

SIMULATION STUDY OF TRANSIENT CURRENT LIMIT CONTROL FOR INDUCTION HEATING

¹M. U. Agu, ²V. N. Agu, ¹C.I. Odeh

¹*Department of Electrical Engineering, University of Nigeria, Nsukka.*

²*Department of Electrical Engineering, Nnamdi Azikiwe University, Awka.*

Abstract

This study proposes a transient current limit control scheme for induction heating based on the study of transient current level control of a 4KW 10KHz VSI fed Induction Furnace during start-up current surge. The furnace was characterized and generated parameters were converted to per unitized values for simulation and study. This generalized model makes any chosen method applicable to induction heating schemes of the series parallel configuration. Three current control schemes are experimented. A comparison of the Methods 1,2 and 3 on the bases of over current limiting capability, heat delivery efficiency and integrity of steady state waveform viz-a-viz the uncontrolled VSI steady state output wave form was made. The Method 3 which was chosen gave a high fidelity replication of the uncontrolled VSI waveform after only five transient cycles with only 0.45% steady-state amplitude error.

1.0 Introduction

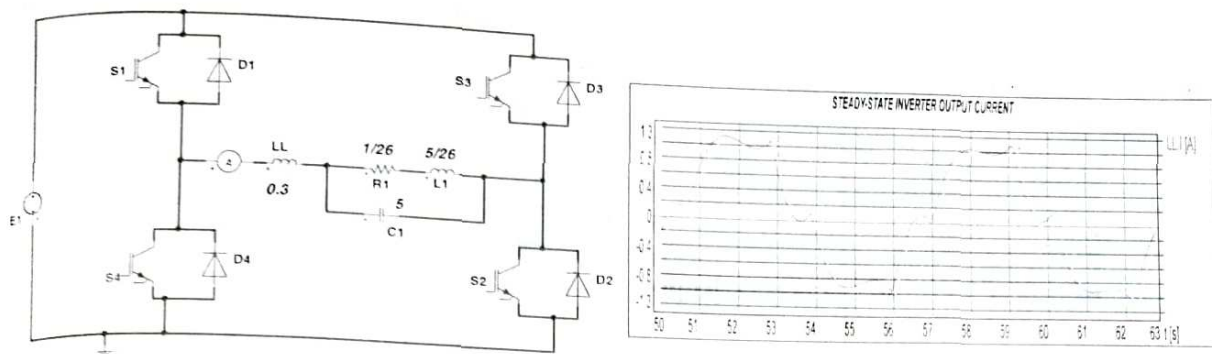
Induction heating furnaces are known to draw large values of current through the voltage source inverter (VSI) during steady state operation. At start-up and during switching, surge phenomena have remained a problem. Various methods have been applied to control the arising surge. Literature on surge analysis are few [1]. Harada et al [2] [3] proposed a complex surge model for forward converters. Mu-Ping Chen et al [1] proposed and simulated a simplified phase locked loop model. Mu-Ping Chen et al [4] also proposed another surge model introducing a non ideal diode in the model.

The approach here is to characterize the induction heating system and model it in a generalized model which can be simulated in SIMPLORER simulation environment. The transient performances are observed for various control algorithms and clamping limits and is utilized to develop a scheme that limits the transient overshoot to a predetermined clamping limit. In this model, a steady state current value is measured while the transient overshoot is observed.

Such large induction heating transient overshoots are known to have damaged power switches. The transient is also to be observed in terms of number of cycles before return to steady state condition. In some operations with devices like SCR, such peak currents would burn out devices rapidly especially if device turn-on time is long. In this case an over current is drawn through a small area of the junction that just commenced to turn-on [5].

2.0 Characterization of the Induction heating load

The induction heating system was characterized and the parameters transformed to a generalized model based on its tank impedance as 1p.u. For the 4KW 8KHz pulsewidth and frequency modulated voltage source inverter powering an induction furnace, the transform parameters are as shown in fig 1a where LL is line inductance. L1, R1 and C1 are tank inductance, resistance and capacitance respectively. S1, S2, S3 and S4 are IGBT, D1, D2, D3 and D4 are freewheeling diodes.



