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Application of Hilbert-Huang Transformation for Identifying the Fault Location on Series Compensated Lines

Abstract. *With the study on the transient state of series compensated lines under symmetrical and asymmetrical fault conditions, it's obtained that low frequency component is much larger than aperiodic component of the measured transient current if the fault location is behind the series compensated capacitor. Due to the non-linear volt-ampere characteristics of MOV, the equivalent capacitive of series compensated device changes with time. Hence, the frequency of low frequency component caused by series compensated capacitor is time-varying. Hilbert-Huang Transformation is applied to analyze the instantaneous frequency and amplitude of the low frequency component to identify the fault location. The simulation results prove this method works.*

Streszczenie. *W artykule przedstawiono metodę lokalizacji awarii symetrycznych i niesymetrycznych w układach kompensacji szeregowej. Określono wpływ charakterystyki napięciowo-prądowej łącznika warystorowego na wartość harmonicznych niższego stopnia, wprowadzanych do sieci. Zastosowano transformację Hilbert-Huang w celu analizy chwilowej częstotliwości i amplitudy składowej niskiej częstotliwości oraz określenia miejsca awarii. Wykonano badania symulacyjne. (**Zastosowanie transformacji Hilbert-Huang w określaniu lokalizacji awarii w liniach z kompensatorami szeregowymi**).*

Keywords: compensated lines, low frequency component, MOV, Hilbert-Huang Transformation, identification of fault location
Słowa kluczowe: linie kompensowane, składowa nisko-częstotliwościowa, MOV,

Introduction

There are many advantages to install series compensated capacitor in transmission lines, such as increase the power transmission capability, improve the stability of power system, improve the quality of voltage, achieve reactive power balance and so on [1, 2]. Hence, the application of compensated capacitor is more and more popular.

However, the application of compensated capacitor brings a lot of new questions to relay protection [3]. Firstly, the existence of compensated capacitor destroys the uniformity of the line impedance, even may cause reverse voltage or current, which has negative influence on relay protection. Secondly, Metal Oxide Varistors (MOV) which has non-linear volt-ampere characteristic is used as over voltage protection of compensated capacitor to avoid damage under high voltage when fault happens on transmission line. The non-linear characteristic of MOV makes it difficult to determine the current flow through compensated capacitor when MOV is conductive. It brings great difficult to the study of compensated lines.

Traditional distance protection will overreach for external fault when it's used on compensated lines. Therefore, the Zone 1 should be set including the capacitance reactance which causes the sensitivity of Zone 1 to be greatly reduced. How to eliminate the negative influence of compensated capacitor on distance protection is a question which needs to be fixed for application of compensated capacitor and protection on compensated lines.

In order to improve the operation characteristic of distance protection on compensated lines and ensure sufficient sensitivity, a lot of studies have been carried out by relevant scholars. Distance protection scheme based on the fault location identification has been proposed [4-8]. In this protection scheme, the Zone 1 of distance protection is set according to the whole line impedance, without consideration of capacitance reactance. If the fault happens before compensated capacitor, the measuring impedance can be compared to setting impedance directly. If the fault location is behind compensated capacitor, it's need to compare the setting impedance with the sum of measuring impedance and absolute value of compensated capacitance reactance to judge whether distance protection should trip or not. The sensitivity of distance protection is improved because it is set according to the whole line impedance, without consideration of capacitance reactance. Therefore, the key of this protection scheme is identifying the fault location correctly. Suonan [4] identified the fault location by use of transient data collected before MOV operation to avoid the influence of the non-linear characteristic of MOV. But in condition that severe fault happens, there is only several millisecond before MOV operation, hence this algorithm requires very high sampling rate which is not suitable for practical application. Chen [5] analyzed and compared the characteristics of calculating along line voltage for fault point before and after the compensated capacitor. Based on it, a new algorithm for identifying fault location is proposed. Jayasinghe [6] identified fault location by analyzing characteristics of fault generated high frequency voltage signals. Liu [7] pointed out that the values of wavelet packet entropy are obviously different between fault points located before SSSC and behind SSSC. Hence, the identification criterion of fault position for series compensated lines with SSSC is put forward. Girgis [8] proposed an adaptive protection scheme for advanced series compensated (ASC) lines based on the differences in the transient current signals for faults encountering and not encountering the ASC.

