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Research on a New Method of Indirect Velocity Measurement for DC Motors

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Received: 28 August 2013 /Accepted: 25 October 2013 /Published: 30 November 2013

Abstract: Focusing on the DC motor indirect velocity measurement without sensors, according to the characteristics of the local mean decomposition, which PF component separated in decreasing order of frequency were arranged, the paper builds adaptive filter (for short, AF). Secondly, the paper determined the order in AF cut-off component to form a band pass filter to extract the commutation current. Finally, with the DC motor commutation, extreme value difference method for getting the current frequency is proposed. Commutation current characteristics respectively based on LMD and EMD are compared with experimental data, and compared the performance of solving commutation frequency by the extreme difference method and wavelet ridge algorithm, Hilbert transform and the arc cosine of LMD. Related experiments prove that the proposed method is feasible and effective. *Copyright © 2013 IFSA.*

Keywords: Commutation current, Local mean decomposition, Adaptive filter, Extreme value difference algorithm, Instantaneous frequency.

1. Introduction

The rotating velocity information of DC motors is contained in the frequency of commutation current, and then the starting rotating characteristic is able to be obtained by analyzing the starting armature current of DC motors [1, 2]. The method has the advantage of no velocity needed and is adapt to be applied in fields of the online measurement and the motors without visible rotation axis [3, 4].

Former research on the indirect velocity measurement of DC motors adopts digital frequency meter [5] or microcontroller system to measure the frequency of commutation pulse amplified and shaped by AC amplifier [6], and the methods rely on serious hardware. Recently research focuses on FFT [7], short-time FFT [8], wavelet packet transform [9], wavelet ridge algorithm [10, 11] and the 2nd generation wavelet algorithm [12]. The steady-state frequency characteristics can be obtained with FFT, and the transform fails in the process before the steady state. The full process frequency characteristics can be obtained with the good ability of time-frequency positioning of the wavelet packet transform, however, it also brings the large calculation and low precision since the discrete wavelet transform and the time-frequency plane of orthogonal decomposition are adopted [10]. Method based on the wavelet ridge adopts the continuous wavelet transform and brings high precision, however, much calculation is also brought since the analytic function is built by the Hilbert transform to solve the frequency in the complex domain. The short-time FFT and the 2nd generation wavelet transform are restricted by the uncertainty principle and hard to achieve good time-frequency results. Methods of the Teager Energy Operator [13] and phase difference [14] are also applied in solving frequency, however, too sensitive to noise.

Article number P_1495

The new method of solving frequency of multiple component signals based on the Hilbert-Huang Transform [15] is popular recently, and it decomposes complex signals into the summation of some IMF (Intrinsic Mode Function) adaptively according to EMD (Empirical Mode Decomposition) and then solves frequency for each IMF with the Hilbert transform with good self-adaptability, however, negative frequency easy appearing.

The local mean decomposition [16] is an adaptive non-linear signal analysis method according to the signal envelope characteristics and decomposes multiple component signals into some product functions of single component one. The PF is made up of the amplitude and frequency modulation function and can solve its instantaneous frequency by computing the derivative, which realizes in the real umber domain and brings the fast computing speed, however, over amplitude of interval of [-1, 1] of the cosine signal often appears.

The paper builds the adaptive filter based on LMD to extract the commutation current comparing to the method of EMD to extract the armature current, and proposes a frequency solving method based on the extreme value difference according to the commutating characteristics of DC motors, which is also compared to methods of wavelet ridge, Hilbert transform and arc cosine in LMD. Results show that the new method presented in the paper is better.

2. The Filtering Principle of LMD

2.1. Basic Principle [17]

For a signal *x(t)*, the local mean decomposition steps follows.

1) Find out the signal *x(t)* the local extreme points of n_i, calculate any two adjacent local extreme points mean m_i, there are:

$$m_i = (n_i + n_{i+1})/2 \quad (1)$$

All the adjacent local mean points mi and mi+1 are connected by broken line, and then smoothed by sliding average algorithm, get the local mean function m11(t).

2) Calculate the envelope estimate a_i

$$a_i = | n_i - n_{i+1} | / 2 \quad (2)$$

Connect each adjacent envelope estimate values a_i and a_{i+1} with broken line, and then smoothed by sliding average algorithm to get the envelope estimate function a11(t).

