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Improvement in Control System for the Medium Frequency Direct Current Resistance Spot Welding System

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Abstract— **The paper deals with a medium frequency direct current resistance spot welding system. The system consists of special electromagnetic structure and works in a particular pattern. After studying the structure, working principle and possible operating modes of the system, a new mathematic model is developed to precisely describe the dynamic behavior of the whole system. A phenomenon that the operation of the system can be in dead zone is observed. And the performance of the system would be deteriorated if the phenomenon is not handled properly. And then a control algorithm is proposed to improve the performance of the system. The effectiveness of the proposed algorithm is verified through a numerical simulation.**

I. INTRODUCTION

Medium Frequency Direct Current (MFDC) Resistance Spot Welding System (RSWS) is extensively used in a large number of industries, such as automotive, nuclear power, home appliances, as well as civil infrastructure products. It has a great many particular positive features in industrial applications [1]. The working process of the RSWS is a very complex one, which involves interactions among electromagnetic, thermal, mechanical, and metallurgical phenomena. Compared to Alternative Current (AC) resistance spot welding device, MFDC RSWS has a more complex structure because it needs to generate a higher frequency than that by its original power supply source. Generally speaking, the working frequency of the MFDC RSWS is about 1000Hz, while the frequency of the original power supply is about 50/60Hz. Some necessary transitions from common electrical power to a low-voltage, high-current and high-frequency electrical power supply should be accomplished. The complex structure and working mechanism of the system may induce some problems [2-4], such as magnetic saturation and unwanted spikes in the currents. Klopcic [2-5] analyzed the special electromagnetic structure and proposed one method to deal with them. However, the work focused on the magnetic saturation and the mathematic model which the work used was developed using electromagnetic features. Thus the work concerned fewer about the variation of welding current. In this paper, after studying the structure and working principle of MFDC RSWS, different possible operating modes of the system is found. The modes can be described by how many diodes in two secondary coils of welding transformer are switched on. And then a new mathematical model is developed to precisely describe the dynamic behavior of the whole system. The model is developed using mutual inductance effects between different coils, which relates the variation of welding current closely. The analysis focuses on the formation and variation of currents in different loops. A phenomenon that the operation will be in a state of dead zone, which means the two diodes are switched on and the welding current will not change regularly following related operations, is observed. Some errors of welding current will be induced if the negative effects resulting from the phenomenon are neglected during the control process. This paper will analyze the phenomenon in detail, and then propose a new algorithm to improve the control efficiency.

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II. STRUCTURE, WORKING PRINCIPLE AND MODES

MFDC RSWS consists of an input rectifier, an H-bridge inverter, a welding transformer with a full-wave rectifier and corresponding load. A detailed schematic presentation of MFDC RSWS is shown in Fig. 1 [4]:

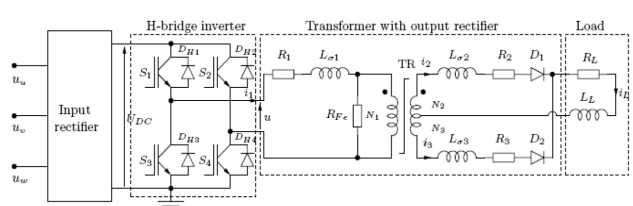

Fig.1. Schematic presentation of MFDC RSWS

The input rectifier is a three-phase full-wave rectifier, which can change the common three-phase alternative current (AC) voltage into a proper single-phase current. The output welding current is controlled by the voltage pulses generated through the pulse width modulation (PWM) controller to drive the H-bridge inverter. In above schematic presentation, the AC voltages u_u, u_v, u_w, which are provided from the common electric grid, are rectified and smoothed through the input rectifier in order to produce an approximate direct voltage U_{DC}. The square wave voltage u, which is the voltage in the transformer's primary coil, is generated by the H-bridge inverter which is composed of IGBT transistors S_1 to S_4 and corresponding diodes D_{H1} to D_{H4}.During working process, the PWM controller is applied to generate IGBT' switching patterns for required input voltages of the welding transformer. In other words, control of the MFDC RSWS is the control of the status of the IGBTs in real time. The welding transformer has one primary coil (denoted by subscript 1 in Fig. 1) and two secondary coils (denoted by subscripts 2 and 3 in Fig. 1). N_1, N_2 and N_3 are the number of turns, i_1, i_2 and i_3 are the currents in the coils, $L_{\sigma 1}$, $L_{\sigma 2}$ and $L_{\sigma 3}$ are the leakage inductances, while R_1, R_2 and R_3 are the ohm resistances of the corresponding transformer's coils. The welding transformer, which contains special nonlinear magnetizing features, is represented by TR. The iron core losses of TR are accounted for by the resistor R_{Fe}. The secondary coils of TR are connected to output rectifier diodes D_1 and D_2. The resistor and induction coil of the load are denoted by R_L and L_L.

The operation for the MFDC RSWS is to regulate the welding current i_L to a magnitude in between the predetermined upper bound I_{MAX} and lower bound I_{MIN} (a desired constant value is the best, but this is impossible to achieve, thus a proper bound is an alternative). At the same time, the magnetic flux density (B) of the transformer's iron core should be in between its upper and lower magnetic saturation bounds[4]: [$-B_M$, B_M]. This can be achieved by changing the input voltage for the welding transformer in three states: U, $-U$, and $0V$, through adjusting the patterns of IGBTs in the H-bridge inverter by PWM controller.

The welding current (i_L) is the sum of the currents in the two secondary coils (Fig.1). A positive input voltage (U) can actuate the top secondary coil; while a negative input voltage ($-U$) can actuate the bottom secondary coil. Hence, both of U and $-U$ can increase the load current. Only a zero input voltage ($0V$) can decrease the load current. However, U and $-U$ can generate the opposite effect for variation of the magnetic flux density (B). For example, if when U increases the load current, but simultaneously B reaches the bound, U must be changed into $-U$, which can also increase the welding current, but B will increase toward the opposite direction, which can avoid the magnetic saturation.

When opposite input voltage is provided, the energy which is stored by inductance coil in original circuit will decrease; while that in the other circuit will increase. And when the welding current should be decreased and a zero voltage is provided, the inductor coil will substitute the power source and a new back circuit will form. Thus in a certain period, both of the two diodes in the secondary coils are switched on at the same time because the inductor coils can suspend the transformation. And this phenomenon can appear when the pattern of input voltage changes between its three states (U,$-U$ and $0V$) because of the same reason. Normally, it is impossible for the two diodes to be switched off at the same time, unless the welding process is over.

Hence, the two diodes can be operated in different modes during the working process: the first is that one diode is switched on and the other diode is switched off, while the second is that both of the two diodes are switched on. These different modes can appear in a certain frequency based on dynamic behaviors of the system. The possible variations of the two diodes are schematically shown in Fig.2:

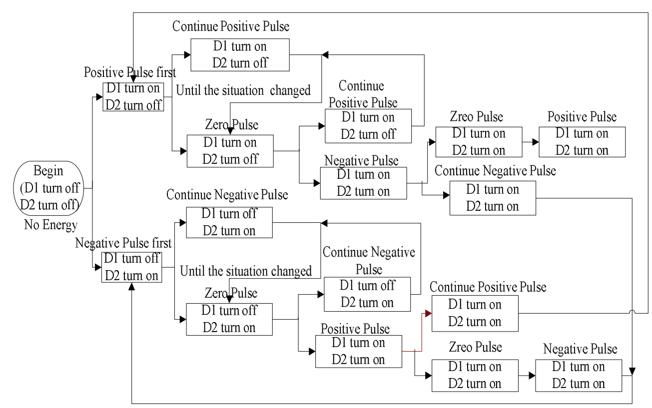

Fig.2. Working statuses of two diodes

In order to comprehend the effects of the different operating modes during the welding process, a detailed analysis based on appropriate mathematic model is needed.

