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Loss of Field Protection of Synchronous Generator Using SVM

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Abstract

The paper deals with the analysis of synchronous generator protection for loss of field condition. The effect of loss of field on the generator and on the system is investigated. The proposed scheme provides the loss of field protection of generator based on simple measurements at the generator terminals instead of direct detection of loss of field. To this end generator terminal quantities are used. For feature extraction discrete wavelet transform (DWT) is applied to the obtained signals. Wavelet energy and wavelet entropy of generator terminal voltage, current, active power output and reactive power output are used as features for loss of field detection. Thereafter, support vector machine (SVM) is used for the classification of loss of field. The investigations suggests that SVM based technique is robust and capable of maintaining its performance under different loading conditions. For obtaining test signal for loss of field a power system model consisting of generator is simulated in PSCAD. The test signals are obtained for varied operating conditions of generator.

Keywords. Loss of Field, Discrete Wavelet Transform, Wavelet Energy, Wavelet Entropy, Support vector machine.

1. Introduction

Loss of field (LOF) in synchronous generator occurs due to different abnormal conditions such as inadvertent opening of field breaker, short circuit or open circuit of field winding and failure of voltage regulator system. This causes synchronous generator to operate asynchronously as an induction generator, with 2% to 5% slip. After this the reactive power required for excitation is absorbed from the power system thereby leading to severe decline in the terminal voltage [1, 2]. The active power output is also decreased due to reduction in internal voltage, creating an imbalance between mechanical power and electric power which leads to loss of synchronism [3].

Generally, for the protection of generator during LOF, offset mho relay is used which measures the terminal impedance using terminal voltage and current. The diameter of mho circle is equal to X_d and negative offset is of $-X'_d/2$[4, 5]. The directional over current relay has been also used which detect LOF by measuring the phase angle between voltage and current [6]. Another approach has been proposed in [7] based on magnetic flux linkage in the air gap. Work in [8] presents LOF detection using decision tree technique. Besides, a scheme using fuzzy set theory is presented in [9]. In [10] LOF detection using artificial neural network is presented.

2.LOF Fundamentals

When the field is lost, due to highly inductive nature of the field circuit the rotor current doesn't become zero instantly rather, it decays at a rate determined by the time constant of the field circuit [3]. The internal voltage decays at the same rate. Thus, the reactive power output of generator decreases and becomes zero after sometime and becomes negative thereafter. The synchronous generator which was initially delivering reactive power starts absorbing it from the system after LOF. This produces a dip in the terminal voltage. As the active power output of generator is proportional to internal voltage, system voltage and sine of load angle, it also gets reduced. With the reduction in active power output, the load angle increases in order to balance the mechanical power input and can increase up to 90 degree. After this the electric power will be less than mechanical power and the generator will lose synchronism [2, 3]. Therefore the generator will run at speed above synchronous speed, as an induction generator, with 2% to 5% slip.

3.Wavelet transform

Wavelet transform is a multi-resolution decomposition fast algorithm which uses the orthogonal wavelet bases to decompose the signal under different scale to components. It is equivalent to recursive filtering of the signal with a low-pass and a high-pass filter. Also wavelet transform has excellent time frquency localisation.When wavelet transform is applied to a discrete signal x(n), it has a low frequency component $A_j(k)$ and a high frequency component $D_j(k)$ at scale j and instant k. the frequency band of information contained in signal component $D_j(k)$ and $A_j(k)$ obtained by reconstruction are as follows

$$D_j(k) : \left[2^{-(j+1)}f_s, 2^{-j}f_s\right]. \quad (1)$$

$$A_j(k) : \left[0, 2^{-(j+1)}f_s\right]. \quad (2)$$

Where $f_s$is sampling frequency

All the components obtained can be added to obtain the original signal x(n)