3) Separate the local mean function m_{11} (t) from the original signal *x (t)*, and obtain the signal H_{11}(t):

$$h_{11}(t) = x(t) - m_{11}(t) \quad (3)$$

4) Divide $h_{11}(t)$ by the envelope estimate function $a_{11}(t)$, get FM signal $s_{11}(t)$:

$$s_{11}(t) = h_{11}(t) / a_{11}(t) \quad (4)$$

Repeat the above steps for S_{11}(t), get the envelope estimation function a_{12} (t), If $a_{12}(t)$ is not equal to 1, indicating that $s_{11}(t)$ is not a pure frequency modulation signal, and then repeat n times until S_{1n} (t) is a pure FM signal, i.e. namely the envelope estimation function of $s_{1n}(t)$ *is* $a_{1(n+1)}$(t)=1, so:

$$\begin{cases} h_{11}(t) = x(t) - m_{11}(t) \\ h_{12}(t) = s_{11}(t) - m_{12}(t) \\ \vdots \\ h_{1n}(t) = s_{1(n-1)}(t) - m_{1n}(t) \end{cases} \quad (5)$$

$$\begin{cases} s_{11}(t) = h_{11}(t)/a_{11}(t) \\ s_{12}(t) = h_{12}(t)/a_{12}(t) \\ \vdots \\ s_{1n}(t) = h_{1n}(t)/a_{1n}(t) \end{cases} \quad (6)$$

Conditions for iterative terminated:

$$\lim_{n\to\infty} a_{1n}(t) = 1 \quad (7)$$

In practical application, in order to avoid excessive decomposition number, we can set a disturbance Δ, the iteration will end when $1-\Delta \le a_{1n}(t) \le 1+\Delta$.

5) Multiply the iterative process envelope estimation function, get the envelope signal a_1 (t):

$$a_1(t) = a_{11}(t)a_{12}(t)\cdots a_{1n}(t) = \prod_{k=1}^{n} a_{1k}(t) \quad (8)$$

6) Obtain the formula (8) in the envelope signal a_1 (t) and pure FM signal s_{1n} (t) multiplied, to obtain the original signal *x (t)*, as a PF component:

$$PF_1(t) = a_1(t) \cdot s_{1n}(t) \quad (9)$$

It contains the highest frequency component of the original signal, It is a single component amplitude modulation and frequency modulation signal, The instantaneous amplitude is the envelope signal $a_1(t)$, the instantaneous frequency $f_1(t)$ can be calculated by pure FM signal $s_{1n}(t)$:

$$f_1(t) = \frac{1}{2\pi} \times \frac{d \arccos(s_{1n}(t))}{dt} \quad (10)$$

7) Separate PF_1 *(t)* components from the original signal *x (t)*, and obtain the signal u_1 (t), u_1 (t) as the new data, repeat the above steps, *k* cycle, until u_k (t) as monotonic function so far.

$$\begin{cases} u_1(t) = x(t) - PF_1(t) \\ u_2(t) = u_1(t) - PF_2(t) \\ \vdots \\ u_k(t) = u_{k-1}(t) - PF_k(t) \end{cases} \quad (11)$$

As can be seen from the above steps, the original signal can be reconstructed by u_k (t) and all PF components, i.e.: $x(t) = \sum_{i=1}^{k} PF_i(t) + u_k(t)$.

2.2. Principle of Building Filter Based on LMD

Adaptive temporal and spatial filter can be built according to the frequency characteristics from high to low of IMF components decomposed based on EMD [18]. LMD has the similar characteristics as EMD and so the similar filter can be achieved.

If removing the PF components finally decomposed and adding the left ones, an equivalent high pass filter is achieved; if removing the components firstly decomposed and adding the left ones, a low pass filter achieved; if removing the components first and finally decomposed and keeping the middle ones, a band pass filter achieved. The adaptive filter (for short, AF) based on LMD is expressed below.

$$\hat{x}(t) = \sum_{l}^{h} PF_i(t) \tag{12}$$

In formula (12), the parameter of l and h is the cut-off component order of AF, and takes values from the interval of [1, N]. N is the maximum order of PF components. $\hat{x}(t)$ is the output signal. While $l>1$ and $h=N$, AF is high pass; while $l>1$ and $h=N$, it is low pass; while $1<l<h<N$, it is a band pass.

The signal decomposing process based on LMD indicates the filter owns the multi-resolution analyzing and adaptive ability, and the cut-off frequency and pass-band relies on the input signal.

2.3. Solving Transient Frequency Based on the Extreme Value Difference

Leading or delayed commutation, and sparking or arc discharging often appears in the commutating process for DC motors. In addition, the process is affected by the pressure on the commutator and touching degree between the brush and commutating segment [2]. All the factors would cause the distortion for the commutation current. In process of current extraction, methods of EMD and LMD are difficult to remove the effect of Leading and delayed commutation [17, 18]. The velocity obtained indirectly at the distorted point will not fit the actual value which does not burst [5].