III. MATHEMATICAL MODEL AND ANALYSIS

A. Mathematical model

In this paper, mutual inductance effect is used to develop a mathematic model, due to the welding transformer works based on the effects between primary and secondary coils. Because the mutual inductance effect relates the variation of welding current closely, the model can reflect the variation explicitly and directly. Following three equations are developed using the effect to describe the voltage balances in the primary and the two secondary coils shown in Fig.1:

$$U(t) = i_1(t)R_1 + (L_1 + L_{\sigma 1})\frac{di_1(t)}{dt} - M_{12}\frac{di_2(t)}{dt} + M_{13}\frac{di_3(t)}{dt}, \quad (1)$$

$$-M_{12}\frac{di_1(t)}{dt} - M_{23}\frac{di_3(t)}{dt} + (L_2 + L_{\sigma 2})\frac{di_2(t)}{dt} + i_2R_2 + (i_2 + i_3)R_L + L_L\frac{d(i_2(t) + i_3(t))}{dt} + U_{d1} = 0, \quad (2)$$

$$-M_{23}\frac{di_2(t)}{dt} + M_{13}\frac{di_1(t)}{dt} + (L_3 + L_{\sigma 3})\frac{di_3(t)}{dt} + i_3R_3 + (i_2 + i_3)R_L + L_L\frac{d(i_2(t) + i_3(t))}{dt} + U_{d2} = 0, \quad (3)$$

where the L_1, L_2 and L_3 are the corresponding coil inductances of the transformer, M_{mn} denotes corresponding mutual inductance coefficient between *m* coil and *n* coil.

The voltages derived from the mutual inductance effects between the primary coil and the two secondary coils have different polarities, because the direction of turns of the upper and lower secondary coils are opposite. In addition, because the voltage of two secondary coils should be balanced, the mutual inductance coefficient between primary coil and two secondary coils are approximately the same ($M_{12} = M_{13}$) normally. Every loop is affected by two voltages derived from mutual inductance effects. Also, the second and third equations cannot be effective all the time; it depends on the status of the corresponding diodes. Additionally, the magnetic flux density of the transformer, which is the criterion of variation of the direction of the nonzero input voltage [3-5], must be obtained likewise. Furthermore, the initial value of the magnetic flux density (*B*) is zero; its variation can be derived based on an equation which describes the voltage balance of the primary coil using the basic electromagnetic features:

$$U(t) = i_1(t)R_1 + L_{\sigma 1}\frac{di_1(t)}{dt} + N_1S_{Fe}\frac{dB}{dt} \quad \text{(4-a)}$$

$$\frac{dB}{dt} = \frac{U(t) - i_1(t)R_1 - L_{\sigma 1}\frac{di_1(t)}{dt}}{N_1S_{Fe}} \quad \text{(4-b)}$$

It is known that values of corresponding parameters, S_{Fe}, N_1, $L_{\sigma 1}$, can be obtained using common method, the real-time value of the magnetic flux density (*B*) can be online obtained according to the above equation.

B. Model Analysis

According to Fig.2 and above mathematical model, the variation of signals in three coils (one primary and two secondary coils) and different operation modes during the welding process can be analyzed in detail.

When one pattern input voltage is provided to increase the welding current, only one diode is switched on, the governing equations ((1)-(3)) can be written as following (using the diode in the top secondary coil as an example):

$$U(t) = i_1(t)R_1 + (L_1 + L_{\sigma 1})\frac{di_1(t)}{dt} - M_{12}\frac{di_2(t)}{dt}, \quad (5)$$

$$-M_{12}\frac{di_1(t)}{dt} + (L_2 + L_{\sigma 2})\frac{di_2(t)}{dt} + i_2R_2 + i_2R_L + L_L\frac{di_2(t)}{dt} + U_{d1} = 0. \quad (6)$$