$$x(n) = D_1(n) + A_1(n) = D_1(n) + [D_2(n) + A_2(n)] = \cdots.$$

$$x(n) = \sum_{j=1}^{J} D_j(n) + A_j(n). \quad (3)$$

For identity replace $A_j(n)$ by $D_{j+1}(n)$ to obtain

$$x(n) = \sum_{j=1}^{J+1} D_j(n). \quad (4)$$

Wavelet energy. wavelet energy is given as sum of square of wavelet transform coefficient. The energy of the coefficients is varrying over different scales depending on the input signal. Wavelet energy of a signal at scale j is given as

$$E_j = \sum_{k=1}^{N} \left|D_j(k)\right|^2. \quad (5)$$

Total energy can be given as

$$E_{tot} = \sum_{j=1}^{J} E_j. \quad (6)$$

Then the normalised values which represent thewavelet energy is

$$p_j = \frac{E_j}{E_{tot}}. \quad (7)$$

Wavelet Entropy: Entropy is the measurement of degree of disorder of signal. It provides useful information about the underlying dynamic process associated with the signal. Entropy defined by shannon can be given as

$$WE = \sum_{j=1}^{J} p_j \ln p_j. \quad (8)$$

4. Supprt Vector Machine(SVM)

SVM is a supervised machine learning method employed for regression and classification analysis. In this paper it is used for classification purpose. A two class prblem is presented for classification. The aim of SVM is to build a model using training set which contains one target and various features[13]. A hyperplane is selected which can best separate two classes. Using this model target value of tesing set is predicted. The hyperplane is given by the Eq. (9).

$$f(x) = w.x + b \quad (9)$$

Where b is bias and w is the normal vector to the hyperplane

5. Simulation Studies

Simulation model. A simplified power system model consisting of generators, transformers, transmission line is modeled in PSCAD to investigate LOF faults. The simulation model includes two salient pole generators (G1 & G2) which are connected to a common bus via a 20kV/230kV Δ/Y step up transformer. The common bus bar is connected to the load bus through 50 km transmission line. Thereafter, the load bus is connected to infinite bus bar via 50 km transmission line. *Fig.1* shows the one line diagram of the simulated system for investigation of LOE. The generator model comprises a synchronous generator, exciter, hydro turbine and governor. The exciter incorporated in the model is a static exciter which is standard IEEE AC1A.

Simulation Cases. Loss of field condition is simulated in generator1 (G1) at time t=3sec while G2 is in healthy operating state. The power factor is taken as 0.9 lagging. The seriousness of the loss of field fault depends on the initial loading of generator. Thus three loading conditions of the generators, i.e., 40%, 60% and 80%, are taken into consideration.

