Time-Frequency Entropy Analysis of Alternating Current Square Wave Current Signal in Submerged Arc Welding

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Abstract—The use of time-frequency entropy to quantitatively assess the stability of alternating current square wave submerged arc welding process considering the distribution features of arc energy is reported in this paper. Time-frequency entropy is employed to calculate and analyze the current signals under different duty cycle, frequency and welding speed in the submerged arc welding process. It is obtained that the greater time-frequency entropy, the less fluctuations, and the more stable welding process. Experimental results are provided to confirm the effectiveness of this approach.

Index Terms—Time-frequency entropy, arc energy, alternating current square wave, submerged arc welding, stability

I. INTRODUCTION

The alternating current square wave submerged arc welding has been widely used in multi-arc submerged welding because it can avoid phenomenon of magnetic blow [1]. It is significant to realize online detection and study arc stability and welding quality by sensing current or voltage signals in welding process [2]. In the process of alternating current square wave submerged arc welding, the arc shape is more complicated than direct-current arc. When current waveform is positive polarity, the arc is stable and large stiffness, droplet transition is easy to implement, and molten pool is deep. When current waveform is negative polarity, the arc climbing up along welding wire, droplet transition is hard to implement, molten pool is shallow, and the arc is prone to be instability in the situation of high current submerged arc welding because of weak self-regulation of thick wire [3]. Current frequency and duty cycle are main parameters of current waveform, and related with arc stability and welding quality, it is needed to match current waveform parameters reasonably to ensure arc stability and welding seam forming quality. In order to quantitatively describe the degree for the energy time-frequency distribution of different operation state of a machine, information entropy theory as a diagnosis criterion has been introduced into the time-frequency distribution by some researchers, and good effect has been obtained in machinery fault diagnosis [4-6].

Welding current is the main parameter of energy signal of alternating current square wave submerged arc welding. The frequency and duty cycle of current waveform are two key parameters to determine the arc energy, and indicate the time and frequency changes of arc energy in welding process. Thus, it is a good method of the information entropy and time-frequency analysis of the arc current signals introduced to judge stability of arc and welding quality in alternating current square wave submerged arc welding [7-8]. In this paper, time-frequency entropy is introduced to analyze the current signals under different welding conditions. The relationship between arc stability and time-frequency entropy of alternating current square wave arc is obtained. It is useful to obtain new knowledge of arc characteristic of alternating current square wave submerged arc welding, and get accurate numerical evaluation of arc stability.

II. TIME-FREQUENCY ENTROPY THEORY AND ALGORITHM

There are some time-frequency analysis methods such as window fourier transformation, continuous wavelet transformation, wigner-ville distribution and hilbert-huang transformation. The time-frequency window in window fourier transformation is immovable, so it can’t meet the frequency and time resolution at the same time. In the process of wavelet transformation, the choice of wavelet basis has a great impact on analysis result with poor adaptation to the whole signal. Wigner-ville has cross-term disturbance, so it is against to the subsequent time-frequency entropy calculation. Hilbert-huang Transform is a new self-adapting time-frequency analysis method. It has higher time-frequency resolution and time-frequency concentration, which is especially suitable to the analysis of arc current signal. Hilbert-huang transform is introduced to conduct
time-frequency analysis of arc current signal.

Hilbert-huang transformation contains empirical mode decomposition and corresponding hilbert spectrum. The signal \( x(t) \) is decomposed into summation of lots of internal mode component Intrinsic Mode Function \( c_i(t) \) and a residual component \( r_n \) as expressed in equation (1),

\[
x(t) = \sum_{i=1}^{N} c_i(t) + r_n
\]

where \( r_n \) is an average trend or a constant. Neglecting the residual component \( r_n \), Hilbert transform of every Intrinsic Mode Function \( c_i(t) \) is performed. Equation (2) can be obtained,

\[
\hat{c}_i(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{c_i(\tau)}{t-\tau} d\tau
\]

The analytic signal \( z_i(t) \) is constructed by equation (2),

\[
z_i(t) = c_i(t) + j \hat{c}_i(t) = a_i(t) e^{j\phi_i(t)}
\]