The matrix form:

$$\begin{pmatrix} L_1 + L_{\sigma 1} & -M_{12} \\ -M_{12} & L_2 + L_{\sigma 1} \end{pmatrix}\begin{pmatrix} \frac{di_1(t)}{dt} \\ \frac{di_2(t)}{dt} \end{pmatrix} = \begin{pmatrix} -R_1 & 0 \\ 0 & -R_2 - R_L \end{pmatrix}\begin{pmatrix} i_1(t) \\ i_2(t) \end{pmatrix} + \begin{pmatrix} U(t) \\ -U_{d1} \end{pmatrix}, \quad (7)$$

Thus:

$$\begin{pmatrix} \frac{di_1(t)}{dt} \\ \frac{di_2(t)}{dt} \end{pmatrix} = \begin{pmatrix} L_1 + L_{\sigma 1} & -M_{12} \\ -M_{12} & L_2 + L_{\sigma 1} \end{pmatrix}^{-1}\left(\begin{pmatrix} -R_1 & 0 \\ 0 & -R_2 - R_L \end{pmatrix}\begin{pmatrix} i_1(t) \\ i_2(t) \end{pmatrix} + \begin{pmatrix} U(t) \\ -U_{d1} \end{pmatrix}\right). \quad (8)$$

The welding current can be written as: $i_L = i_2 + i_3 = i_2$, and the variation tendency:

$$\frac{di_L}{dt} = \frac{di_2(t)}{dt} = -\frac{1}{|L_s|}[M_{12}R_1i_1(t) + (L_1 + L_{\sigma 1})(R_2 + R_L)i_2(t) + U_{d1}], \quad (9)$$

where, the pre- coefficient can be derived by:

$$|L_s| = (L_1 + L_{\sigma 1})(L_2 + L_{\sigma 2}) - M_{12}^2. \quad (10)$$

When the welding current or magnetic flux density reaches the bounds, the pattern of input voltage (*U*,*-U* and *0V*) should be changed immediately. As a result, the two diodes will be switched on at the same time. Then the voltages of the two secondary coils must satisfy the following two equations, respectively:

$$-M_{12}\frac{di_1(t)}{dt} - M_{23}\frac{di_3(t)}{dt} + (L_2 + L_{\sigma 2})\frac{di_2(t)}{dt} + i_2R_2 - (i_2 + i_3)R_L - L_L\frac{d(i_2(t) + i_3(t))}{dt} > U_{d1}, \quad (11)$$

$$-M_{23}\frac{di_2(t)}{dt} + M_{13}\frac{di_1(t)}{dt} + (L_3 + L_{\sigma 3})\frac{di_3(t)}{dt} + i_3R_3 - (i_2 + i_3)R_L - L_L\frac{d(i_2(t) + i_3(t))}{dt} > U_{d2}. \quad (12)$$

In this situation, three governing equations ((1)-(3)) are effective, they can be written in the following matrix form:

$$\begin{pmatrix} L_1 + L_{\sigma 1} & -M_{12} & M_{13} \\ -M_{12} & L_2 + L_{\sigma 2} + L_L & -M_{23} + L_L \\ M_{13} & -M_{23} + L_L & L_3 + L_{\sigma 3} + L_L \end{pmatrix}\begin{pmatrix} \frac{di_1(t)}{dt} \\ \frac{di_2(t)}{dt} \\ \frac{di_3(t)}{dt} \end{pmatrix} = \begin{pmatrix} -R_1 & 0 & 0 \\ 0 & -R_2 - R_L & -R_L \\ 0 & -R_L & -R_3 - R_L \end{pmatrix}\begin{pmatrix} i_1(t) \\ i_2(t) \\ i_3(t) \end{pmatrix} + \begin{pmatrix} U(t) \\ -U_{d1} \\ -U_{d2} \end{pmatrix}. \quad (13)$$

