Research on current harmonic suppression of PMSM based on mathematical morphology

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Abstract. Due to the existence of power converter dead time, flux harmonics and other nonlinear factors, the motor phase current contains a large number of high-order harmonics, so the electromagnetic torque generated by the interaction of current and flux also contains various orders of harmonics. In order to eliminate current harmonics, mathematical morphology filter is proposed to suppress current harmonics. However, the single-scale morphological filtering has shortcomings in preserving information details. In order to make up for the deficiency of the traditional single-scale morphological filtering in preserving information details, a weighted multi-scale mathematical morphology method is proposed to suppress the current harmonics.

1. Analysis of the basic theory of mathematical morphology

1.1 Basic operations of morphology

The basic operations of morphology include erosion, dilation, open operation and closed operation. In order to study the physical meaning of morphology, the domain of definition can be set as \( F = \{0,1,2,\ldots,N - 1\} \). The input signal \( f(n) \) is a discrete function defined on \( F \). Let \( g(n) \) be the structure function, whose domain of definition is \( G = \{0,1,2,\ldots,M - 1\} \), and \( N >> M \). Then the expansion operation of \( f(n) \) with respect to \( g(n) \) is defined as follows:

\[
(f \oplus g)(n) = \max_{m=0,1,\ldots,M-1} \{f(n - m) + g(m)\} \quad n = 0,1,\ldots,N - M
\]

Expansion operation represents the process of expansion, which can make the target expand and the cavity shrink, thus filling the concave part. The definition of corrosion operation of \( f(n) \) with respect to \( g(n) \) is as follows:

\[
(f \odot g)(n) = \max_{m=0,1,\ldots,M-1} \{f(n - m) + g(m)\} \quad n = 0,1,\ldots,N + M - 2
\]

1.2 Analysis on the selection of structural elements

The effect of mathematical morphology filtering is affected by structural elements. Therefore, it is necessary to select appropriate structural elements to achieve the best filtering effect. This paper analyzes the different filtering performance of linear structure and semicircle structure, and obtains the filtering effect picture of sinusoidal signal processed by different element structures.
As can be seen from Figure 1, the signal obtained with linear structural elements contains little interference. The signal of semi-circular structure element has a great shake, so the signal of linear structure element is better than that of semi-circular structure element. In this paper, linear structural elements can be used to process the harmonic signal.

1.3 Analysis of width selection of structural elements

Whether the length of the structure elements of mathematical morphology is an appropriate value affects the filtering effect. By using linear structural elements with different widths to process sinusoidal signals, we can get the selection rules of width of structural elements.

As can be seen from Figure 2, With the increase of the width of the linear structure element, the sinusoidal signal content in the signal processed by the filter is gradually suppressed. When the width value increases to a certain value, the original signal will eventually become a straight line. the width value continues to increase, the signal is still a straight line, resulting in waveform distortion. Therefore, excessive width will cause damage to the original signal, resulting in the loss of signal details. When the width is small, the content of sinusoidal signal in the signal processed by the filter is obvious. Although it can protect the details of the original signal, it can not suppress the sinusoidal signal effectively. Generally, the width of 20-30 is suitable.
2. Construction of mathematical morphology filter

2.1 Principles of multiscale morphology
Multi scale morphology combines multi-scale operation and morphology principle, and adds scale to the traditional parameter selection of structural elements. Through the multi-scale description of a certain signal, the result of gradually matching the characteristics of a certain graph is achieved. Multi scale morphology transforms the signal with different scale structural elements.

Assuming that $T$ is a morphological transformation, the multi-scale morphological transformation of $T$ to signal $X$ is a cluster of transformations $\left\{ T_s | s > 0, s \in \mathbb{Z} \right\}$. Where, $T_s$ is defined as:

$$T_s(X) = sT(X/s) \quad s > 0$$

(3)

Now suppose that the input signal $f(n)$ is a discrete function defined on $F = 0, 1, \cdots, N - 1$, and the structural element $g(n)$ is a discrete function defined on $G = 0, 1, \cdots, M - 1$, and $N \gg M$, then the multi-scale morphological expansion operation of $f(n)$ with respect to $g(n)$ is as follows:

$$(f \circ g)_s(n) = s(f/s \circ g)(n) = f \circ sg(n)$$

(4)

The corrosion operation is as follows:

$$(f \bullet g)_s(n) = s(f/s \bullet g)(n) = f \bullet sg(n)$$

(5)

Where $n = 0, 1, 2, \cdots, N - 1$. $sg$ is the structural element in $s$-Scale, and $g$ is expanded by $s - 1$ times to get $sg$:

$$sg = g \oplus g \oplus \cdots \oplus g$$

(6)

By cascading the multi-scale morphological erosion and expansion, the multi-scale morphological open and close operations can be obtained, thus forming a basic multi-scale morphological filter. The operation of $f(n)$ with respect to the multiscale morphology of $g(n)$ is as follows.