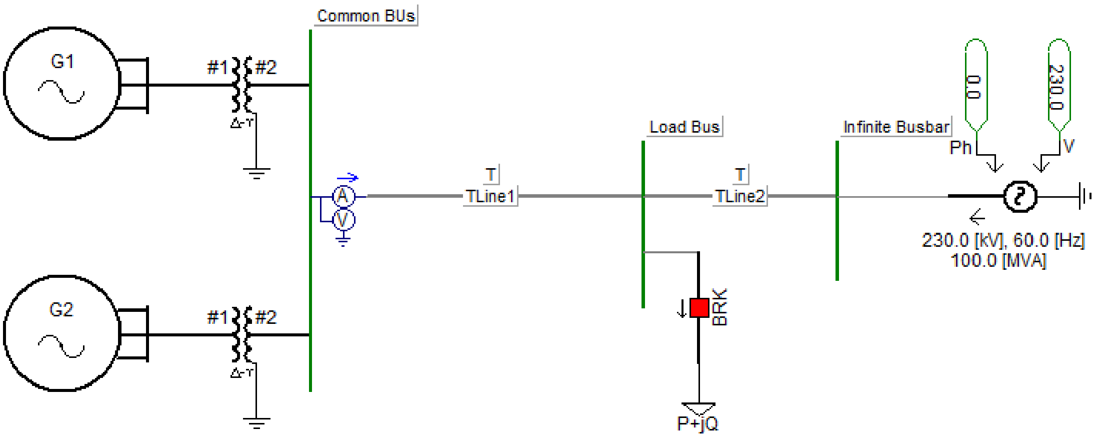


Fig.1. Single line diagram of the simulated model in PSCAD

Simulation Results: After occurrence of LOF at time t=3sec, the reactive power output of generator start decreasing at a steady rate from 0.34 p. u. to zero after one second and goes up to 0.9 p. u. in negative direction. After loss of synchronism it starts oscillating around 0.9 p. u. with a deviation of 0.2 p. u. (*Fig.2 (a)*). Thus the generator starts absorbing reactive power from the system. This leads to dip in terminal voltage from 1.01 p. u. to 0.54 p. u. and oscillate around 0.6 p. u. after loss of synchronism (*Fig2. (b)*). There is not a very large change in the active power output initially after loss of field which is around 0.72 p. u., but after loss of synchronism it suddenly reduces to 0.24 p. u. and oscillates around 0.28 p. u. (*Fig.2 (a)*). The load angle also increases (*Fig.2 (d)*). After 90^o there is a loss of magnetic coupling between stator and rotor field which leads to loss of synchronism.

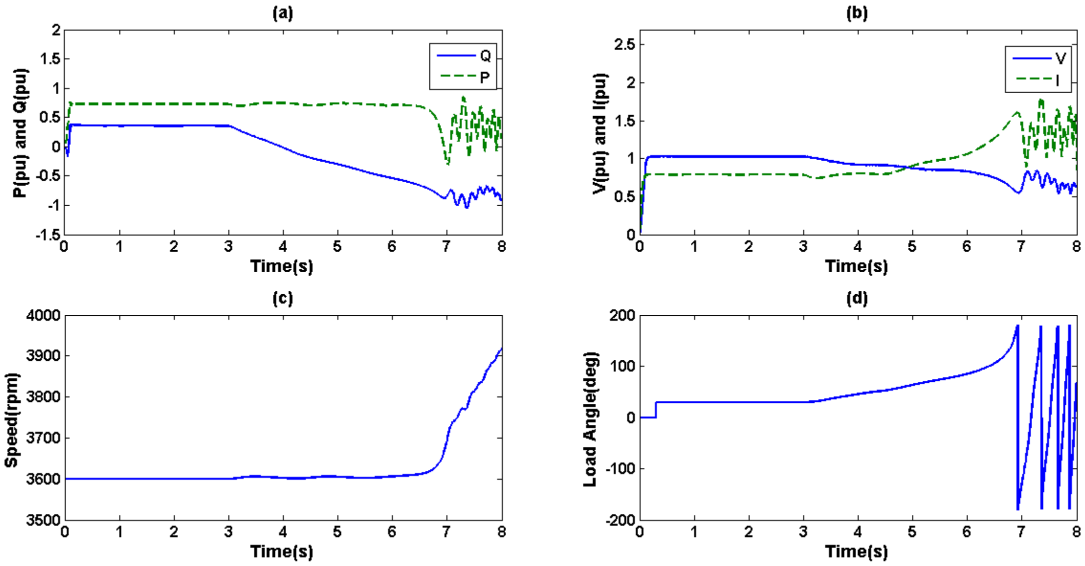
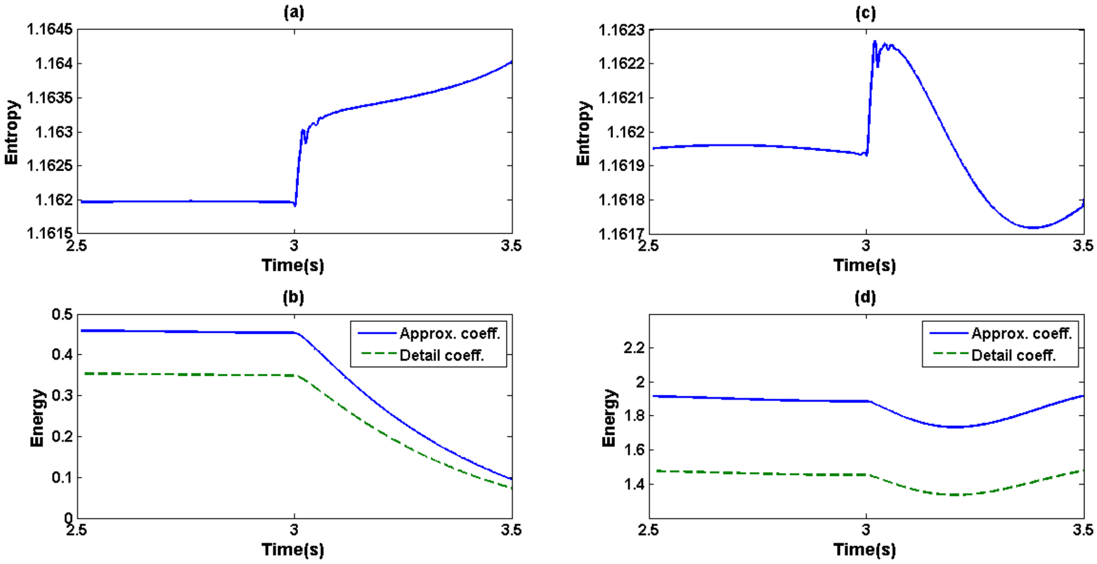