(a) The generalized model of the induction heating system

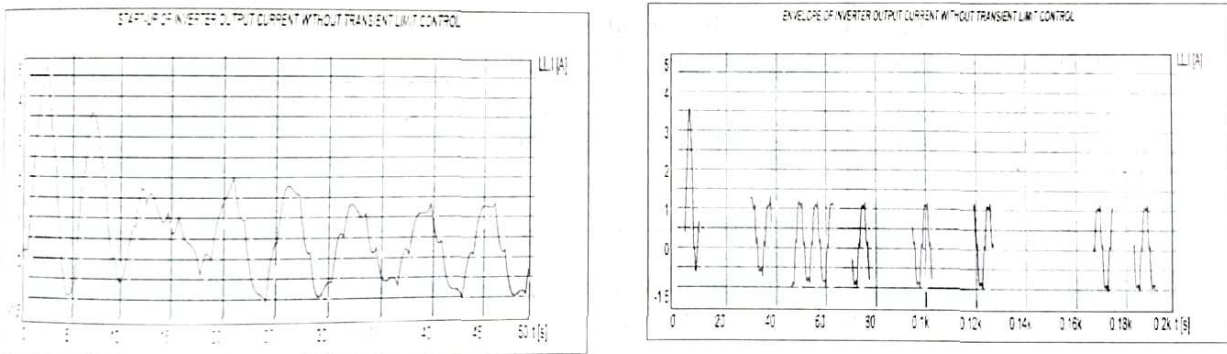
(b) Steady state output current of the VSI

Fig. 1. Model of induction heating scheme and steady state output current

The generalized model enables the introduction of LL if the analysis is targeted on a plant converting from a Current Source Inverter (CSI) to Voltage Source Inverter (VSI) system.

The simulated steady state inverter current of fig 1a is shown in figure 1b. The transient state current level and envelope of fig 1b are

shown in fig 2a & 2b. It is observed that while the steady state current level is at 1.3 p.u, the transient level is at 4.5 p.u and lasts for about 5 cycles. Such large overshoots are inimical to device live. Any attempt to size the devices to take such levels of surge becomes expensive and results in a bulky set-up.



(a) Transient current of fig. 1

(b) Current envelope of fig. 1

Fig.2. Output current transient and envelope of fig.1

3.0 Current Limit Control

Three methods of the transient state current limit control were studied. Each method is intended to be embedded in the control algorithm of the inverter power devices.

Method-1

Table 1. Method-1 algorithm

IF($t \leq 25$)	ELSE IF($t > 150$ AND $t < 175$)	ELSE IF($t > 250$ AND $t < 275$)
{	{	{
P1.PHASE := -85;	P1.PHASE := -65;	P1.PHASE := -45;
P2.PHASE := -275;	P2.PHASE := -295;	P2.PHASE := -315;
P3.PHASE := -95;	P3.PHASE := -115;	P3.PHASE := -135;
}	}	}

<pre> P4.PHASE := -265; } ELSE IF (t > 50 AND t < 75) { P1.PHASE := -80; P2.PHASE := -280; P3.PHASE := -100; P4.PHASE := -260; } ELSE IF (t > 100 AND t < 125) { P1.PHASE := -75; P2.PHASE := -285; P3.PHASE := -105; P4.PHASE := -255; } ELSE IF (t > 125 AND t < 150) { P1.PHASE := -70; P2.PHASE := -290; P3.PHASE := -110; P4.PHASE := -250; } ELSE IF (t > 175 AND t < 200) { P4.PHASE := -245; } ELSE IF (t > 200 AND t < 225) { P1.PHASE := -60; P2.PHASE := -300; P3.PHASE := -120; P4.PHASE := -240; } ELSE IF (t > 225 AND t < 250) { P1.PHASE := -55; P2.PHASE := -305; P3.PHASE := -125; P4.PHASE := -235; } ELSE IF (t > 300 AND t < 325) { P1.PHASE := -35; P2.PHASE := -325; P3.PHASE := -145; P4.PHASE := -215; } ELSE IF (t > 325 AND t < 350) { P4.PHASE := -210; } } </pre>	
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The Method-1 algorithm is shown in table 1 and the simulated transient current level and current envelope are shown in fig. 3a and 3b respectively.