Due to the influence of the nonlinear characteristic of MOV, the transient current measured by protective relay is nonstationary time-frequency signal when fault happens on compensated lines. Traditional Fourier analysis method based on periodic signal model has large error when it's used to analyze this transient current. Although the theory of wavelet transformation has high distinguishability both in time-domain and frequency domain, it can't ensure the best decomposition effect because its basis function is pre-defined and not self-adaptive to the change of signal frequency [9]. Based on the detailed analysis about transient state of compensated line when all kinds of fault happen, the present paper identifies the instantaneous frequency and magnitude of transient current to identify the fault location by application of Hilbert-Huang Transformation. Lots of simulation data verify the validity of this method.

Transient state analysis of compensated line under fault condition

A. Three phase short circuit

As shown in Fig.1, three-phase short circuit happens at point F. The distribution capacitance and conductance to the ground are ignored.

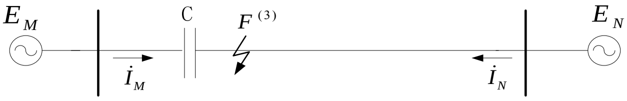


Fig.1 Three-phase fault on series compensated line

For the Protection N, the fault location is before compensated capacitor. The fault circuit can be regarded as series circuit which consists of R and L. The characteristic equation of its differential equation is:

(1) $$Lp + R = 0$$

The eigenvalue is:

(2) $$p = -\frac{R}{L}$$

It means that there is only dc component in transient current measured by Protection N when fault happens before compensated capacitor. The amplitude of this dc component is influenced by angle of line impedance and the happen moment of fault.

For Protection M, the fault location is behind compensated capacitor. The fault circuit can be regarded as series circuit which consists of R, L and C. The characteristic equation of its differential equation is:

(3) $$Lp^2 + Rp + \frac{1}{C} = 0$$

The eigenvalues are:

(4) $$p_{1,2} = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} = -\beta \pm j\omega'$$

In (4), $\beta = \frac{R}{2L}$, $j\omega' = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \approx \sqrt{-\frac{1}{LC}} = j\omega_0$

The absolute value of compensated capacitor reactance is smaller than reactance, so $\omega_0 < \omega$. It means that the transient current measured by Protection N is low frequency component when three phase short circuit happens behind compensated capacitor. The smaller compensation degree, the further fault location and the smaller operation mode of system, the lower the frequency of the low frequency component is.

B. Single phase grounded fault

As shown in Fig.2, single phase grounded fault happens at point F. The distributing capacitance and conductance to the ground are ignored. For the Protection N, the fault location is before compensated capacitor. For Protection M, the fault location is behind compensated capacitor. The transient state under single phase grounded fault is analyzed by application of Laplace transformation. Denotes combination impedance shown in Fig.2 (b) as $Z_1(p)$, $Z_2(p)$ and $Z_0(p)$, then $Z_1(p) = Z_2(p)$.It can be obtained that

(5) $$\dot{I}_{1k}(p) = \dot{I}_{2k}(p) = \dot{I}_{0k}(p) = \frac{\dot{U}_k(p)}{2Z_1(p) + Z_0(p)}$$

Substitute parameters in Fig.2 (b),

(6) $$\dot{I}_{1k}(p) = \frac{Z_{1\Sigma}(p) Z_{0\Sigma}(p) \dot{U}_k(p)}{2A(p)}$$

