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전력계통의 고임피던스 고장으로부터 혼돈 특성 추출에 관한 연구

A Study on Extracting Chaotic Properties from High Impedance Faults in Power Systems

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ABSTRACT

Previous studies on high impedance faults assumed that the erratic behavior of fault current would be random. In this paper, we prove that the nature of the high impedance faults is indeed a deterministic chaos, not a random motion. Algorithms for estimating Lyapunov spectrum and the largest Lyapunov exponent are applied to various fault currents in order to evaluate the orbital instability peculiar to deterministic chaos dynamically, and fractal dimensions of fault currents, which represent geometrical self-similarity are calculated. In addition, qualitative analysis such as phase planes, Poincare maps obtained from fault currents indicate that the irregular behavior is described by strange attractor.

1. Introduction

High impedance faults(HIF) can be described as those faults which do not draw sufficient fault current to be recognized and cleared by the overcurrent devices in common use in the utility industry. Since these faults behavior are affected by the surface conditions, duration of arcing, so reveal unsteady non-periodic oscillation, asymmetrical shape of waveforms.

Numerous detection methods[7-12] have been suggested for such fault detection, but there is no perfect solution to solve it. In recent years, a fractal geometry [15] has been applied to current of HIF, however, many problems remain in applying only a dimensional analysis, such as the decision of the delay time and the scaling region necessary for the reliable correlation integral.

In this paper, these irregular dynamics are analyzed by chaotic analysis in order to prove the existence of a certain degree of low dimensional chaos in HIF. Not only phase plane and Poincare map are implemented but also quantification of chaos is presented by estimation of Lyapunov spectrum, the largest Lyapunov exponent, correlation dimension.

As a result, the largest Lyapunov exponents of the fault currents are estimated to be positive that by definition are the most striking evidence for chaos. In addition non-integer correlation dimensions, strangeness in phase plane and Poincare map indicate that chaotic properties really existed in HIF.

The organization of this paper is as follows. In section 2, HIF currents and state reconstruction by delay embedding method are presented in the framework of chaotic analysis. The qualitative and quantitative analysis are applied to HIF currents in section 3 and 4. Conclusions of the paper are summarized in section 5.

2. HIF current & State reconstruction

The fault currents are measured from three-phase four-wire multi-grounded distribution line at Gochang, Korea, in 1997. Faults data are quantized and sampled with a sampling time 100 [μ sec] and summarized as below.

- Data sampling time : 100 [μ sec]
- Number of samples : 10,000
- Data bit : 12 bit
- Data channel :
  7 channel (V_a, V_b, V_c, I_a, I_b, I_c, I_N)
- Faults on sidewalk, sandy soil, gravelly place, automobile

Various faults, which have different contacted objects,

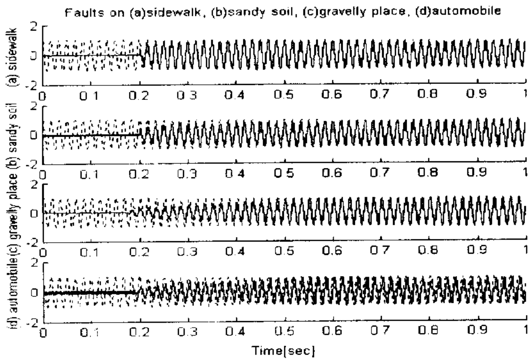

Fig. 1. Current and voltage waveforms of HIF

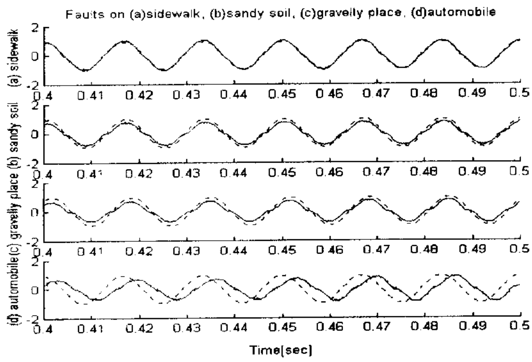

Fig. 2. Current and voltage waveforms of HIF ($t \in [0.4, 0.5]$)

are shown by Fig. 1 and Fig. 2.