Thus:

$$\begin{pmatrix} \frac{di_1(t)}{dt} \\ \frac{di_2(t)}{dt} \\ \frac{di_3(t)}{dt} \end{pmatrix} = \begin{pmatrix} L_1 + L_{\sigma 1} & -M_{12} & M_{13} \\ -M_{12} & L_2 + L_{\sigma 2} + L_L & -M_{23} + L_L \\ M_{13} & -M_{23} + L_L & L_3 + L_{\sigma 3} + L_L \end{pmatrix}^{-1}\left(\begin{pmatrix} -R_1 & 0 & 0 \\ 0 & -R_2 - R_L & -R_L \\ 0 & -R_L & -R_3 - R_L \end{pmatrix}\begin{pmatrix} i_1(t) \\ i_2(t) \\ i_3(t) \end{pmatrix} + \begin{pmatrix} U(t) \\ -U_{d1} \\ -U_{d2} \end{pmatrix}\right). \quad (14)$$

The components in the two secondary coils are considered the same in normal conditions, and $U_{d1} = U_{d2}$.

And $$\frac{di_L}{dt}=\frac{di_2}{dt}+\frac{di_3}{dt}=f(1)i_1+f(2)i_2+f(3)i_3 \tag{15}$$

Then: $$f(1)=(-R_1)/\left|L_d\right|\cdot[M_{12}(L_3+L_{\sigma3}+L_L)-M_{13}(M_{23}-L_L)+ M_{12}(M_{23}-L_L)-M_{13}(L_2+L_{\sigma2}+L_L)], \tag{16}$$

$$f(2)=\frac{1}{\left|L_d\right|}\left\{\begin{array}{l}(R_2+R_L)[(L_1+L_{\sigma1})(M_{23}-L_L)+M_{12}M_{13}-(L_1+L_{\sigma1})(L_3+L_{\sigma3}+L_L)+M_{13}^2] \\ +R_L[(L_1+L_{\sigma1})(M_{23}-L_L)+M_{12}M_{13}-(L_1+L_{\sigma1})(L_2+L_{\sigma2}+L_L)+M_{12}^2]\end{array}\right\}, \tag{17}$$

$$f(3)=\frac{1}{\left|L_d\right|}\left\{\begin{array}{l}(R_3+R_L)[(L_1+L_{\sigma1})(M_{23}-L_L)+M_{12}M_{13}-(L_1+L_{\sigma1})(L_2+L_{\sigma2}+L_L)+M_{12}^2] \\ +R_L[(L_1+L_{\sigma1})(M_{23}-L_L)+M_{12}M_{13}-(L_1+L_{\sigma1})(L_3+L_{\sigma3}+L_L)+M_{13}^2]\end{array}\right\}, \tag{18}$$

where the pre-coefficient can be derived by:

$$\begin{aligned}\left|L_d\right|&=(L_1+L_{\sigma1})[(L_2+L_{\sigma2}+L_L)(L_3+L_{\sigma3}+L_L)-(M_{23}-L_L)^2] \\ &+M_{12}[-M_{12}(L_3+L_{\sigma3}+L_L)+M_{13}(M_{23}-L_L)] \\ &+M_{13}[M_{12}(M_{23}-L_L)-M_{13}(L_2+L_{\sigma2}+L_L)].\end{aligned} \tag{19}$$

In most cases, the secondary coils should be symmetric, thus $M_{12}=M_{13}$, $L_3+L_{\sigma3}+L_L= L_2+L_{\sigma2}+L_L$. In this situation: M_{12} $(L_3+L_{\sigma3}+L_L)$-M_{13} $(M_{23}-L_L)$ = - [M_{12} $(M_{23}-L_L)$ – M_{13} $(L_2+L_{\sigma2}+L_L)$], hence $f(1)=0$. From equation (16), if $f(1)=0$, it means that the welding current is not affected by current in primary coil directly. The welding current will change only because of the variations of currents in two secondary coils. The welding current would decline in this operating mode, i.e. $di_L/dt<0$. In other words, input voltage cannot affect the welding current directly until this mode terminates by itself. It means the operation of system enter a state of dead zone. Therefore, the performance of the system may be affected.