In (5) and (6),

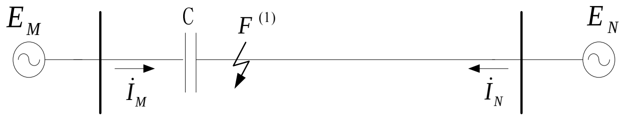
$$Z_1(p) = Z_2(p) = \frac{Z_{1M}(p) Z_{1N}(p)}{Z_{1M}(p) + Z_{1N}(p)}$$

$$Z_0(p) = \frac{Z_{0M}(p) Z_{0N}(p)}{Z_{0M}(p) + Z_{0N}(p)}$$

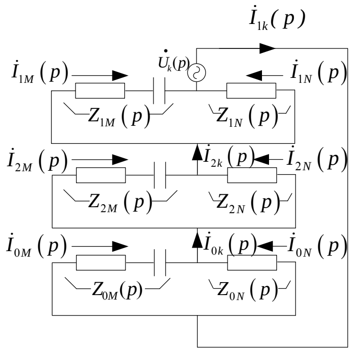
$$A(p) = Z_{0\Sigma}(p) Z_{1M}(p) Z_{1N}(p) + Z_{1\Sigma}(p) Z_{0M}(p) Z_{0N}(p)$$

$$Z_{1\Sigma}(p) = Z_{1M}(p) + Z_{1N}(p)$$

$$Z_{0\Sigma}(p) = Z_{0M}(p) + Z_{0N}(p)$$



(a) single phase grounded fault on series compensated line



(b) diagram of equivalent sequence network

Fig.2 Single phase grounded fault on series compensated line

Sequence currents measured by Protection M are:

(7) $$\left.\begin{aligned} \dot{I}_{1M}(p) = \dot{I}_{2M}(p) &= \frac{Z_{1N}(p)}{Z_{1\Sigma}(p)} \dot{I}_{1k}(p) \\ &= \frac{Z_{1N}(p) Z_{0\Sigma}(p) \dot{U}_k(p)}{2A(p)} \\ \dot{I}_{0M}(p) &= \frac{Z_{0N}(p)}{Z_{0\Sigma}(p)} \dot{I}_{1k}(p) \\ &= \frac{Z_{0N}(p) Z_{1\Sigma}(p) \dot{U}_k(p)}{2A(p)} \end{aligned}\right\}$$

(8) $$\left.\begin{aligned} \dot{I}_{aM}(p) &= \frac{\left[2Z_{1N}(p) Z_{0\Sigma}(p) + Z_{0N}(p) Z_{1\Sigma}(p)\right] \dot{U}_k(p)}{2A(p)} \\ \dot{I}_{bM}(p) &= \frac{\left[Z_{0N}(p) Z_{1\Sigma}(p) - Z_{1N}(p) Z_{0\Sigma}(p)\right] \dot{U}_k(p)}{2A(p)} \\ \dot{I}_{cM}(p) &= \dot{I}_{bM}(p) \end{aligned}\right\}$$

Primitive function of phase currents measured by Protection M can be obtained by application of inverse Laplace transformation.

The expression of phase currents measured by Protection N can be obtained by similar approach.

The denominators of all the current are the same, which means that they have the same characteristic equation. Here, the characteristic equation is five-order, having one real root and two pairs of conjugate complex root. The real root is related to aperiodic component which damps exponentially. Two pairs of conjugate complex root are related to two low frequency components which have damped oscillation. All these components exist at both side of the transmission line, but their amplitudes are very different. The aperiodic component is produced by series circuit of Side N which consists of R and L. And aperiodic component appears in phase A of Side M is because of the existence of mutual inductance. Therefore, the aperiodic component in phase A of Side M is very small. As the same, the low frequency components are produced by series circuit of Side M which consists of R, L and C. The mutual inductance caused by the low frequency components is small. Hence, the low frequency components existing in phase A of Side N is very small, which can be neglected usually.

The distribution of aperiodic component and low frequency components under phase-to-phase fault and phase-to-phase grounded fault is similar with that of single phase grounded fault.