In these Fig, dashed lines are voltage waveforms, and solid lines are faults current waveforms.

From Fig. 1, we choose only $t \in [0.45, 0.5]$, and present Fig. 2.

The faults behavior, Fig. 2, are affected by the surface conditions, and are characterized by unsymmetrical half cycles, unsteady change of magnitudes, irregular oscillations.

Because the data of HIF are single variable time-series (that is voltages and currents of each phase), we applied an embedding method proposed by Takens[5], in order to reconstruct phase plane. The embedding refer to the process by which a representation of the attractor can be reconstructed from a set of scalar time series. The form of such reconstructed states is given as follows.

$$X_i = [x(t),\ x(t+\tau),\ \cdots,\ x(t+(m-1)\tau)] \qquad (1)$$

where $x(t)$ is an fault current, τ is a delay time, and m is an embedding dimension. It is a key factor to choose

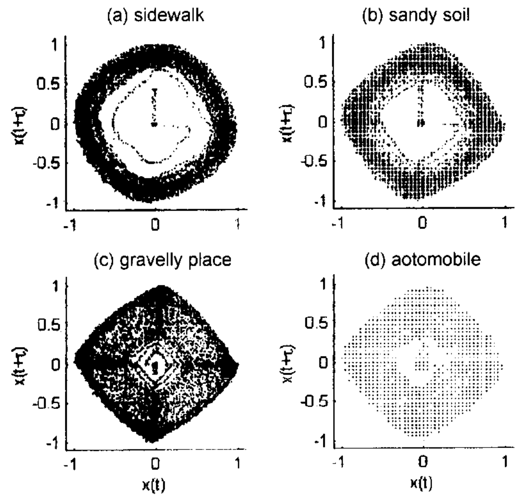

Fig. 3. Phase plane of HIF current waveforms

the delay time and embedding dimension, so we choose τ is 42 using an auto-correlation time and sample interval between Poincare section. Embedding dimension is chosen 3 because nearest false neighbour disappears in that dimension.

3. Qualitative Analysis

With reconstructed states, the qualitative chaotic degree of HIF currents is analyzed in this section using embedding phase planes and Poincare maps.

We reconstruct the orbit of the attractor from HIF current with the embedding dimension m = 3, the delay time $\tau = 42$. and the number of states N=10,000

Fig. 3 shows phase plane of these embedding states which are originally fault currents when distributed line is grounded on (a)sidewalk, (b)sandy soil, (c)gravelly place, and (d)automobile.

As a result, orbits, which never exactly repeat like periodic motions, and tend to fill up a certain section of the phase space, have fine structures like chaotic strange attractors.

Poincare map is an sampling process which chooses an m-1 dimensional hyper-plane and records only the states which intersect this plane. The results of Poincare maps are shown in Figures 4 and 5 with choosing different hyper plane.(Fig. 4 : perpendicular to x-axis, Fig. 5 : mean plane)

Results show Poincare maps do not consist of either a finite set of points(periodic motion) nor a closed orbit(quasi periodic or torus) but have some

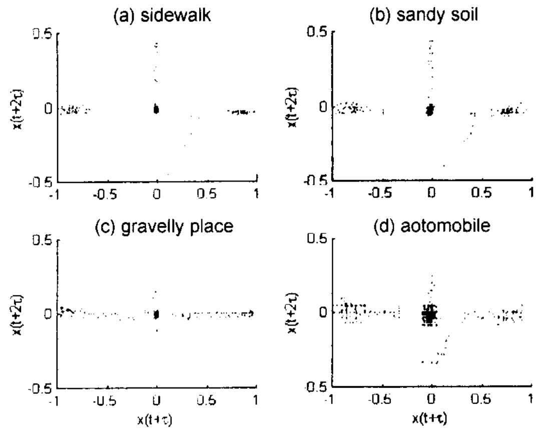

Fig. 4. Poincare map of HIF current waveforms (perpendicular to x-axis)

