Spike Detection of Disturbed Power Signal using VMD

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Abstract

Most of the electronic equipments are susceptible to power disturbances. Transients are one of the most damaging power disturbances among them. In this paper, a modern adaptive signal decomposition technique called Variational Mode Decomposition (VMD) is used for the detection of impulsive transients or spikes from power signals. VMD decomposes the signal effectively into several Intrinsic Mode Functions (IMF). Each IMF assumes to have a central frequency. The VMD algorithm focuses on finding these central frequencies and intrinsic mode functions using an optimization methodology called Alternating Direction Method of Multipliers (ADMM). In case of spike on a single tone signal like power signal, it is observed that the information about the original signal is dissolved in any of the modes and also observed that the energy of this mode will be higher when compared to other modes. Using the spectral information of this mode the signature of original signal is preserved. The proposed methodology is found to give good result in case of single tone signals.

Keywords: Variational Mode Decomposition (VMD); Hilbert Transform; ADMM; Transients; power signal.

1. Introduction

Now-a-days most of the equipments such as programmable logic controllers, computer terminals, home appliances, diagnostic systems etc are quite susceptible to power disturbance such as impulsive and oscillatory transients, harmonics, notching, voltage sags, voltage swells, and the power interruptions. All these disturbances
reduce the quality of service and raise the failure rates. Transients are the most damaging power disturbances, which is mainly caused by load turning on and off, equipment faults, lightning, and more. Impulsive transients or spikes are short duration burst of energy whose spectrum is flat\cite{1,12}. Power signals are those signals having infinite signal energy or their signal power is finite\cite{13}. In this paper, the variational adaptive decomposition method called VMD is used for the detection of impulsive transient or spike from the power signals. VMD is an adaptive signal decomposition method recently pioneered by Konstantin Dragomiretskiy and Dominique Zosso\cite{14}, which decomposes the signal into several IMF’s. Each IMF assumes to have a central frequency. The VMD algorithm focuses on finding these central frequencies and intrinsic mode functions using an optimization methodology called ADMM. The accumulation of the IMF’s ensures complete reconstruction of the original signal\cite{14}. Various methods are available for the detection of transients. These methods are based on Fast Fourier transform (FFT), wavelet, wavelet packet transforms, short-time Fourier transform (STFT), S-transform, and Wigner-Vue distribution (WVD)\cite{1-11}. Detection and localization of transients is not an easy task because they typically have different shapes, frequency contents, durations and amplitudes which are not known in many systems and applications. The spiked signal is given to VMD and it is observed that the information about the original signal is available in one of its modes, which can be obtained by simple energy calculation on all modes. The mode with information of the original signal has higher energy compared with other modes and this can be observed in the experiment discussed in this paper. From the spectral information of this mode, the signature of the original power signal is preserved. This method is found to give good results in case of single tone signals. This paper is organized as; section II gives a brief overview about the theory of spikes and VMD. In section III, the experiment results and further discussions are given and section IV finally concludes this paper.

2. Materials and Methods

2.1. Spikes

Spikes are short duration non-stationary noise signals whose amplitude at temporal instant cannot be predicted. Spikes are observed as impulses superimposed to the fundamental frequency. These are caused by load turning on and off, equipment faults, effect of discharging of stored energy when turned off, lightning, and more\cite{1,15}. The frequency spectrum of the spike is flat. Fig 1 illustrates spike and its frequency spectrum.
2.2. Variational Mode Decomposition

VMD is a modern adaptive decomposition method that decomposes the signal into various intrinsic mode functions (IMF). Intrinsic Mode Functions are amplitude modulated-frequency modulated (AM-FM) signals, modelled as:

\[ u_k(t) = A_k(t) \cos(\phi_k(t)) \]  