In conclusion, it can be considered that aperiodic component is much larger than low frequency components in transient current measured by protection when fault location is before compensated capacitor. And low frequency components are much larger than aperiodic component when fault location is behind compensated capacitor. This phenomenon can be used to identify the fault location on series compensated lines. In order to take both reliability and sensitivity into account, and consider the influence of calculating error, the criterion identifying the fault location is shown in (9):

$$R_{ld} = \frac{Sum(lf)}{Sum(dc)} \geq 2 \qquad (9)$$

In (9), $Sum(lf)$ represents total value of low frequency components, $Sum(dc)$ represents total value of aperiodic components.

If (9) is satisfied, fault location is behind compensated capacitor. Else, fault location is before compensated capacitor.

Influence of non-linear characteristic of MOV on transient components

Take three phase short circuit as example to analyze the influence of non-linear characteristic of MOV on transient current component. The typical series compensated device is shown in Fig.3.

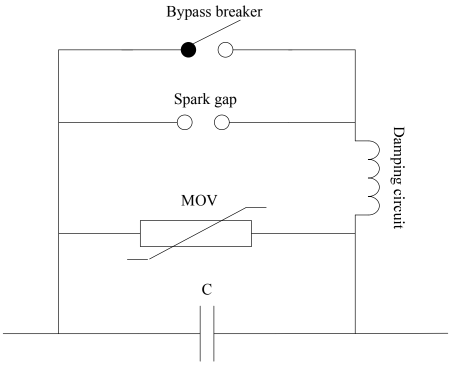


Fig.3 Diagram of typical series compensated device

The MOV shown in Fig.3 has significant non-linear volt-ampere characteristic, as shown in Fig.4.

There is no current through MOV under normal load condition. Hence, the resistance of MOV is considered as infinite. In case that fault happens, if short circuit current make the terminal voltage of MOV exceed its nominal voltage, MOV operates in linear working range. In this condition, MOV appears as a constant resistance, the terminal voltage of MOV will increase with the increase of current. If the terminal voltage of MOV exceeds its nominal voltage to a certain value, the change of voltage will be nonlinear to the current. The resistance of MOV will decrease greatly with the increase of current. The resistance characteristic of MOV in a basic cycle is shown in Fig.5.

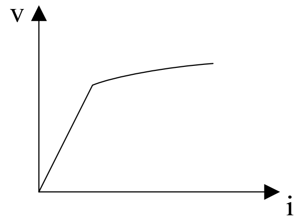


Fig.4 Non-linear volt-ampere characteristics of MOV

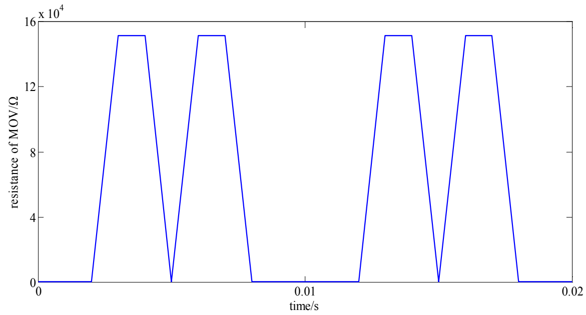


Fig.5 The variation of MOV resistance within a basic cycle

In condition that the bypass breaker and spark gap don't trip, the equivalent impedance of compensated device Z_{eq} is:

$$Z_{eq} = \frac{R_{MOV}\left(1 - j\omega C \cdot R_{MOV}\right)}{1 + \left(\omega C \cdot R_{MOV}\right)^2} \qquad (10)$$

The equivalent capacitive reactance X_{Ceq} is:

$$X_{Ceq} = 1 \Big/ \left(\frac{1}{\omega C \cdot R_{MOV}{}^2} + \omega C \right) \qquad (11)$$

In (10) and (11), R_{MOV} is the resistance of MOV.

It's obtained from (11) that the equivalent capacitive reactance X_{Ceq} decreases with the decrease of resistance R. As the resistance of MOV is time-varying, the equivalent capacitive reactance X_{Ceq} changes in a basic cycle. Therefore, frequency of the low frequency current component which appears in fault transient state is also time-varying. This time-varying frequency is called "instantaneous frequency".