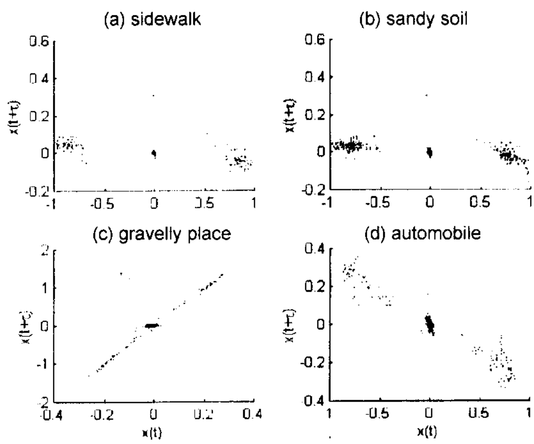

Fig. 5. Poincare map of HIF current waveforms (mean-plane)

characteristic organization, so behavior is chaotic.

4. Quantitative Analysis

Quantifying chaos with Lyapunov exponents(a measure of the divergence of nearby trajectories, which is a positive number for chaotic systems), and correlation dimension(non-integer for chaotic systems) is presented in this section, because it is unreliable to prove chaotic properties only with qualitative analysis.

These quantifiers may help distinguish chaotic behavior from noisy behavior and determine how many variables are needed to model the dynamics of the HIF.

Firstly, we evaluate Lyapunov spectrum with method proposed by Eckmann and Ruelle[3], and represent the result in Fig. 6 and Table 1.

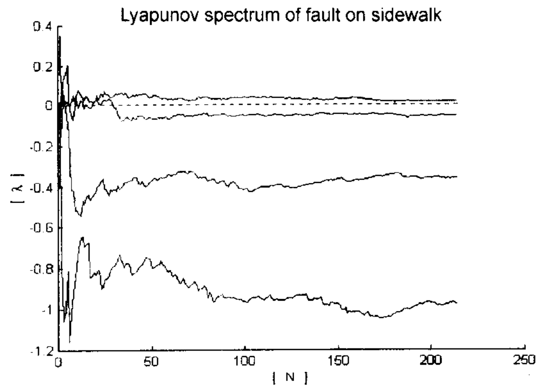

Fig. 6. Lyapunov spectrum of fault on sidewalk

Table 1. The relationship between the reconstructed dimensions and the largest Lyapunov exponent (Fault on sidewalk)

reconstructed dimension	largest Lyapunov exponent
2	-0.03152
3	-0.00841
4	0.023442
5	0.035108
6	0.066879
7	0.075614
8	0.172473
9	0.191109
10	0.310261

The reliability on estimated values of Lyapunov spectrum is confirmed in Fig. 6, which shows convergence characteristics except the smallest Lyapunov exponent.

However, with a careful interpretation on the results of the relation between the embedding dimensions and the largest Lyapunov exponent presented in Tabel 1, we can extract the following relation.

$$\lambda_{\max} \propto m \tag{2}$$

Such a dependence of $\lambda_{\max}$ on m could be one of the warnings that applied algorithm does not work well. So, we abandon these results and apply a robust method that embeddings are only used to distinguish between false and true neighbours, proposed by Kantz[2] to estimate the largest Lyapunov exponent.

