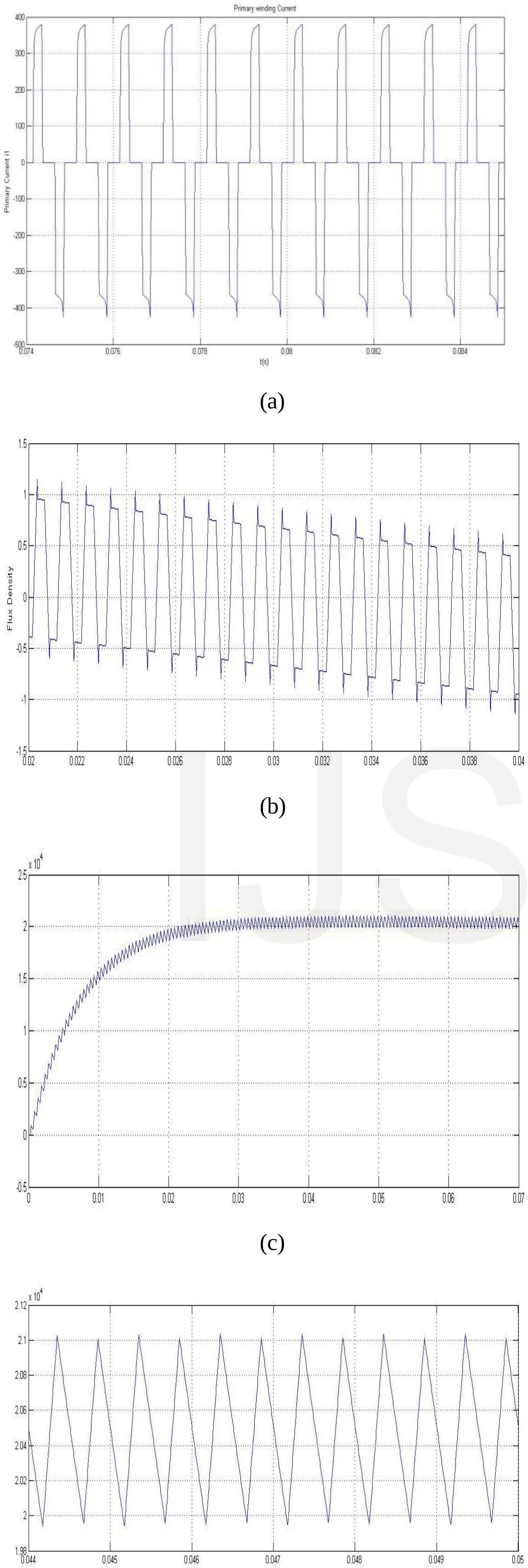
Fig. 5 : Current mode control of PI control

The current-mode control scheme is presented in Fig.5(b) An additional inner control loop feeds back an inductor current signal, and this current signal, converted into its voltage analog, is compared to the control voltage. This modification of replacing the sawtooth waveform of the voltage-mode control scheme by a converter current signal significantly alters the dynamic behavior of the converter, which then takes on some characteristics of a current source.

The output current in PWM converters is either equal to the average value of the output inductor current or is a product of an average inductor current and a function of the duty ratio. In practical implementations of the current-mode control, it is feasible to sense the peak inductor current instead of the average value. As the peak inductor current is equal to the peak switch current, the latter can be used in the inner loop, which often simplifies the current sensor. Note that the peak inductor (switch) current is proportional to the input voltage. Hence, the inner loop of the current-mode control naturally accomplishes the input voltage-feed forward technique. Among several current-mode control versions, the most popular is the constant-frequency one that requires a clock signal. Advantages of the current- mode control are the input voltage feed forward, the limit on the peak switch current, the equal current sharing in modular converters, and the reduction in the converter dynamic order. The main disadvantage of the current-mode control is its complicated hardware, which includes a need to compensate the control voltage by ramp signals (to avoid converter instability).Among other control methods of converters, a hysteretic (or bang-bang) control is very simple for hardware implementation. However, the hysteretic control results in variable frequency operation of semiconductor switches. Generally, a constant switching frequency is preferred in power electronic circuits for easier elimination of electromagnetic interference and better utilization of magnetic components.

IV RESULTS AND DISCUSSION

Here outputs of Hysteresis and PI controllers are presented and discussed.