In traditional Fourier analysis, frequency spectrum is defined as sine or cosine function with constant amplitude on the whole signal range. If this definition is extended, the instantaneous frequency should also be sine or cosine function which means instantaneous frequency should be defined by a period of sine or cosine function. But this definition is meaningless to nonstationary time-frequency signal. Hence, traditional Fourier analysis is not suitable for analysis of nonstationary time-frequency signal with instantaneous frequency.

Hilbert-Huang Transformation

In order to overcome the limitations of Fourier analysis, N.E.Huang and others proposed a new principle of signal analysis—Hilbert-Huang Transformation [10]. Hilbert-Huang transformation consists of EMD (Empirical Mode Decomposition) and Hilbert transformation. The original signal is decomposed as sum of IMFs (intrinsic mode function, IMF) by EMD. Meaningful instantaneous frequency can be obtained by applying Hilbert transformation to each IMF to give accurate expression of the change of frequency along with the time variation. Hilbert-Huang transformation is a self-adaptive time-frequency analysis method. It can do time-frequency decomposition according to the regional time-varying characteristic of signal to overcome the defect that traditional analysis method present nonstationary, non-linear signal as meaningless harmonic.

EMD is based on the following three hypothesis:(1) there is more than one maximum point and minimum point, (2) characteristic time scale is defined according to time variation between extreme points, (3) if there are only inflection points but no extreme point, differentiation can be applied to find the extreme points, and final results can be obtained by integration of components.

The concrete steps of EMD are: for any real signal $s(t)$, find all maximum points and minimum points of $s(t)$ firstly. Then, connect all the maximum points and minimum points by a smooth curve respectively. Considering these two curves as upper envelope and lower envelope of $s(t)$, calculate their mean curve $m_1(t)$. Subtract $s(t)$ with $m_1(t)$ to obtain $h_1(t)$.

(12) $$s(t)-m_1(t)=h_1(t)$$

Ideally, $h_1(t)$ should be an IMF, because $h_1(t)$ is constructed to satisfy the requirements of IMF. But even though the fitting of envelopes is very well, the small convex hull on slope of signal will become to be new extreme point during sifting. These new extreme points are left out in previous sifting. Therefore, it is need to carry out sifting again and again to recover all superimposed wave with small amplitude.

Considering $h_1(t)$ as original signal to repeat above-mentioned steps, it's obtained that,

(13) $$h_1(t)-m_{1,1}(t)=h_{1,1}(t)$$

Carry out sifting for *k* times until $h_{1,k}(t)$ becomes to be an IMF, that is

(14) $$h_{1,k-1}(t)-m_{1,k}(t)=h_{1,k}(t)$$

Then one IMF is decomposed from the original signal, called first-order IMF. Denote it as

(15) $$c_1(t)=h_{1,k}(t)$$

In order to ensure that the IMF has enough physical significance both on its amplitude and frequency, it is needed to limit the sifting times.

Huang and others proposed two termination criteria. The first one is that when

(16) $$SD=\sum_{t=0}^{T}\left[\frac{\left|h_{1,k-1}(t)-h_{1,k}(t)\right|^2}{\left|h_{1,k-1}(t)\right|^2}\right]$$

between 0.2 and 0.3, the sifting is terminated. The second one is sifting should be terminated when extreme points are equal to zero crossing point.

Generally speaking, $c_1(t)$ should contain the component with smallest period in original signal. Subtract original signal with $c_1(t)$ to obtain the first-order residual signal.

(17) $$s(t)-c_1(t)=r_1(t)$$

The first-order residual signal contains components with larger period, so it's need to consider the $r_1(t)$ as new original signal to repeat the abovementioned steps to obtain second-order,…,N-order residual signal.