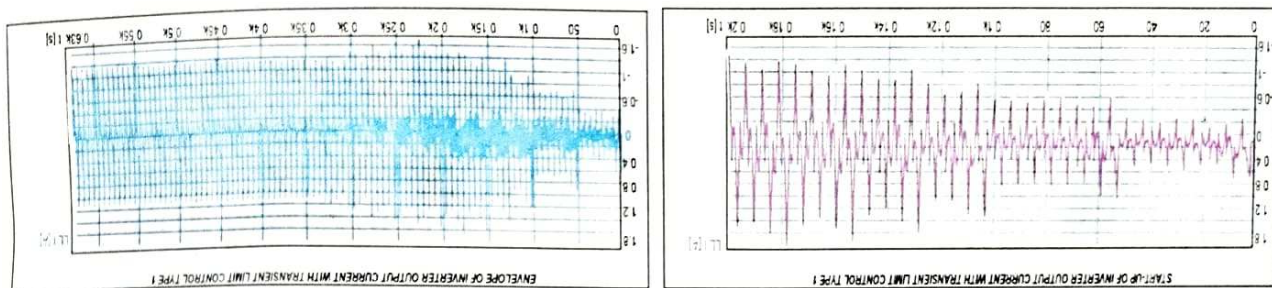


Fig.3. Method 1 transient current and current envelope
(a) Transient current
(b) Current envelope

Method-2

Method-2 algorithm

1. $S.VAL > 0$ AND $S.DVAL > 0$
2. $LL1 \geq 1.2$ OR ($S.VAL \leq 2 * \sin(2 * \pi / 3)$ AND $S.DVAL < 0$)
3. $S.VAL \leq 0$ AND $S.DVAL < 0$

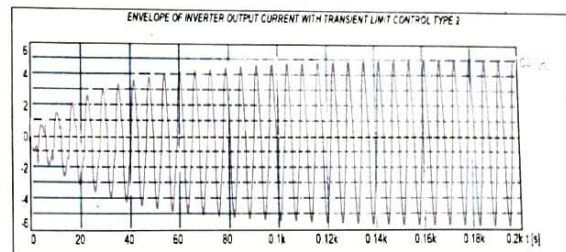
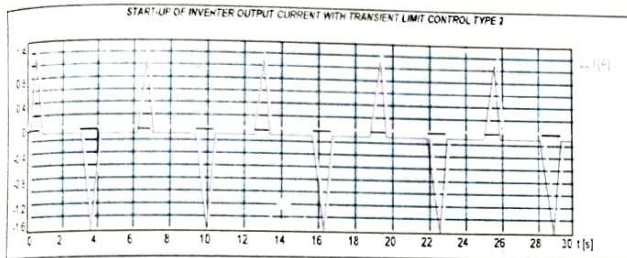
4. $LL.I \leq -1.5$ OR ($S.VAL \geq -2 \cdot \sin(2 \cdot \pi/3)$ AND $S.dVAL > 0$)

2	X	X	X	X	S1	S2	S3	S4
3	S3	S4	X	X	S1	S2	X	X
4	X	X	X	X	S1	S2	S3	S4

The Method-2 algorithm is shown with its switching table in table 2. The simulated transient current level and envelopes are shown in fig 4a and 4b respectively.

Table 2. M-2 Switching table

Algorithm	ON				OF			
1	S1	S2	X	X	S3	S4	X	X



(a) Transient current

(b) Current envelop

Fig.4. Method 2 transient current and current envelop

Method-3

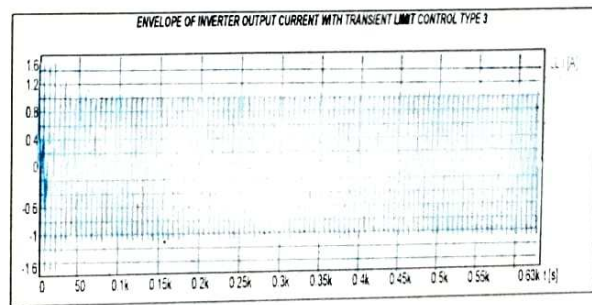
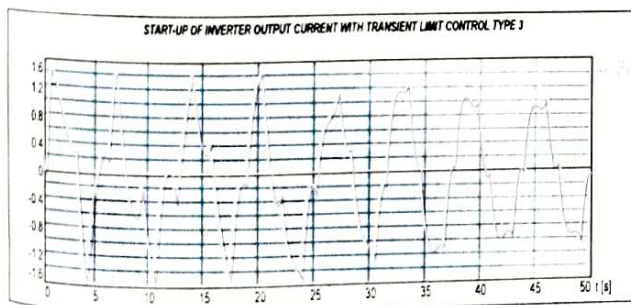
Method-3 algorithm