According to the definition of frequency, the period is the time interval between two adjacent wave crests and troughs and the reciprocal of period can be considered to be the frequency at middle time for adjacent crests or troughs, which is called the extreme valve difference method based on the middle point. Assuming the commutation current is shown as $i_{hx}(t)$, the frequency solution follows.

Step (1) Find out all the peak values of $i_{hx}(t)$ and set them to be shown as $i_{hx}(\tau_k)$; τ_k indicates the peak time with $k = 1,2,\cdots,N$, and N the total peak number.

Step (2) If the coming time for the 1st peak is equal to zero, turn to Step (3), or make the mirror extension process to solve the end effect and then go to Step (3).

Step (3) The frequency at middle time for adjacent crests or troughs is shown below with the sample frequency shown as f_s.

$$f\left(\frac{\tau_k + \tau_{k-1}}{2}\right) = \frac{f_s}{\tau_k - \tau_{k-1}} \tag{13}$$

Step (4) Verify whether the frequencies robust.

Step (5) Plot the transient frequency wave in the way of least squares fitting.

The method of positioning extreme values to solve frequency has clear physical meaning and resolves the frequency burst problem caused by the leading or delayed commutation and spark factors.

3. Indirect Velocity Measurement Formula and the Signal Acquisition System

3.1. Formula for Indirect Velocity Measurement

The formula is shown as the following [4].

$$f_n = \frac{c \times m \times n \times p}{60} \tag{14}$$

In the formula, the parameter of m, n, p indicates correspondingly number of commutating segments, rotating velocity, and number of motor pole pairs. The parameter of c is a coefficient relying on m taking the value of 1 when m is even, while taking 2.

3.2. The Signal Acquisition System

The acquisition system shown in Fig. 1 contains permanent magnet DC motor of ZYTD-50SRZ-R, Holzer current sensor of LSTR25N, data acquisition card of RTUSB2850, PC and DC power adapter.

As shown in Fig. 1, the no load current of ZYTD-50SRZ-R is 0.18 A, no load rotating velocity is 2000 rmp with the polar pair number of 1 and commutating segment number of 12. With regard to parameters above, the maximum frequency of commutation current should be less than 40 Hz. The sample frequency chosen in the paper is 20 kHz with the acquisition data shown in Fig. 2.

As shown in Fig. 2, the armature current contains plenty of noise signals from transient to the steady state.

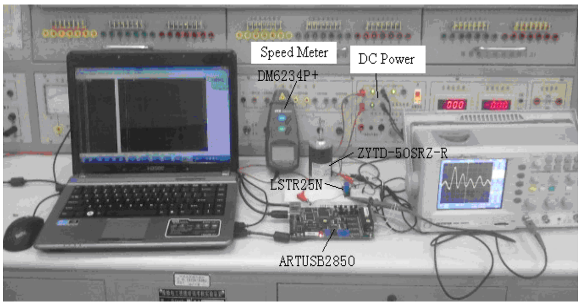


Fig. 1. Signal acquisition system for DC motors.

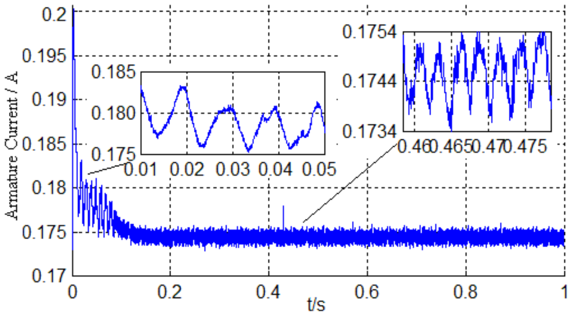


Fig. 2. The armature current signal without load.

4. Experimental Result Analysis

The PF components decomposed based on LMD from the armature current in Fig. 1 are shown in Fig. 3.

And in order to verify the completeness of LMD, the summation operation of all PF components and residual functions are adopted to reconstruct the original signal. The error waveform of difference between the reconstructed and original signal is shown in Fig. 4.

As shown in Fig. 4, the error degree is in the level of 10^{-17}, which proves method of extracting commutation current based on LMD is feasible.

Fig. 3 shows that all the PF components are in the frequency order from high to low. PF1 and PF2 with small amplitude and high frequency can be assumed to be noise. PF3 with the amplitude increasing and lower decreasing can be assumed to be the commutation current component. The frequency of other PFs keeps decreasing and PF7 can be thought approximately as the DC component. With the analysis above, the cut-off component for the band pass filter describe in Formula (12) is fixed with the order of *l=3 and h=6.* So the AF output signal is the commutation current shown in Fig. 5.