(18) $$\left.\begin{aligned} &r_1(t)-c_2(t)=r_2(t)\\ &\dots\\ &r_{N-1}(t)-c_N(t)=r_N(t)\end{aligned}\right\}$$

The whole decomposition should be terminated if one of the following criteria is satisfied: (1) component $c_N(t)$ or $r_N(t)$ is small enough, (2) the residual signal $r_N(t)$ becomes to be a monotonic function.

Synthesizing above all, it can be obtained that:

(19) $$s(t)=\sum_{n=1}^{N}c_n(t)+r_N(t)$$

Then do Hilbert transformation for each IMF to obtain that

(20) $$c_n'(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{c_n(\tau)}{t-\tau}d\tau$$

Construct analytic signal $z_n(t)$ as:

(21) $$z_n(t)=c_n(t)+jc_n'(t)=a_n(t)e^{j\phi_n(t)}$$

In (21),

$$a_n(t)=\sqrt{c_n^2(t)+c_n'^2(t)},\quad \phi_n(t)=\arctan\frac{c_n'(t)}{c_n(t)}$$

The instantaneous frequency $\omega_n(t)$ is

(22) $$\omega_n(t)=\frac{d\phi_n(t)}{dt}$$

The instantaneous frequency expression of signal is shown in (23).

(23) $$s(t)=\mathrm{Re}\sum_{n=1}^{N}a_n(t)e^{j\phi_n(t)}=\mathrm{Re}\sum_{n=1}^{N}a_n(t)e^{j\int\omega_n(t)dt}$$

Here, residual signal $r(t)$ is neglected. Denotation 'Re' means taking real part. The distribution of amplitude and frequency along with time variation can be obtained with (23), called Hilbert spectrum. The Hilbert spectrum is denoted as:

(24) $$H(\omega,t)=\sum_{n=1}^{N}a_n(t)e^{j\int\omega_n(t)dt}$$

Marginal spectrum is defined as:

(25) $$h(\omega)=\int_{-\infty}^{+\infty}H(\omega,t)dt$$

Marginal spectrum reflects the contribution of each component with different frequency to amplitude on the whole signal range.

Application of Hilbert-Huang Transformation for identifying the fault location on series compensated line

Fig.6 shows the typical diagram of series compensated line with two sources. The length of whole line is 200km, positive-sequence impedance is Z_1=8.04+j60.62 Ω, and zero-sequence impedance is Z_0=38.66+j181.86 Ω. The compensated device locate at Side N, the compensated degree is 48%.

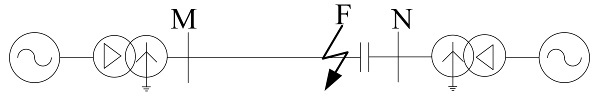
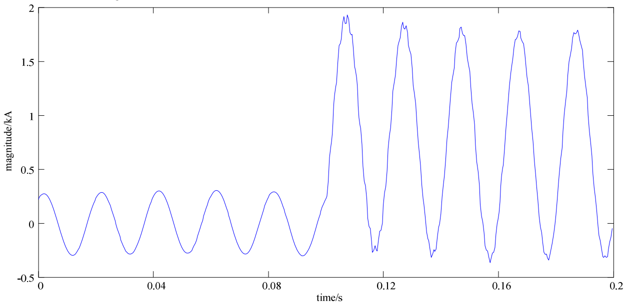
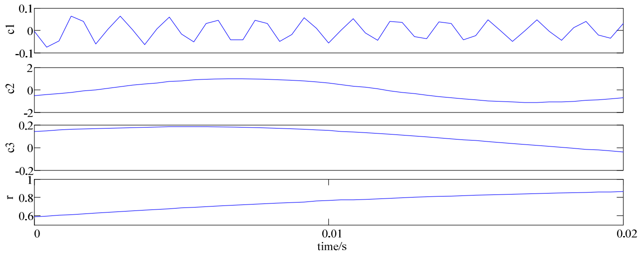