To control the welding current precisely, its variation tendency in every operating mode should be considered. However, because of the existence of the inductor coils and threshold voltages of diodes, the response has a certain delay. The latter's effect is very small and can be ignored. The former's effect should be compensated. From above analysis, when the system enters the state of dead zone, welding current would decline. If the tendency of welding current is not needed to be increased, the state of dead zone will cause no harm. However, if the tendency of welding current needed to be increased, more errors will be induced. Hence, a proper control method should be developed in order to improve the performance of the system.

IV. ALGORITHM DESIGN AND SIMULATION

A. Improved Control Algorithm

Klopcic [6] proposed a close-loop control algorithm named Advance Hysteresis Control (AHC) which focused on how to avoid magnetic saturation. The work used a hardware system to online detect the magnetic flux density (B). The upper and lower bounds of the welding current and magnetic flux density were set in advance. According to the two kinds of bounds, the input voltages would be switched between the different operating modes as stated. However, the varying patterns of welding current during the welding process were not analyzed in detail; and there were more errors in the control of welding current.

The algorithm proposed in this paper is an improve version of the Klopcic's control algorithm [6]. In other words, Klopcic's control method is the base of our proposed method. The algorithm keeps welding current (i_L) and magnetic flux density (B) in between their upper and lower bounds at the same time through adjusting the patterns of the input voltage. After the welding current enters the predetermined current range, the nonzero voltage will not cease until the welding current reaches the upper bound. At the moment, only one diode is switched on. Then the input voltage will be cancelled to decrease the welding current. The operating mode which two diodes are switched on simultaneously will dominate the process. When the welding current reaches the lower bound, the sign of the input voltage should be changed into positive or negative to increase its value. However, the welding current will decline continually because at the same time, both of the two diodes are still switched on. This state will last for a period until energies in two secondary coils will have been exchanged. And more errors will be induced during the process.

Additionally, another important element should also be considered. It is known that the magnetic flux density should also be within its two bounds in order that the iron core of the transformer is not in the state of magnetic saturation. During the welding process, change of the magnetic flux density is the top priority. It means that when the magnetic flux density reaches its upper or lower bound, the pattern of the input voltage must be changed immediately. Then the system must enter into the state of dead zone and energies in two secondary coils would be exchanged, no matter what the former status is. The sudden changes may also induce more errors of the welding current because the welding current is about to decline during this process. The influences induced by the two elements can be shown in Fig.3:

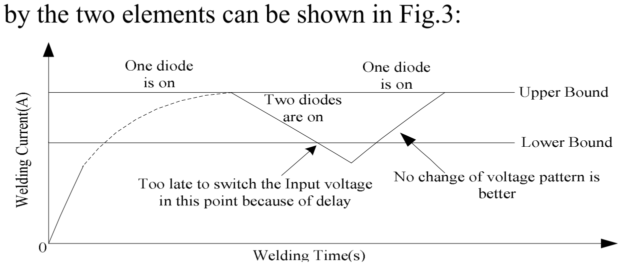

Fig.3. Schematic presentation of operating errors of welding current

For the proposed algorithm, the goal is to have only one diode is switched on when the welding current reaches the lower bound, and then the current increasing process will begin immediately. Furthermore, during the increasing process, no any interrupt (change pattern of input) occurs.

Firstly, in the predicting phase, some change rates should be obtained using experiences of the former closest effective points in real time: 1, the two change rates of the currents in the upper secondary coil and bottom secondary coil when a positive input voltage is provided; 2, the two change rates of the currents in the upper secondary coil and bottom secondary coil when a negative input voltage is provided. Then according to the direction of magnetic flux density, the polarity of the upcoming input voltage can be obtained. The duration of the welding current hovering at the lower bound every time when the input voltage is zero can be obtained using corresponding change rates. For example, during the energy exchanging process, if i_2 is decreasing, the duration when the operating mode of dead zone terminates is: $T_1=i_2/u_1$ (change rate of i_2 in this mode). Furthermore, at the same time, the duration when the state of the two diodes being switched on terminates from the current time if the nonzero voltage is provided can be obtained using the change rates in advance. For example: if U will be provided, in every point, the $T_2=i_2/u_2$(the change rate of i_2 when nonzero voltage is provided). If $T_1<T_2$, nonzero voltage should be provided in advance. This measure can guarantee when welding current reaches the lower bound, only one diode is switched on just in time and current increasing process can begin at once. The schematic presentation is shown in Fig.4 (a).