(1)

where phase denoted as \( \phi_k(t) \) is a non-decreasing function, \( \phi_k(t) \geq 0 \), the envelope, \( A_k(t) \) is non-negative, \( A_k(t) \geq 0 \), and both the envelope \( A_k(t) \) and the instantaneous frequency, \( \omega_k(t) = \frac{d\phi_k(t)}{dt} \) vary much slower than the phase \( \phi_k(t) \) \(^{16,17} \). The algorithm focuses on finding the IMF and its central frequencies using an optimization methodology called Alternating Direction Method of Multipliers (ADMM). The accumulation of the IMF’s ensures complete reconstruction of the original signal. The original formulation of the optimization problem is continuous in time-domain \(^{14} \). For decomposing a signal into \( k \) modes, the formulation will be to minimize the sum of the variation of bandwidths of \( k \) modes such that the addition of the \( k \) modes are equivalent to the original signal. Here, the unknowns are \( k \) central frequencies and \( k \) functions centered at those frequencies. As the unknown is a function, calculus of variation is applied to derive the optimal functions. Bandwidth of an AM-FM signal primarily depends on both, with the maximum deviation of the instantaneous frequency \( \Delta f = \max(\omega_k(t) - \omega_j(t)) \) and the rate of change of instantaneous frequency. Dragomiretskiy and Zosso proposed \(^{14} \) a function that can measure the bandwidth of an Intrinsic mode function \( u_k(t) \). At first they computed Hilbert transform of the \( u_k(t) \). The definition of Hilbert Transform is as follows \(^{18} \):

\[ Hf(t) = \frac{1}{\pi} \text{pv} \int_{-\infty}^{\infty} \frac{f(v)}{t-v} dv \]  

(2)

where \( \text{pv} \) stands for the Cauchy principal value of the integral. The inverse Hilbert Transform is given as \(^{18} \):

\[ H^{-1} = -H \]  

(3)

Let the computed Hilbert transform of the \( u_k(t) \) be denoted as \( u_k^{\text{H}}(t) \) and the analytic function can be represented as \( (u_k(t) + ju_k^{\text{H}}(t)) \). The frequency spectrum of this function is one sided (exists only for positive frequency) and assumed to be centered on \( \omega_k \). By multiplying this analytical signal with \( e^{-j\omega_k t} \), the signal is frequency translated to be centered at origin, which makes the calculations easier.

\[ u_k^{\text{M}}(t) = (u_k(t) + ju_k^{\text{H}}(t))e^{-j\omega_k t} \]  

(4)

The integral of the square of the time derivative of this frequency translated signal, which gives the variation, is a measure of bandwidth of the Intrinsic mode function \( u_k(t) \).

\[ \Delta \omega_k = \int (\partial_t u_k^{\text{H}}(t))(\partial_t (u_k^{\text{H}}(t)))dt \]  

(5)

where, \( \partial_t (u_k^{\text{H}}(t)) = \partial_t \left[ (\delta(t) + \frac{j}{\pi t}) \ast u_k(t) \right] \)

It is a function whose spectrum is around origin (baseband). Magnitude of time derivative of this function when integrated over time is a measure of bandwidth. This integral operation can also be expressed in terms of norm.

\[ \Delta \omega_k = \left\| \partial_t \left[ (\delta(t) + \frac{j}{\pi t}) \ast u_k(t) \right] \right\|_2 \]  

(6)

The sum of bandwidths of \( K \) modes is given by \( \sum_{k=1}^{K} \Delta \omega_k \). In order to minimize the resulting variational formulation, the constrained objective function is given as,

\[ \min_{u_k, \omega_k} \left\{ \sum_{k} \left\| \partial_t \left[ (\delta(t) + \frac{j}{\pi t}) \ast u_k(t) \right] \right\|_2^2 \right\} \]  

\[ \text{s.t.} \ \sum_{k} u_k = f \]  

(7)
where \( f \) is the original signal, \( u_k \) is the \( k^{th} \) IMF, \( \omega_k \) is the central frequency of \( k^{th} \) mode. By converting constrained problem to unconstrained problem the calculations will be easier. The ADMM method converts this into an unconstrained optimization problem as follows:

\[
L(u_k, w_k, \lambda) = \alpha \sum_k \left[ \left( \left( \delta(t) + \frac{j}{\pi t} \right) \ast u_k(t) \right) e^{-jo_k t} \right]^2 + \left\| f - \sum_k u_k \right\|_2^2 + \left\langle \lambda, f - \sum_k u_k \right\rangle
\]