Fig.6 Simulation model of series compensated line

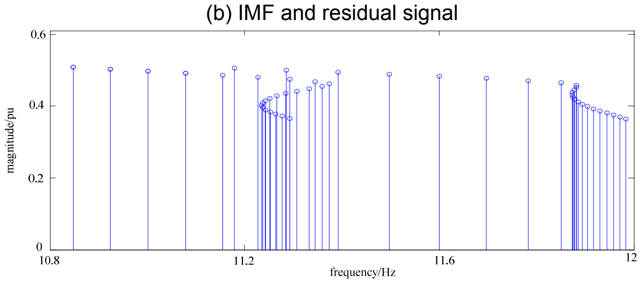
When phase A is grounded at point F located at end of line, the fault current of Phase A measured by protection of both Bus M and Bus N and the relevant Hilbert-Huang Transformation results are shown in Fig.7 and Fig.8 respectively.



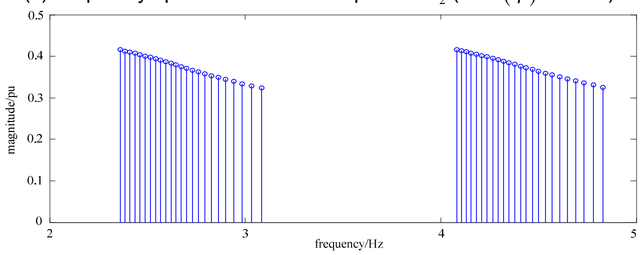
(a) measured fault current of Phase A



(b) IMF and residual signal

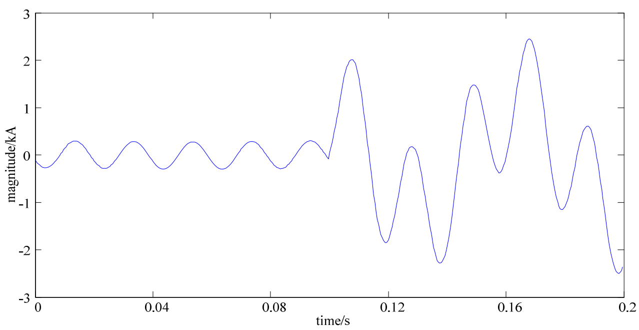


(c) frequency spectrum of IMF component c_2 ($Sum(lf)$ =13.99)

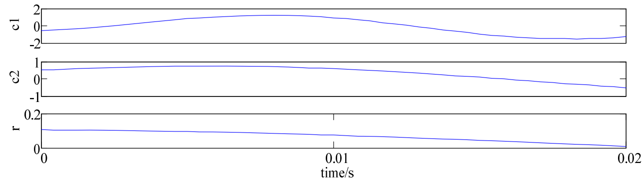


(d) frequency spectrum of residual signal r ($Sum(dc)$ =21.53)

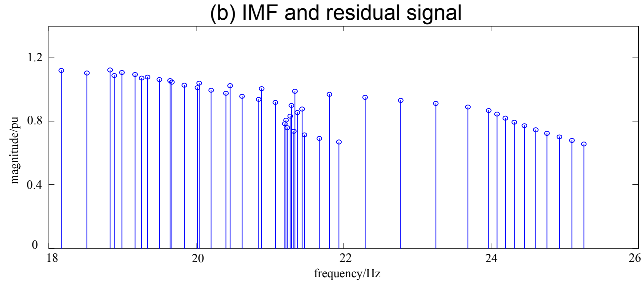
Fig.7 Hilbert-Huang Transformation of A phase current measured by protection of Bus M



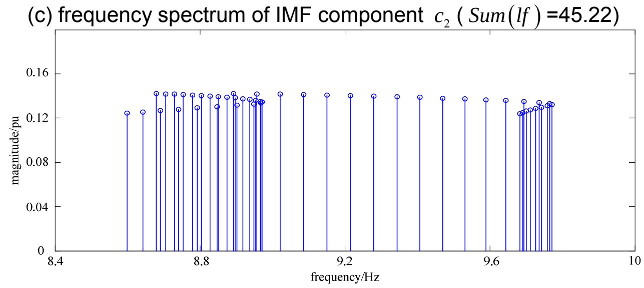
(a) measured fault current of Phase A



(b) IMF and residual signal



(c) frequency spectrum of IMF component c_2 ($Sum(lf)$ =45.22)



