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ORIGINAL PAPER

Wavelet operated single index based fault detection scheme for transmission line protection with swarm intelligent support

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Abstract

In this paper, an optimal wavelet operated single index-based relay is proposed for power transmission line protection. Apart from existing usage of wavelet transform in fault detection studies, swarm assistance is provided for optimal setting of threshold values for accomplishing fast and reliable detection of faults. For this threshold assistance, particle swarm optimization (PSO) is used. Here, three individual instantaneous current signals of three phases is processed through discrete wavelet transform and based on extraction of frequency coefficients, a unique fault detection index is designed. This way of threshold setting reduces excessive computational burden and produces 100% reliable results without violating accuracy during normal and extreme operating conditions of faults in a quick time. The performance of proposed method is evaluated by its own swarm intelligence in the process of optimal search of threshold by extensive case studies. This is not possible with manual checking of threshold by random case studies. All the results are carried out in MATLAB/SIMULINK environment.

Keywords Fault detection unit · Discrete wavelet transform · Optimal threshold setting · Particle swarm optimization

1 Introduction

In order to reduce the overall damage and cascaded failures subjected to faults in power system, fast and accurate fault detection units are necessary. For design of such fault detection units, wavelet transform (WT) is extensively used by many researchers [1–4]. However, in fault detection algorithms, pre set threshold value plays a vital role

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for proper decision to operate protection relay which influences speed, accuracy and reliability. Further it should activate fault classification and location algorithms for isolation and restoration of the system.

Till date, no systematic approach has been proposed for setting of optimal threshold index as discussed below. In [2–4], WT is used for protection of transmission lines. For fault detection, first and second level decomposition coefficients of Daubechies 4 (db4) wavelet family are used. Similar to [2], in [3], WT is extended for protection of parallel transmission lines. In both cases, different thresholds are used for decision making but no systematic approach is followed for setting of these thresholds.

Boundary protection of series compensated transmission lines using DWT with db4 as a mother wavelet is presented in [5]. Instead of taking individual instantaneous phase currents, a model signal is taken with three phase currents and it is processed further through wavelet filters to extract frequency components. That paper has also used level-1 decomposition coefficients and finally the abnormal condition is detected by using a threshold value (0.3). In that paper, threshold values are selected from extensive case studies. In [6], a combined wavelet and artificial neural network (ANN) approach is introduced where the energy spectra of the level-5 approximation and the level-3 detail coefficients of three-phase currents are used for fault detection by comparing with preset thresholds. A discrete form of continuous wavelet coefficients is used in [7, 8] for fault detection in distribution systems. In that paper also, decision is generated if the value 'D' is greater than the pre set value of the fault detection activating threshold (DAT). Here 'D' is maximum peak value of phase displacement between zero-sequence voltage and zero-sequence current. Along with DAT, other thresholds are defined but no specific procedure is framed for selection of all these threshold values [2–13]. The common shortcoming of all these papers is selection of threshold which misleads the system under certain cases. In recent years also, WT with additional features [14–20] are applied in power system component protection studies with same shortcomings.

In this paper, an attempt is made for setting of threshold value using swarm intelligence. Without increasing computational burden of the algorithm, based on extracted wavelet coefficients, a unique threshold value is designed and optimal value of the threshold is achieved by particle swarm optimization (PSO) algorithm. This way of setting gives accurate, reliable results with fast response. The rest of paper is organized as follows: Sect. 2 describes the proposed method along with problem formulation for systematic threshold approach. The setting of optimal threshold along with test system to investigate the performance of proposed method is illustrated in Sect. 3. The performance evaluation is presented in Sect. 4 followed with discussions in terms of protection attributes and finally the paper is concluded in Sect. 5.