Where the amplitude function \( a_i(t) \) and phase function \( \phi_i(t) \) are obtained as eqs.(4) and (5) respectively,

\[
a_i(t) = \sqrt{c_i^2(t) + \hat{c}_i^2(t)}
\]

\[
\phi_i(t) = \arctan \frac{\hat{c}_i(t)}{c_i(t)}
\]

The instantaneous frequency \( f_i(t) \) can be further obtained by eq. (5) as follows,

\[
f_i(t) = \frac{1}{2\pi} \frac{d\phi_i(t)}{dt}
\]

In this way, the following equation (7) can be obtained,

\[
x(t) = RP \sum_{i=1}^{N} a_i(t) e^{j\phi_i(t)} = RP \sum_{i=1}^{N} a_i(t) e^{j \int \omega_i(t) dt}
\]

Where \( RP \) is real part. Equation (7) is defined as Hilbert spectrum and is written as eq. (8),

\[
H(\omega, t) = RP \sum_{i=1}^{N} a_i(t) e^{j \int \omega_i(t) dt}
\]

Eq.(8) describes the accurate changing law of time and frequency of signal amplitude in the whole frequency ranges. Signal amplitude is expressed as function of time and instantaneous frequency in the three dimensions space. It also can be expressed as contour line of time-frequency plane.

The method of information entropy introduced into time-frequency analysis is to divide time-frequency plane into \( N \) equal area blocks. Each block energy is supposed as \( W_i(i=1,2,\ldots,N) \), the total energy of the time-frequency plane is \( A \). Each block energy is normalized by \( q_i = W_i/A \), thus \( \sum_{i=1}^{N} q_i = 1 \), which corresponds with initial normalization condition of information entropy calculation. Based on the formula of information entropy, formula of time-frequency entropy \( s(q) \) based on Hilbert-huang transformation is written as eq. (9),

\[
s(q) = -\sum_{i=1}^{N} q_i \ln q_i
\]

According to the basic property of information entropy, the more uniform is the \( q_i \) distribution, the larger is the value of time-frequency entropy \( s(q) \), while the less uniform is the \( q_i \) distribution, and the smaller is the value of time-frequency entropy.

III. TIME-FREQUENCY ENTROPY CALCULATION OF ARC CURRENT SIGNAL

Experiments have been done by alternating current square wave submerged arc welding machine MZE1800 developed by South China University of Technology. The material of work piece is low carbon steel with slab thickness of 20mm, the welding wire trademark is H08A with diameter of 4.0mm, welding flux is HJ431. Current signals is collected by sensor SML1500E/S60 and data acquisition card PCI-1718HGU in the experiments, the waveform of sampling is 25 kHz, sample time is 20s in each welding process. Time-frequency entropy calculation is done by 125000 points from the whole acquisition data.

1) Current signal analysis of different duty cycle

Under the given voltage of 38V, current amplitude of 650A, welding wire extension of 22mm, frequency of 50Hz and welding speed of 0.6m/min, the waveform of welding arc current with increasing duty cycle are shown in fig.1, fig.2, fig.3, fig.4, fig.5, fig.6, and fig.7.

Each 5000 collected data is analyzed with Hilbert-huang transformation, 25 time-frequency entropy value \( S_a \) in each duty cycle is obtained. \( S_{avg} \) is the average of \( S_a \). The calculation result of time-frequency entropy \( S_a \) is shown in fig.8.
Fig.8 Time-frequency entropy in different duty cycle