(d) frequency spectrum of residual signal r ($Sum(dc)$ =5.15)

Fig.8 Hilbert-Huang Transformation of A phase current measured by protection of Bus N

In Fig.7 and Fig.8, IMF component c_3 of the Phase A current measured by Protection M and IMF component c_2 of the Phase A current measured by Protection N are low frequency components. Residual signal of the Phase A current measured by Protection M and Protection N contain both aperiodic component and low frequency components. The reason is that decomposition is terminated because there is no extreme point in residual signal r. But the criterion in (9) has large margin, it still can identify fault location correctively.

Tables 1,2,3 show Hilbert-Huang transformation results of fault current when Phase A grounded fault, Phase A grounded fault with transition resistance(100Ω) and three phase fault happen at end, middle and headend of transmission line respectively.

Table 1 Hilbert-Huang Transformation results when faults happen at the end of line

Fault type	Protection M			Protection N		
	$Sum(lf)$	$Sum(dc)$	R_{ld}	$Sum(lf)$	$Sum(dc)$	R_{ld}
Ag (0Ω)	13.99	21.53	0.65	45.22	7.00	6.46
Ag (100Ω)	1.93	9.82	0.20	18.21	2.75	6.62
ABC	14.35	35.59	0.40	40.58	5.57	7.29

Table 2 Hilbert-Huang Transformation results when faults happen at the middle of line

Fault type	Protection M			Protection N		
	$Sum(lf)$	$Sum(dc)$	R_{ld}	$Sum(lf)$	$Sum(dc)$	R_{ld}
Ag (0Ω)	23.17	24.41	0.95	35.30	5.15	6.85
Ag (100Ω)	2.58	10.83	0.24	14.73	1.93	7.63
ABC	11.32	33.39	0.34	31.94	11.48	2.78

Table 3 Hilbert-Huang Transformation results when faults happen at the start of line

Fault type	Protection M			Protection N		
	$Sum(lf)$	$Sum(dc)$	R_{ld}	$Sum(lf)$	$Sum(dc)$	R_{ld}
Ag (0Ω)	25.34	40.53	0.63	24.31	9.65	2.52
Ag (100Ω)	3.46	13.13	0.26	12.28	1.38	8.90
ABC	24.45	55.96	0.44	26.41	10.38	2.54

It can be obtained from the three tables that if the fault happens before compensated capacitor, the ratio of total value of low frequency components and total value of aperiodic components, which is represented by R_{ld}, is lower than 1. And if the fault location is after compensated capacitor, R_{ld} is bigger than 2. It means that wherever the fault happens, the proposed criterion which is express in (9) can identify fault location correctively. And it has great tolerance of transition resistance.

Conclusions

The present paper analyzes the transient state of series compensated transmission line under all kinds of fault by application of Laplace operation method. It can be considered that aperiodic component is much larger than low frequency components in transient current measured by protection when fault location is before compensated capacitor, and low frequency components is much larger than aperiodic component when fault location is behind compensated capacitor. Therefore, paper proposes a criterion based on ratio of total value of low frequency components and total value of aperiodic components.

Due to the influence of non-linear volt-ampere characteristic of MOV, the equivalent capacitive reactance X_{Ceq} is time-varying. Therefore, frequency of the low frequency current component which appears in fault transient state is also time-varying. Traditional Fourier analysis is not suitable for analysis of transient fault current appears when fault happens on series compensated line. The present paper identifies the instantaneous frequency and amplitude of transient current to identify the fault location by application of Hilbert-Huang Transformation. Lots of simulation data indicate that this method can identify fault location correctly. And it has great tolerance of transition resistance.

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