2 Proposed method

In this paper, relay activation task is accomplished by directly comparing the extracted wavelet decomposed coefficients of three-phase currents with a preset threshold. The optimum value of the threshold is set via PSO. Direct comparison of wavelet decomposed coefficients with PSO assisted threshold value not only reduces the com-

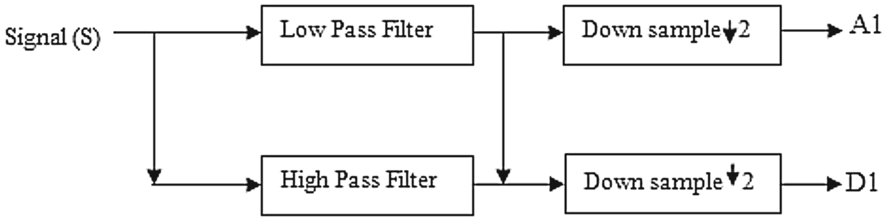


Fig. 1 Decomposition of time signal using discrete wavelet transform

putational burden, but also ensures fast and reliable fault detection and activates other functional blocks of relay. The detail computational steps and working principle of proposed algorithm is provided below.

2.1 Overview of wavelet transform and selection of mother wavelet for fault detection

Wavelet transform is an effective time frequency transformation technique for wide range study and analysis of non-stationary signals [2–4]. By using wavelets, function in time domain can be analyzed at various frequency levels of resolutions. The one-dimensional wavelet transform is expressed as,

$$w_f(a,b) = \int_{-\infty}^{\infty} x(t).\varphi_{a,b}(t).dt \tag{1}$$

where $x(t)$ is a time domain signal and $\varphi_{a,b}(t)$ is the transformation function $\varphi_{a,b}(t)$ depends on the choice of mother wavelet family having fixed and controllable parameters such as length of window, interval of frequency etc., which influences the process of decomposition. In this process of frequency component extraction, different mother wavelet families are employed. Commonly for detection of break point analysis [20], Haar wavelet family is more suitable. At the instant when the fault is initiated in the transmission line, the instantaneous current/voltage signals undergo sudden variation and hence Haar wavelets are useful for extraction of frequency components to discriminate such variations in broad manner. In this paper, single level one dimensional decomposition using 'Haar' wavelet family is used for extraction of detailed coefficients for further process as shown in Fig. 1. On the other hand, over the time interval $(-\infty, +\infty)$, the parameters used in Haar wavelet family are fixed and hence extraction of frequency components is simple as shown in Eq. (2). The Haar mother function can be expressed as,

$$\varphi_{a,b}(t) = \begin{matrix} 1 & 0 \le t \le 0.5 \\ -1 & 0.5 \le t \le 1 \\ 0 & otherwise \end{matrix} \tag{2}$$

In the process of decomposition, at each level l, the low and high frequency components of the signal are reanalyzed using the approximation coefficients a_l and the detail coefficients d_l decomposed with the help of low pass filter w_0 and high pass filter w_l and is expressed mathematically as in (3) and (4),

$$a_l(r) = \sum_k w_0(l_k - 2k)a_{l-1}(l_k) \tag{3}$$

$$d_l(r) = \sum_k w_l(l_k - 2k)a_{l-1}(l_k) \tag{4}$$

In earlier methods for fault detection studies, wavelets were used by several researchers [2–10]. But after extraction of frequency components of various levels, several measures are taken like entropy [20], absolute sum [2–4], and cumulative sum [21] etc., for reliable detection purpose to discriminate faults from other non-fault disturbances. Even such discriminations need a suitable threshold which is achieved by examining wide variety of case studies. In this paper, this discrimination is achieved without using any additional measures. By providing optimal threshold search for extracted frequency components directly using PSO, reliable and accurate detection can be achieved. This is the main advantage of the proposed method.