Tab.1 are welding parameters and the calculation results of time-frequency entropy in different duty cycle with the same frequency of 50Hz. The arc current and voltage in tab.1 are the mean value of the collected current and voltage in the welding process. Fig.1, fig.2, fig.3, fig.4, fig.5, fig.6 and fig.7 show that the welding process is stable. Among them, fig.3, fig.4, and fig.5 are smaller current wave with the duty cycle of 0.4, 0.5, and 0.6 respectively. In the same condition of welding current, voltage, frequency and speed, when duty cycle is small, the welding process is unstable. Because the negative half-wave predominates in a long time to melt welding wire, the welding wire droplet is in a state of big droplet slag wall transition. With increasing of duty cycle, the positive half-wave arc predominates in a long time, negative half-wave arc predominates in a short time, welding wire droplet shrinks and transits from the slag wall, current wave become smaller and the welding process become more stable. When duty cycle is up to 0.7, the actuation duration of positive half-wave arc is too long and the negative half-wave arc action time is too short, the welding wire droplet grow up and following with part droplet transition from the slag wall, so the arc stiffness are smaller and current wave become bigger. From the point of the analysis, the most stable and the smallest current wave are achieved in the balance of welding wire melting and droplet transition with reasonable matching of actuation duration of positive and negative half-wave. Duty cycle of 0.4, 0.5 and 0.6 are the best welding specifications under the given voltage. From tab.1, it can be seen that the duty cycle of 0.4, 0.5 and 0.6 have largest time-frequency entropy.

Tab.1 shows that time-frequency entropy gradually increase as the duty cycle from small to large, the time-frequency entropy increase up to the maximum at duty cycle of 0.5. The time-frequency entropy is a measure of complexity, so it should be large as current wave are regular. The duty cycle exceed 0.5, time-frequency is reduced. It indicates that duty cycle of alternating current square waveform submerged arc welding is a factor to effect the time-frequency entropy, and is
closely related with stability of welding process. The bigger is the time-frequency entropy, the more stable is the welding process. In fact, it is a token of stability increase as duty cycle from small to large at a low duty cycle, because this process is a transition process from instable big droplet to stable ones. Therefore, time-frequency entropy can be used as the stability judgment criteria of alternating current square wave submerged arc welding in condition of the particular welding current, voltage and different duty cycle of current waveform.

Fig.8 shows the fluctuations of time-frequency entropy calculation process. It also can be seen from the process of time-frequency entropy calculation that the more stability of submerged arc welding process is, the smaller of fluctuations of current and time-frequency entropy are. The standard deviation $\sigma (S_a)$ is the numerical description of fluctuations of time-frequency entropy calculation process, the smaller is the $\sigma (S_a)$, and the smaller is the fluctuations. Tab.1 shows that standard deviation of time-frequency entropy is the smallest with current waveform duty cycle at 0.4, 0.5 and 0.6, which indicates that the fluctuations under these duty cycle are smallest and most stability. It is also verified that duty cycle at 0.4, 0.5, and 0.6 are the best current waveform parameters in the proposed above condition.

2) Analysis of current signals in different frequency

Under the given voltage of 38V, current amplitude of 750A, welding wire dry extension of 22mm, welding speed of 0.8m/min and duty cycle of 0.5, the waveform of welding arc current with increasing frequency are shown in fig.9, fig.10, fig.11 and fig.12. Fig.13 and tab.2 are the calculation results of time-frequency entropy and welding parameters in different frequency welding current waveform.

From fig.9, fig.10, fig.11 and fig.12, it is obtained that the stability of welding process becomes better with the current frequency increases in welding process, it is no short circuit, interruption arc and good welding seam formation. Tab.2 shows that the time-frequency entropy increases as frequency changed from small to large. It also explains that the more stable is the arc, the larger is the time-frequency entropy, while the less stable is the arc, and the smaller is the time-frequency entropy. Therefore, time-frequency entropy can be used as the stability judgment criteria of alternating current square wave submerged arc welding in condition of the same duty cycle and different frequency of current waveform.

<table>
<thead>
<tr>
<th>Duty cycle $(D)$</th>
<th>Arc current $(I/A)$</th>
<th>Arc voltage $(U/V)$</th>
<th>Frequency $(f/Hz)$</th>
<th>Wire diameter /mm</th>
<th>Dry extension /mm</th>
<th>$S_{avg}$</th>
<th>$\sigma (S_a)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>643</td>
<td>37</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.1523</td>
<td>0.00856</td>
</tr>
<tr>
<td>0.3</td>
<td>640</td>
<td>37</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.2640</td>
<td>0.006854</td>
</tr>
<tr>
<td>0.4</td>
<td>632</td>
<td>36</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.3612</td>
<td>0.004718</td>
</tr>
<tr>
<td>0.5</td>
<td>651</td>
<td>38</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.4758</td>
<td>0.002153</td>
</tr>
<tr>
<td>0.6</td>
<td>644</td>
<td>38</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.3524</td>
<td>0.002805</td>
</tr>
<tr>
<td>0.7</td>
<td>638</td>
<td>37</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.2556</td>
<td>0.005625</td>
</tr>
<tr>
<td>0.8</td>
<td>635</td>
<td>37</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>0.1538</td>
<td>0.007562</td>
</tr>
</tbody>
</table>