1. $S.VAL > 0$ AND $S.dVAL > 0$
2. $LL.I \geq 1.5$ OR ($S.VAL \leq 2 \cdot \sin(2 \cdot \pi/3)$ AND $S.dVAL < 0$)
3. $S.VAL \leq 0$ AND $S.dVAL < 0$
4. $LL.I \leq -1.5$ OR ($S.VAL \geq -2 \cdot \sin(2 \cdot \pi/3)$ AND $S.dVAL > 0$)

Table 3. M-3 Switching table

Algorithm	ON				OF			
1	S1	S2	X	X	S3	S4	X	X
2	S1	S3	X	X	S2	S4	X	X
3	S3	S4	X	X	S1	S2	X	X
4	S2	S4	X	X	S1	S3	X	X

The Method-3 algorithm is shown with its switching table in table 3. The simulated transient current level and envelopes are shown in fig. 5a and 5b respectively.



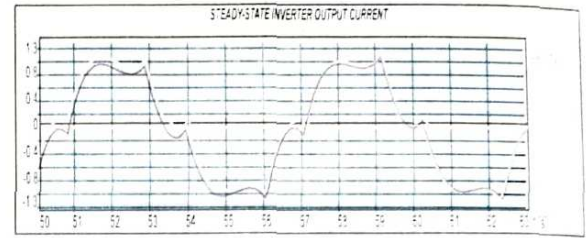
(a) Transient current

(b) Current envelop

Fig.4. Method 1 transient current and current envelop



(a) Method 3 controlled



(b) Uncontrolled

Fig.5. Controlled vs Uncontrolled steady state wave form fidelity comparison

Defining I_{ts} as transient current level, I_{ss} as steady state current level, T_{td} as transient time behavior before attaining steady state value, A_{ts} as approximate area under I_{ts} and A_{ss} as approximate area under I_{ss} , table 4 is used to compare the three transient control methods. The comparison is based on (i) the transient current limit control capability assessed by the maximum current overshoot (ii) the heat delivery efficiency measured by the area under the transient and steady state current waveforms, and (iii) the integrity conformity of the post-control waveform to the uncontrolled VSI steady state output current as an index of steady state performance fidelity of a control scheme.

Table 4. Comparison of methods 1,2 and 3 transient current limit control

S/N	Parameter	Method 1	Method 2	Method 3	Remarks.
1	I_{ts} (p.u)	1.7	1-5.5	1.5	
2	I_{ss} (p.u)	1.2	5.5	1.1	
3	T_{td}	sluggish	sluggish	fast	
4	A_{ts} (p.u)	0.4	0.2	0.6	
5	A_{ss} (p.u)	0.6	0.6	0.9	
6	Wave fidelity	Poor	very poor	very high	

- (1) The task of limiting the uncontrolled transient overshoot of 4.6p.u was achieved by the three types to varying degrees with method 1 achieving best result.
- (2) The speed of response in coming to steady state operation was poorly achieved by methods 1 and 2

- (3) The limiting of maximum overshoot was best achieved by method 3 with 1.5 p.u followed by method 1 with 1.7p.u.
- (4) A larger area under the transient state current graph was best achieved by type 3 with about 0.6 p.u and 0.99p.u at transient and steady state respectively.
- (5) The method 3 waveform has a high fidelity to the uncontrolled VSI waveform. Its steady state current value is 1.1p.u compared to 1.15p.u of the uncontrolled waveform. This is a 0.45% error.

4.0 Conclusion

It is observed from comparison, that method 3 yields very effective limiting of the transient current as well as conducive to more heat by rapidly attaining steady state value. In induction heating, fast heating is a major issue. Method 3 also returns rapidly (within five cycles) to the uncontrolled steady state waveform thereby respecting the integrity of the designed output. It is therefore recommended for use as a current limiting control for both transient and short circuit levels. By its algorithm which was successfully simulated is aborts any current tending to exceed 1.5p.u and keeps the switches off until the current level returns to 1.5p.u. During simulations, it was found that a current clamping index of 1.5p.u gave high fidelity steady state waveform. Values from 1.45p.u down to 1.2p.u resulted in increasing waveform distortion. This implies that the devices will need to be rated 36.36% higher. This is considered a great saving when compared to the uncontrolled transient value of 4.5p.u which demands a 309% over rating

for the devices with 1.1p.u steady state current rating.

References

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