Fig. 2. Generator characteristic during LOF.(a) reactive and active power output, (b) terminal current and voltage(rms), (c) speed(rpm), (d) load angle(deg)

Feature Extraction. For feature extraction discrete wavelet transform is applied to the obtained terminal signals. Mother wavelet used is daubechies4 (db4) due to its suitability for analysis of power signals. Each signal is decomposed up to level 5. The sampling frequency used for the operation is 1 kHz. Thereafter, wavelet entropy and wavelet energy is calculated using Eq.8 and Eq.5 respectively, and are used as features for classification of LOF.



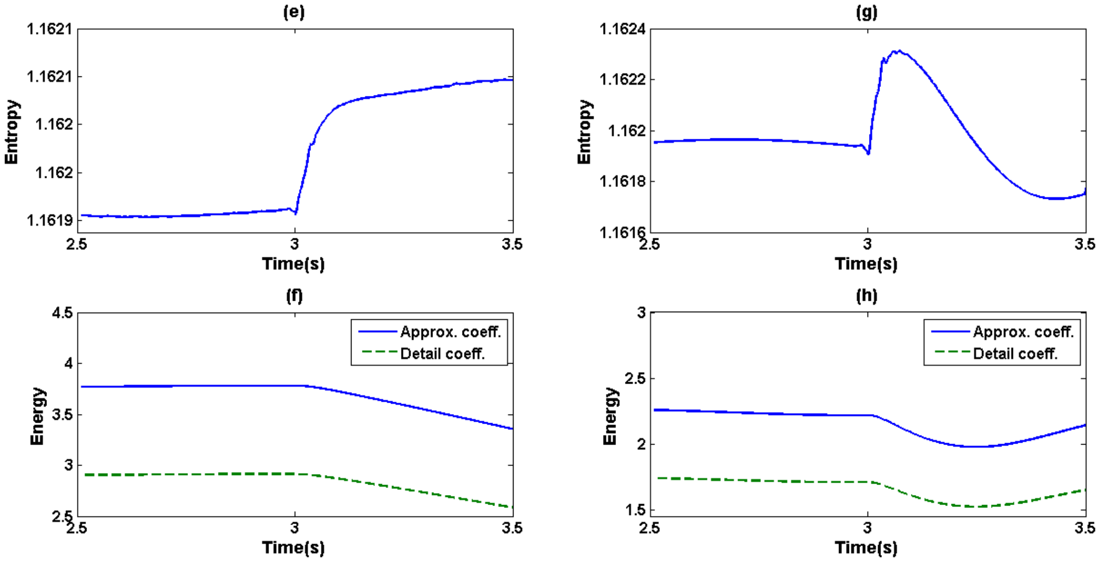


Fig. 3. Features extracted. (a),(c),(e),(g)-Wavelet entropy of Q, P, V, I. (b),(d),(f),(h)-wavelet energy of detail and approximate coefficient(level 5) for Q, P, V, I