![Figures and tables](https://placehold.it/150x150)
Under the given voltage of 40V, current amplitude of 780A, welding wire extension of 22mm and duty cycle of 0.5, the waveform of welding arc current with different welding speed are shown in fig.14, fig.15, fig.16 and fig.17. Fig.18 and Tab.3 are the calculation results of time-frequency entropy and welding parameters at different welding speed.

Table 3. Welding parameters and time-frequency entropy at different welding speed

<table>
<thead>
<tr>
<th>Welding Speed $v$ (m/min)</th>
<th>Frequency $f$ (Hz)</th>
<th>Arc current $I$ (A)</th>
<th>Arc voltage $U$ (V)</th>
<th>Duty cycle $D$</th>
<th>Wire diameter $d$ (mm)</th>
<th>Dry extension $s$ (mm)</th>
<th>$S_{avg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>50</td>
<td>777</td>
<td>40</td>
<td>0.5</td>
<td>4</td>
<td>22</td>
<td>0.447376</td>
</tr>
<tr>
<td>1.0</td>
<td>50</td>
<td>768</td>
<td>39</td>
<td>0.5</td>
<td>4</td>
<td>22</td>
<td>0.151775</td>
</tr>
<tr>
<td>1.0</td>
<td>80</td>
<td>778</td>
<td>40</td>
<td>0.5</td>
<td>4</td>
<td>22</td>
<td>0.376791</td>
</tr>
<tr>
<td>1.1</td>
<td>100</td>
<td>779</td>
<td>40</td>
<td>0.5</td>
<td>4</td>
<td>22</td>
<td>0.373109</td>
</tr>
</tbody>
</table>

With the same current waveform parameters, current fluctuation becomes larger as the welding speed increases. When the welding speed is 1.0m/min, there are a few short circuits, broken arc, instable welding process and weld seam molding surface existed some contraction. Tab.3 shows that the time-frequency entropy decreases as welding speed increases, and it is minimum occurs at the speed of 1.0m/min. When the frequency of alternating current square wave is up to 80Hz, there is no short circuit broken arc, stable welding process with good weld seam molding. When the frequency is up to 100Hz, welding speed can be raised up to 1.1m/min, the welding process are stable and good weld seam molding. Tab.3 shows that the time-frequency entropy is larger both in the condition of welding speed of 1.0m/min at the
frequency of 80Hz and 1.1m/min at the frequency of 100Hz, which indicates that it can keep the stability of arc by heightening frequency of current waveform appropriately in the welding process. It is also verified that the time-frequency entropy can be used as criterion of stability of alternating current square wave submerged arc welding.

IV. CONCLUSIONS

1) The calculation and analysis of time-frequency entropy show that time-frequency entropy value relates with frequency and duty cycle of alternating current square wave and stability of alternating current square wave submerged arc welding process. The more stable is the welding process, the larger is the time-frequency entropy. When frequency and duty cycle of alternating current square wave are matched reasonably, the time-frequency entropy is up to the maximum. On the other hand, the more unstable is the welding process, the larger is the fluctuations of time-frequency entropy.

2) By calculating and analyzing the time-frequency entropy of current signals at different welding speed, it is verified that the larger time-frequency entropy indicates the more stable arc. This research indicates that the time-frequency entropy can be used as stability evaluation criterion for alternating current square wave submerged arc welding.

ACKNOWLEDGMENT

This work was supported in part by a grant from financial support from National Natural Science Foundation of China (51005073), Scientific Research Fund of Hunan Provincial Education Department (10C0682), Ph. D Start Fund (E51088), Project of Hunan Provincial Research Scheme (2009TP4038-2), also from Aid program for Science and Technology Innovative Research Team in Higher Educational Institutions of Hunan Province, are gratefully acknowledged.

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