In addition, the errors induced by changing of input voltage because of variation of the magnetic flux density (B) should also be reduced. When the welding current is beyond the upper bound, the change rates of the variation of B under former the different status of input voltages (U, -U, and 0V) are collected, and then the predicting value of B after an integrated cycle can be obtained if no other measure is taken. The cycle means a process that welding current from upper bound to lower bound, and back to the upper bound.

$$B_{final}=B_{current}+B_{decrease}+B_{increase}, \quad (20)$$

If the value is beyond any bound, the opposite input voltage should be provided to reverse the direction of the magnetic flux density though the welding current is in between the bounds. Otherwise, an appropriate point should be found to switch on the opposite input voltage in advance, in order to make the negative effect not be induced in an integrated cycle. The measure makes the changing process of direction of B occur utilizing the duration when the welding current should be decreased in the state of dead zone. Hence the negative welding current decreasing time below the lower bound (which can induce errors and postpone the current increasing process) can be reduced. The schematic presentation is shown in Fig.4 (b).

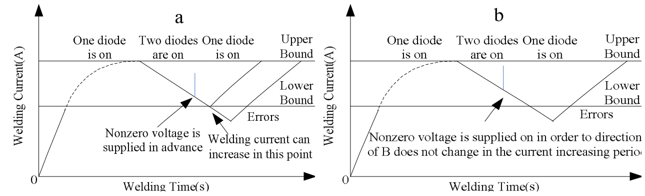

Fig.4. Schematic presentation of the improved control algorithm

B. Simulation result and analysis

Then the improved control algorithm can be tested using above mathematical model by corresponding numerical simulation. Fig.5 is a simulating diagram produced by MATLAB. It can show the key variables during the process (simulating parameters: input AC voltage of 380V, 50Hz, R_1=10mΩ, $R_2=R_3$=40μΩ, $N_1:N_2$=42:1, S_{Fe}=6e-4m^2, L_L=1μH,$L_{\sigma 1}$=10μH, $L_{\sigma 2}=L_{\sigma 3}$=1μH, threshold voltage of the diodes are U_d=0.8V, the load resistance changes following the theoretical variation tendency [7], all the setting values refer to the application-level implementation or Klopcic's work[6]), The predetermined welding current bounds using in the simulation: [14500, 15500] (Unit: A).

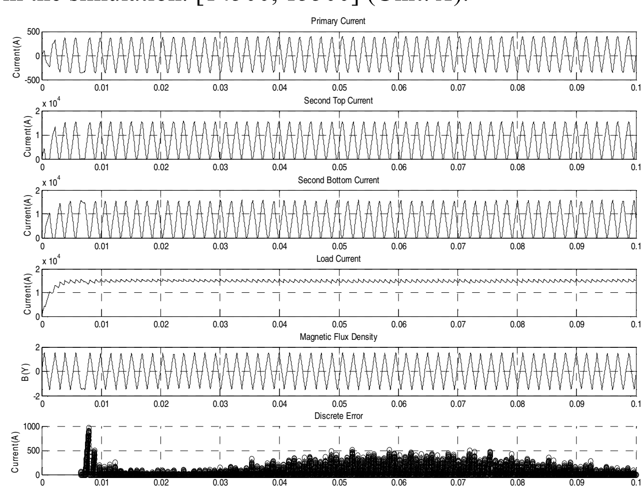

Fig.5. Simulation results and errors using the improved control algorithm

It indicates that using the improved control algorithm, 20.85% of the points are out of the preset bounds, and the mean value of errors is 31. Fig.6 is the corresponding simulating results with the same simulating conditions using Klopcic's control algorithm.