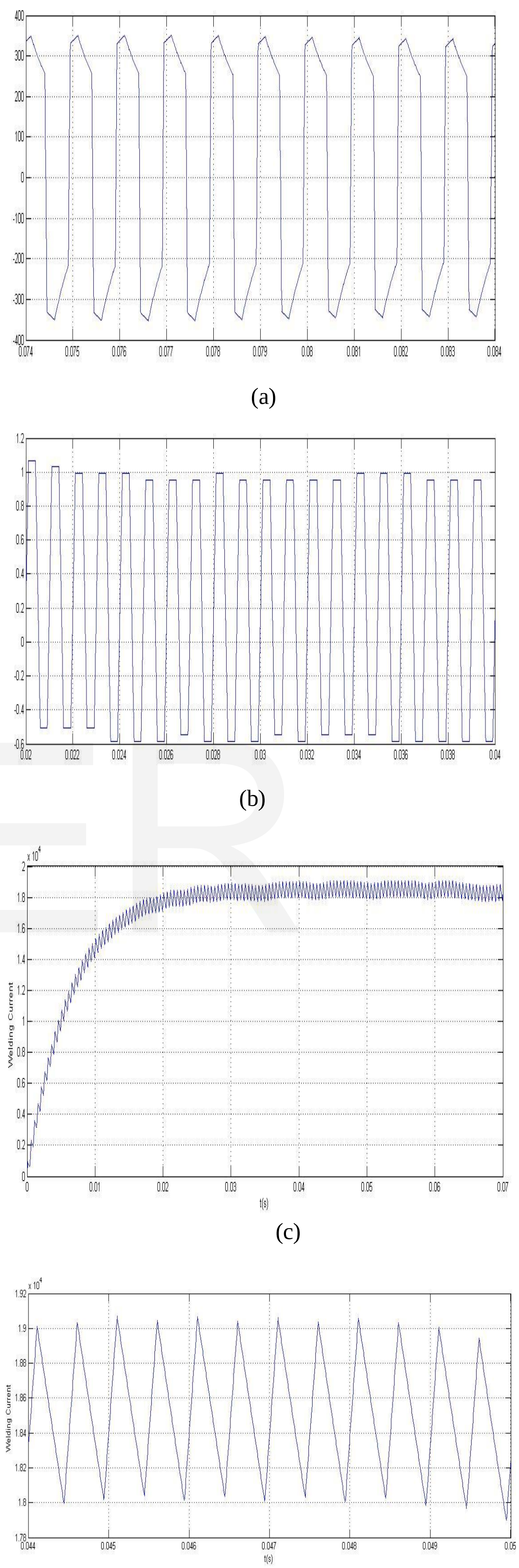
(a)

(b)

(c)

(d)

Fig (6) : Hysteresis controller (a)Primary Current(b)Fluxdensity (c)and(d)time behavior of welding current



(a)

(b)

(c)

(d)

Fig (7) : Hysteresis controller (a) Primary Current (b)Fluxdensity (c)and(d)time behavior of welding current

Simulation of two controllers are presented in fig.(6) and (7).Primary current andflux density waveforms of Hysteresis and PI controller are shown in fig.6.(a) and (b) and fig.7(a) and (b). Fig.6 and 7. (c) and (d) are showing time behaviour welding current.

From the simulation results of two controllers, spikes in the primary currents are eliminated successfully in order to maintain the saturation level of flux density within in the prescribed limits. i.e., -1T to 1T in PI control can be seen in fig. 7(a). The magnitude of welding current 0.19 mA where as in Hysteresis 022 mA. Hysteresis controller is not able to maintain the welding current as flux density reaching the saturation level but PI controller is able to maintain welding current successfully and eliminating the spikes in the primary current shown in fig.7(c).

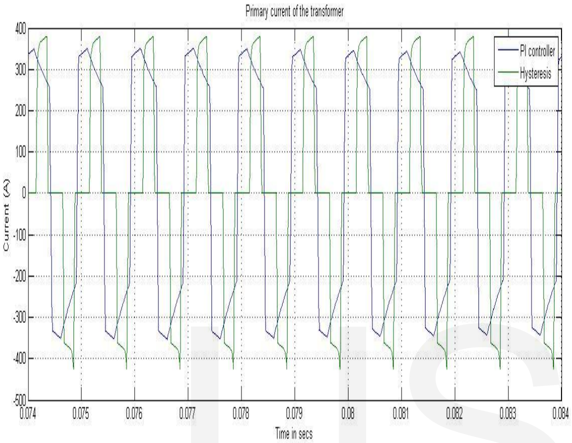


Fig.(8) : combined response of primary current of Hysteresis and PI controller

Preset value for primary current is -400A to 400 A. This limits is not maintained with Hysteresis controller in which it is going beyond preset value with saturation shown in fig.(8) can be shown with green line where as in PI control, preset value of primary current is maintained and eliminated spikes successfully in order to prevent the over current protection switch-off can be shown in fig.(8) with blue line.

Performance of PI control for control of flux density and welding current can be further improved by Intelligence methods.

V CONCLUSION

In this paper, two controllers such as Hysteresis and PI are successfully designed. Based on the results and the analysis, a conclusion has been made that PI controller gives better performance than Hysteresis controller. PI controller is capable of controlling the nonlinear RSWS system. The responses of each controller were plotted in one page. Simulation results in Fig. 7 and Fig. 8 show that PI controller has better performance compared to Hysteresis controller in controlling the nonlinear RSWS system. Further improvement need to be done for both of the controllers. PI controller having shortest possible rise time and settling time than the Hysteresis controller. PI controller should be improved further by artificial intelligence method.

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