Open operation:

$$(f \circ g)_s(n) = f \circ g \circ \cdots \circ g \oplus g \oplus \cdots \oplus g$$

(7)

Closed operation:

$$(f \cdot g)_s(n) = f \oplus g \oplus \cdots \oplus g \oplus g \oplus \cdots \oplus g$$

(8)

Where $n = 0, 1, \cdots, N - 1$.

Finally, by cascading the multi-scale morphological operations, the multi-scale morphological open close ($M_{OC}$) and multi-scale closed open ($M_{CO}$) filters can be obtained.

$$M_{OC}(f)_s(n) = ((f \circ g)_s \cdot g)_s n = 0, 1, \cdots, N - 1$$

(9)

$$M_{CO}(f)_s(n) = ((f \cdot g)_s \circ g)_s n = 0, 1, \cdots, N - 1$$

(10)

2.2 Design and construction of weighted multiscale morphology
In order to make up for the shortcomings of the traditional single-scale morphological filtering in preserving information details. Considering the small-scale structural elements, the denoising ability is weak, but the signal details can be well preserved. The large-scale structural elements have strong denoising ability, but can make the signal blurred. Moreover, different scale structural elements have different adaptability to different shape signals. Therefore, the method of combining the signal features of each scale is considered to obtain better morphological features than a single fixed scale, so as to achieve better harmonic suppression. According to the previous analysis of multi-scale morphology, a weighted multi-scale morphological filter is constructed.

Let the scale range of structural elements be $S_k = \{ S_1, S_2, \ldots, S_k \}$, then the signals of each order in $k$ effective scales can be obtained:

$$(f)_{sk} g(n) = \frac{1}{2} [M_{CO}(f)_{sk}(n) + M_{OC}(f)_{sk}(n)]$$

(11)

Then, the multi-scale weighted signal is obtained as follows:
\[(f)_{sk} \cdot g(n) = \sum_{k=1}^{K} w_k \cdot (f)_{sk} \cdot g(n) \quad (12)\]

In the above formula, \(w_k\) is the weight factor. Considering that different scales have different harmonic suppression effects on different frequencies, if the weight of large scale is set larger and the weight of small scale is set smaller, then the harmonic with high frequency can be filtered out and the details of the original waveform can be protected.

The main idea of weighted multi-scale morphological filtering is to use different scale structures to check the signal to be processed in order to obtain better morphological information.

3. Simulation experiment of mathematical morphology harmonic suppression

In order to verify the superiority of weighted multi-scale morphological filtering in harmonic suppression of synchronous motor, this chapter also compares with the fixed scale morphological motor harmonic suppression method.

Taking the synchronous motor as the controlled object, the traditional fixed scale morphology and weighted multi-scale morphology filtering methods are used to carry out the simulation experiment of motor harmonic suppression. The effectiveness of the proposed strategy is verified by analyzing the current disturbance and harmonic content. The mathematical morphology harmonic suppression simulation of synchronous motor is built as follows:

![Diagram](image)

**Figure 3. The mathematical morphology harmonic suppression simulation.**

The experimental results of q-axis current with fixed scale and multi-scale morphological filtering are shown in the following figure.

![Graphs](image)

**Figure 4. fixed scale morphological filtering.**

**Figure 5. multi-scale morphological filtering.**

Figure 5 is the result of multi-scale morphological filtering. Compared with the result of fixed scale morphological filtering in Figure 4, it can be concluded that the harmonic suppression effect of weighted...
multi-scale morphology is more obvious than that of single scale morphology, and the current is more smooth.

In order to further verify the superiority of the weighted multi-scale method in harmonic suppression, the harmonic content of two different methods can be analyzed.

Figure 6. fixed scale morphological filtering.

Figure 7 is the harmonic content diagram of weighted multi-scale morphological filtering. Compared with the harmonic content diagram of fixed scale morphological filtering in Figure 6, it can be seen that the 5th harmonic content is reduced from 2.5% to 1.2%, the 7th harmonic content is reduced from 1.3% to 0.25%, the 11th harmonic content is reduced from 1.8% to 0.6%, and the 13th harmonic content is reduced from 2.1% to 0.8%. It can be seen that the harmonic content after the weighted multi-scale harmonic suppression is less, so it can be concluded that the harmonic suppression effect of the weighted multi-scale morphology is better than that of the traditional fixed scale harmonic suppression.

Finally, the improvement of three-phase current of synchronous motor in the two harmonic suppression methods is needed to analyze.
The Phase A current filtered by weighted multi-scale morphology is shown in Figure 10. Compared with the original current and the current after using fixed scale morphological filter, the motor harmonic suppression method based on weighted multi-scale morphology proposed in this paper has a better suppression effect on the harmonic current. Current filtered by weighted multi-scale morphology is significantly improved, and the harmonic content is significantly reduced.

4. Conclusions
To sum up, the harmonic suppression method of synchronous motor based on weighted multi-scale mathematical morphology filter proposed in this chapter can effectively suppress the current harmonics in the motor. Compared with the fixed scale morphological filtering, the proposed method is more effective and the harmonic suppression effect is more obvious.

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