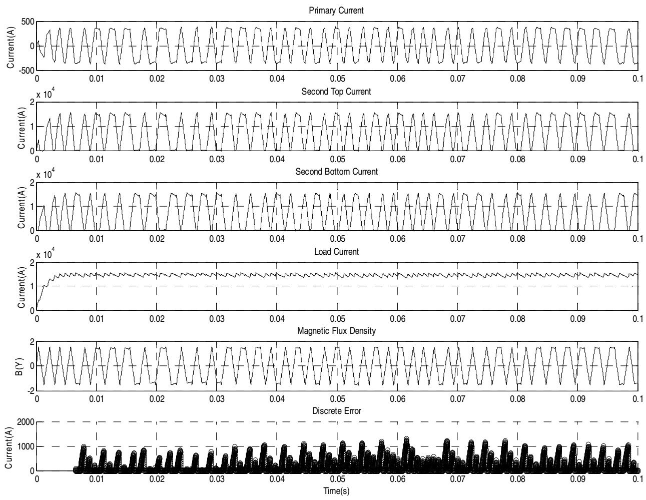

Fig.6. Simulation results and errors using Klopcic's control algorithm

Using the Klopcic's control algorithm, 70.05% of the points are out of the preset bound, and the mean value of errors is 152.

The results show that using the same simulating conditions, the errors induced by improved control algorithm is smaller than that of Klopcic's control algorithm. The same numerical simulation can be carried out in different conditions.

According to above two figures, the state of dead zone exists in both two simulations (nonzero values in the second and third rows simultaneously). The improved control algorithm weakens the negative effects resulting from this state. Because the corresponding pattern of input voltage is provided in advance, the duration when system enters the state of dead zone but the welding current is below the lower bound at the same time is deceased. Detailed diagram can reflect the situation as shown in Fig.7 (Left one denotes Fig.5, right one denotes Fig. 6):

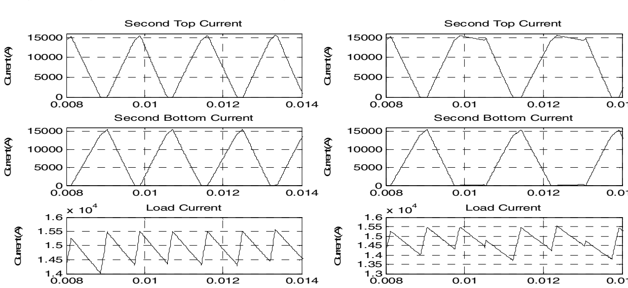

Fig.7. Detailed Simulation results of the two control algorithms

In addition, the improved control algorithm may need fewer sensors to detect necessary variables during the welding process in practical application. The values of welding current in primary coil and two secondary coils can be obtained using common sensors; the welding current is the sum of the currents in two secondary coils. The magnetic flux density can be obtained by either special hardware sensor or online calculation based on equation (4). And then the corresponding change rates which would be used in the improved control algorithm can be obtained easily, too.

V. Conclusion

A mathematical model of MFDC RSWS based on mutual inductance effects is presented in this paper. The model predicts that it is possible for two diodes of the two secondary coils to be switched on at the same time if input voltage changes from one state into the other between its three states (*U, -U* and *0V*). When this phenomenon occurs, the operation of the system enters the state of dead zone. The performance of the system would be deteriorated if the phenomenon is not dealt with properly. A new algorithm is proposed to improve the performance of the close-loop control system. The proposed algorithm is able to estimate the durations when the welding current and magnetic flux density reach their bounds. And thus the corresponding input voltages can be provided in advance to reduce the negative effect resulting from the state of dead zone. Simulation result indicates the effectiveness of the proposed algorithm is better than that of the algorithm without prediction. The further modifications and improvement will be carried out to make the control more properly.

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