Classification using SVM. Now a dataset is obtained consisting of 12 features, i.e., 3 each for every terminal signal. Using the above obtained features, classification is done using support vector machine. Training and testing set for each loading conditions contains 726 samples and 242 samples respectively. Model is also trained to operate only during LOF and not during stable swing condition. Different kernel functions are employed for mapping the training data into kernel space. Thereafter, the accuracy of classification using various kernel functions is calculated and the most suitable kernel function for the purpose is determined.

Table.1. Classification accuracy for 40% initial loading

S.	Input Features#				Accuracy (in %) For Different Kernel Function				
No.	Q	P	V	I	Linear	Quadratic	Polynomial	Radial Basis Function	Multilayer Perceptron
1	*	*	*	-	96.69	98.76	100	97.52	88.43
2	*	*	-	*	97.52	95.87	99.59	98.35	71.08
3	*	-	*	*	94.22	99.17	100	96.69	93.81
4	-	*	*	*	95.87	99.17	99.59	97.11	64.88
5	*	*	*	*	97.11	99.59	100	97.94	85.54

Table.2. Classification accuracy for 60% initial loading

S. No.	Input Features#				Accuracy (in %) For Different Kernel Function				
	Q	P	V	I	Linear	Quadratic	Polynomial	Radial Basis Function	Multilayer Perceptron
1	*	*	*	-	97.52	99.17	100	97.94	97.11
2	*	*	-	*	97.94	98.76	99.17	96.69	96.69
3	*	-	*	*	95.04	99.17	100	97.11	95.87
4	-	*	*	*	96.28	98.76	99.59	97.94	92.15
5	*	*	*	*	98.35	99.17	100	96.69	96.69

Table.3. Classification accuracy for 80% initial loading

S. No.	Input Features#				Accuracy (in %) For Different Kernel Function				
	Q	P	V	I	Linear	Quadratic	Polynomial	Radial Basis Function	Multilayer Perceptron
1	*	*	*	-	97.52	99.17	100	97.94	97.11
2	*	*	-	*	97.94	98.76	99.17	96.69	96.69
3	*	-	*	*	95.45	99.17	100	97.11	95.87
4	-	*	*	*	96.69	98.76	99.59	97.94	92.15
5	*	*	*	*	97.94	99.17	100	96.69	96.69

Input Features are wavelet entropy and energy of terminal signals
* considered for classification,
- not considered

6. Conclusion

A new method is presented in this paper for the detection of loss of field using discrete wavelet transform and support vector machine. The proposed method is simple and robust maintaining its performance under different loading conditions. After estimating the classification accuracy for LOF using different kernel functions, it can be concluded that the best suited kernel function for the detection of LOF is polynomial kernel. The proposed method is also trained to successfully distinguish between stable swing operation and loss of field fault.

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Appendix

System Data		Generator Data	
Positive Sequence Impedance	0.0068+j0.096 p. u.	Rated MVA	406 MVA
Zero Sequence Impedance	0.007157+j0.00251p.u	Rated Voltage	20 kV
System Voltage	230 kV, L-L rms	Rated p.f.	0.9
System Frequency	60 Hz	Xd	1.746 p.u.
		Xq	1.138 p.u.
		X'd	0.44 p.u.
Transformer Data		X"d	0.28 p.u
Rated MVA	450	X'q	0.35 p.u.
Rated Voltage	20/230	X"q	0.345 p.u
Z%	10%	T'do	6.15
Connection Mode	DY11	T"do	0.039
		Inertia	3.117 s