With comparing to Fig. 2, it shows that the band pass AF well keeps the commutation current while removing the high frequency noise and low frequency DC current.

The DC components by EMD [17] and LMD are shown in Fig. 6 (a), and the commutation current in Fig 6 (b).

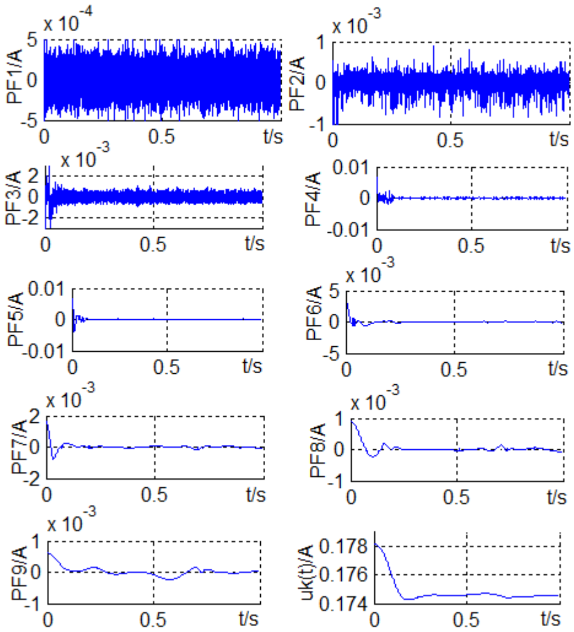


Fig. 3. PF components and residual function.

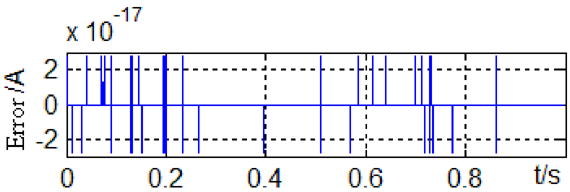


Fig. 4. Error signal between reconstructed and original signal.

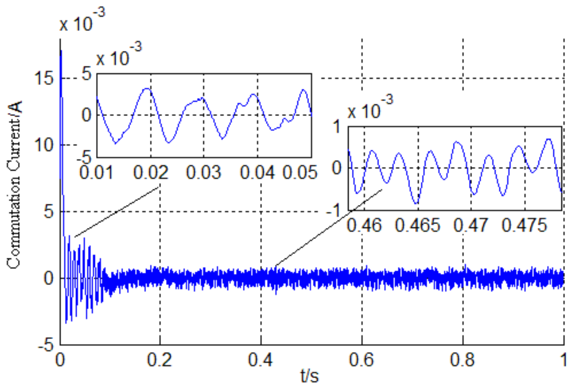
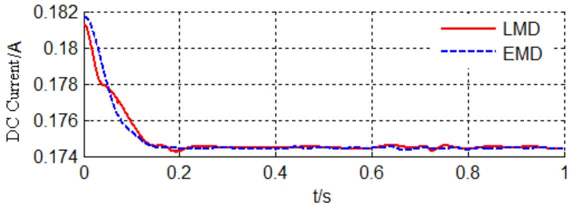


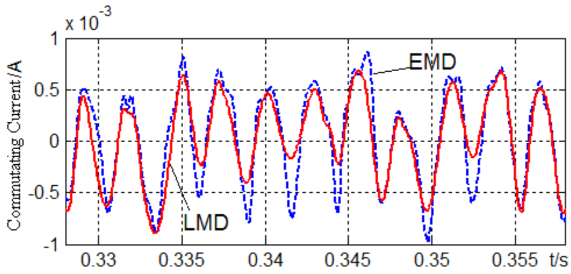
Fig. 5. Commutation current by LMD.

As shown in Fig. 6(a), the DC component extracted with EMD performs better in the starting process, and the ones with both methods perform similarly; as shown in Fig. 6(b), the commutation current extracted with LMD performs smoother waveform.

With the experimental environment of K480P-i5G PC, Win7 OS and Matlab 7.12, the time for obtaining all the IMF components by EMD based on screening stop criterion by Rilling [17] with the default settings is 2.463026 s, while time for extracting all the PF components by LMD with the disturbance quantity of Δ=0.0001 is 1.193508 s. That proves that it is faster for LMD and more suitable for the measurement in real time mode.



(a) DC components by LMD and EMD.



(b) Commutation current by LMD and EMD.

Fig. 6. Waveform comparison with LMD and EMD.

Fig. 7 shows the solved frequency by methods of the extreme value difference and the wavelet ridge algorithm, and Fig. 8 shows the Fourier spectrum of the starting current.