(8)

In ADMM philosophy, the solutions for one variable at a time assuming all others are known. Here the control parameters are \( \alpha \), the balancing parameter of the data-fidelity constraint, \( \lambda \), lagragian multiplier, \( \tau \), time-step of the dual ascent. The algorithm for VMD is,

1. Initialize \( \hat{u}_{k0}, \hat{w}_{k0}, \hat{\lambda}_0 \), \( n \leftarrow 0 \)
2. Repeat \( n \leftarrow n + 1 \)
3. For \( k=1: K \) do
4. Update \( u_k \) for all \( \omega \geq 0 \)
   \[
   u_{k}^{n+1} \leftarrow \frac{\hat{f} - \sum_{i\neq k} \hat{u}_{k+1}^{n+1} - \sum_{i\neq k} \hat{u}_{i}^{n} + \hat{\lambda}^{n}}{1 + 2\alpha(\omega - \omega_k)^2}
   \]
5. Update \( \omega_k \):
   \[
   \omega_{k}^{n+1} \leftarrow \frac{\int_{0}^{\infty} \omega |\hat{u}_{k}^{n+1}(\omega)|^2 d\omega}{\int_{0}^{\infty} |\hat{u}_{k}^{n+1}(\omega)|^2 d\omega}
   \]

(9)

(10)

3. Results and Discussions

In this section, the validation of proposed methodology is done by using power signals. The signal used in this experiments is defined as:

\[ s = A \sin(2\pi ft) \]

(11)

with \( f = 5Hz \) and \( A = 1 \), illustrated in Fig 2(a) and 2(b). For obtaining the power disturbance we are manually adding few spikes to this signal, illustrated in Fig 2(c) and 2(d). The spiked signal is then given for VMD, the input parameters used are \( \alpha \) (2000), the balancing parameter of the data-fidelity constraint, \( \tau \) (0), time-step of the dual ascent (pick 0 for noise-slack), \( K \), the number of modes to be recovered. It is observed that the information about the original signal is available in one of its modes illustrated in Fig 3, which can be obtained by simple energy calculation of all modes. From Fig 4 it is clear that mode 1 contains the information about the original signal. According to the proposed method the signature of the original signal is preserved from the spectral information of mode 1, illustrated in Fig 5. The comparison between the original and the preserved signal has been carried out and is observed that the error rate between them is very less i.e. 0.014. The proposed method is also compared with Wavelet and Overcomplete Dictionary (OCD) methods and is observed that Wavelet method gives an error rate of 0.063 and OCD method gives an error rate of 0.00004. So the proposed method for single tone signal is observed to be more effective than Wavelet method.
Fig 2. (a), (b) The signal used for the experiment and its spectrum, (c), (d) the transient disturbed signal and its spectrum.

Fig 3. (a), (b) Spiked signal and its spectrum, (c)- (j) all modes of the spiked signal and its spectrum.
Fig 4. Identifying which mode contains the information of original signal and it is observed that mode 1 contains the information.

Fig 5. The result we obtained from the proposed method. (a), (b) the mode which contains the information of original signal and its spectrum, (c), (d) the signature of the original signal by the proposed method and its frequency spectrum, (e)-(f) the original input signal and its spectrum.

The proposed methodology is experimented for multitone signals and it is observed that the information about signal is available in any of its modes, illustrated in Fig 6. The number of modes should be such a way that it should be greater than the number of frequency components taken. And it is also observed that when the number of modes is very high the proposed methodology fails for multitone signal.
4. Conclusion

In this paper, a simple method to detect the impulsive transients or spikes from power signals using VMD itself is proposed. VMD was applied to the power signal, disturbed by impulsive transients. Simple energy calculations were carried out on the resulted modes and it was observed that the highest energy mode contained the original signal information. Using the spectral information of this higher energy mode, the signature of the original signal was effectively preserved for single tone signals. The effect of this method for multitone signals was observed. For multitone signals, when the number of modes increases, the proposed method fails.

References

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