This algorithm evaluates the following eq.

$$S(\tau) = \frac{1}{N}\sum_{t=1}^{N} \ln\left(\frac{1}{|u_t|}\sum_{t \in u_t} dist(X_t,\ X_i;\tau)\right) \tag{3}$$

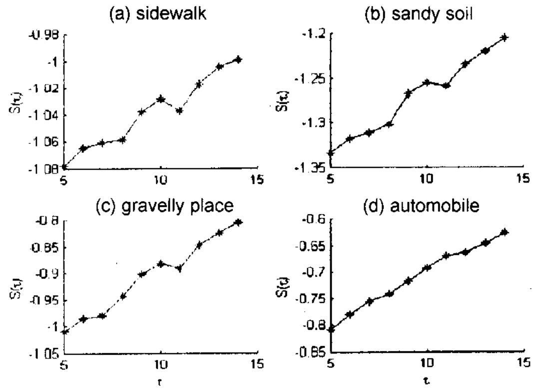

Fig. 7. Direct estimation of largest Lyapunov exponents for fault currents
[Faults on (a)sidewalk, (b)sandy soil, (c)gravelly place, (d)automobile]

Table 2. Largest Lyapunov exponents of HIF currents

Fault on	λ_{max}
sidewalk	0.0086
sandy soil	0.0143
gravelly place	0.0231
automobile	0.0199

where N is the number of reconstructed state, X_t is a reference point, X_i is an ε-near neighbor of $X_t(u_t)$, and τ is the relative time.

The largest exponent is estimated the slope of the curve τ vs. $S(\tau)$, and Fig. 7 shows this relation and the estimated values(largest Lyapunov exponent in HIF currents) is represented as Table 2.

The correlation dimension is derived from correlation sum which defined as follow.

$$C^m(r) = \lim_{N\to\infty} \frac{1}{N^2} \sum_{i,j=1}^{N} H(r-|X_i - X_j|) \quad (4)$$

Here, N is the number of state, r is the radius and H(τ) is a heavy-side function of parameter τ is normally defined as

$$H(\tau) = \begin{pmatrix} 1(\tau \geq 0) \\ 0(\tau < 0) \end{pmatrix} \quad (5)$$

Using Eq (4), correlation dimension is evaluated as the slope of Fig. 8. Table 3 shows correlation dimensions of fault currents under various surface condition.

Chaotic behavior of HIF currents are summarized as follows.

- Largest Lyapunov exponent : all HIF currents have positive Lyapunov exponent which by definition are the most striking evidence for chaos.
- Correlation dimension : all non-integer values which show self-smilarity.

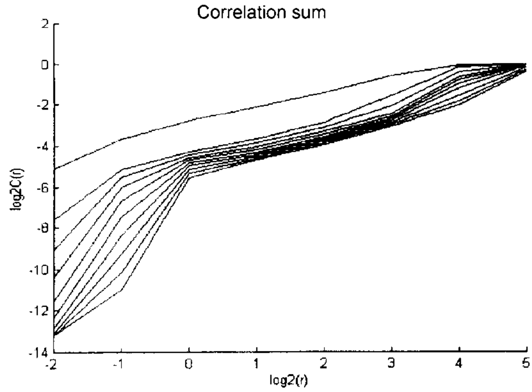

Fig. 8. Correlation summation calculated from HIF current (Fault on sandy soil)

Table 3. Correlation dimensions of HIF currents

Fault on	Correlation dimension
(a) sidewalk	0.9874
(b) sandy soil	0.9936
(c) gravelly place	1.0146
(d) automobile	0.9987

5. Conclusion

We estimate Lyapunov exponent, and correlation dimension of various fault currents in order to prove the existence of a certain degree of deterministic chaos in HIF. As a result, the largest Lyapunov exponents of the fault currents are estimated to be positive that by definition are the most striking evidence for chaos and non-integer correlation dimensions represent that fault currents of HIF have self-similarities.

In addition, we confirm that characteristics of chaos in HIF using time-series, phase plane and Poincare map.

These results show that irregular dynamics of HIF really have a certain degree of low dimensionai chaotic properties.

An algorithm which uses these properties is expected for detecting HIF in power system effectively.

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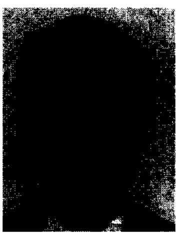

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