Comparing with Fig. 7 and Fig. 8, method of extreme difference can be effective for solving the frequency of the commutation current extracted by EMS and LMD. That three frequency waveforms go into the steady state at the same time in Fig. 7 proves the difference method is right. It also shows that the commutation current waveform with LMD is smoother and no bursting than that with EMD in the starting transient process; and the frequency waveform by the wavelet ridge algorithm which has large fluctuation in the boundary of steady state is smoother than that by the extreme difference.

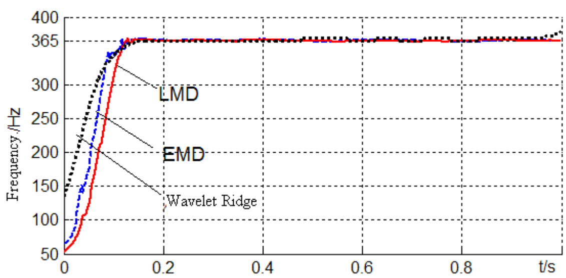


Fig. 7. Transient Frequency with methods of the extreme difference and the wavelet ridge algorithm.

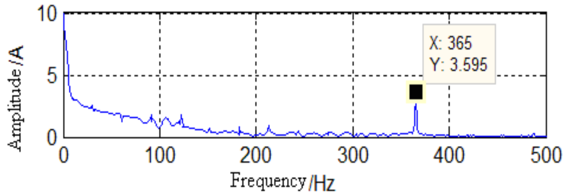


Fig. 8. Fourier spectrum of the armature current in the starting process without load.

In addition, the time for solving frequency with the wavelet ridge algorithm of the type of cmor6-2 wavelet and scale of 1:300 is 12.633830 s, while the time with extreme difference method is 0.385791 s, which is more suitable for the real time application.

Fig. 9 shows the frequency waveforms of main modes by Hilbert Transform and LMD arc cosine method, and the former has large amplitude and many mutation points because the commutation current is not regular cosine wave and the commutating process is very complex.

LMD adopts the moving average algorithm like the filter window in the process of obtaining the pure FM function to solve the frequency, and the waveform is smoother than that of HHT, but has some fluctuation because the value of the FM function is often beyond the interval of [-1, 1].

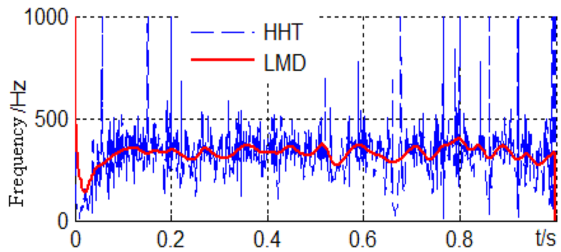


Fig. 9. Frequency waveforms of main modes by Hilbert Transform and LMD arc cosine method.

According to Formula (12), the rotating velocity is plotted in Fig. 10 showing the steady velocity is 1825 rmp, and the fluctuation range is less than ±5 rmp, which proves the method proposed in the paper is feasible.

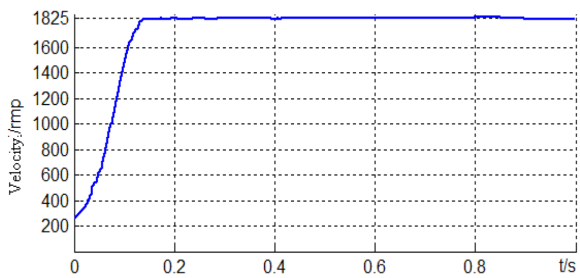


Fig. 10. Rotating velocity of DC motors without load.

5. Conclusions

The adaptive filter based on LMD is built in the paper, and the methods of EMD and LMD in extracting the commutation current form DC motors with no load are compared with experimental data. A new method of solving commutation current based on the extreme value difference is also proposed and compared to methods of LMD arc cosine, Hilbert transform and wavelet ridge algorithm. Some conclusion follows.

1) Comparing to EMD, LMD extracts smoother commutation current and performs faster speed, which is more suitable for the real time application.

2) The frequency can be solved by the extreme value difference method.

3) With regard to solving frequency of commutation current by EMD and LMD, the waveform with LMD is smoother in the starting transient process.

4) The transient frequency characteristics with the wavelet ridge algorithm are better, but have large fluctuation in the boundary of steady state.

5) Comparing to the wavelet ridge algorithm, the speed in solving frequency with the extreme difference is increased by 96.95 % and it is suitable used in real time mode.

6) Methods of the LMD arc cosine and Hilbert transform are not suitable to solve frequency directly.

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