2.2 Relay activation algorithm

In order to design suitable detection index for discrimination of faults, the absolute sum of the level-1 detailed coefficients of individual phases is used. The computation of the proposed fault detection index (FDI) at kth instant is given as,

$$d_1(k) = |d_{1a}(k)| + |d_{1b}(k) + |d_{1c}(k)| \tag{5}$$

In Eq. (5), $d_{1a}(k)$, $d_{1b}(k)$and $d_{1c}(k)$ are the Haar wavelet level-1 detailed coefficients of phase-a, phase-b and phase-c currents respectively. $d_1(k)$ is the overall fault detection index. The proposed algorithm detects a fault, if

$$d_1(k) \geq \nu \tag{6}$$

In Eq. (6), ν is the pre designed threshold. In literature, it is found that the value of ν is fixed by extensive case studies. But in this paper, the setting procedure of threshold ν is adopted using PSO.

2.3 Systematic approach for setting optimum threshold value

For fast, accurate and reliable detection of transmission line faults, optimal minimum setting of the threshold is an essential requirement. The available fault detection algorithms set thresholds mainly through extensive simulation studies without following any systematic approach. However, using such methods of threshold setting, fast and reliable fault detection may not be ensured. To ensure fast and reliable fault detection, a PSO assisted algorithm is employed for setting an optimum threshold value by formulating an objective function subjected to a set of constraints. The objective function of the problem is formulated as,

$$\nu = min\{f_i(l)\} = min\{min(d_{i,j,k})\} \tag{7}$$

In detail, the objective function is,

$$\nu = \min\{f_1(l), f_2(l), f_3(l), f_4(l), f_5(l), f_6(l), f_7(l), f_8(l), f_9(l), f_{10}(l), f_{11}(l)\} \tag{8}$$

The sub optimal eleven functions in Eq. (8) are:

$$f_i(l) = \min\{d_{i,1,1}, d_{i,2,1}, \ldots d_{i,K,1}, \ldots, d_{i,K,N}\} \tag{9}$$

where i represents fault type, K represents iteration number and N is the solution (population). $d_{i,j,k}$ represents peak magnitudes of real positive detailed coefficients of first level decomposition of Haar wavelets. Here, $i = 1, 2 \ldots 11$ represents the eleven types of faults (AG, BG, CG, AB, BC, AC, ABG, BCG, ACG, ABC and ABCG) occur in transmission lines. For this objective function, location of fault is the only variable included over the length of the transmission line is taken as inequality constraint and is expressed as,

$$0 \leq l \leq L \tag{10}$$

where L is the total length of the transmission line to be protected. Constraint in Eq. (10) is theoretically valid over the entire interval $(0, L)$. But in simulation studies with distribution models, small ϵ is considered without violating the configuration parameters. Therefore, Eq. (10) is modified as

$$\epsilon \leq l \leq L - \epsilon \tag{11}$$

However, fault inception angle/time and fault resistance also affect the magnitude of FDI. Hence the problem can be extended by imposing two additional constraints mentioned in Eqs. (12) and (13) after achieving optimal value of detection index by considering the given problem as 1-dimensional problem over the 11 sub functions in main objective function of Eq. (8).

$$t_{min} \leq T_{ins} \leq t_{max} \tag{12}$$

$$R_{min} \leq R_f \leq R_{max} \tag{13}$$

In Eq. (12), T_{ins} is the fault inception time or fault initiation time. t_{min} and t_{max} are the minimum and maximum limits of fault initiation time in seconds. These limits should be selected such that the difference between the maximum value to minimum value is equal to time period (for 50 Hz, 0.02 s; for 60 Hz, 0.0167 s) of actuating signal during normal condition. In Eq. (13), R_f is the fault resistance. R_{min} and R_{max} are the minimum and maximum limits of fault resistances in Ohms. Subjected to above practical constraints, the optimum value of threshold ‘ϑ’ is obtained by PSO as discussed below.

2.4 Overview of particle swarm optimization (PSO)

The process of identification of minimum threshold value for more reliable detection unit becomes an optimization problem, which can be solved by a well-accepted Meta heuristic particle swarm optimization algorithm. This is a kind of population-based optimization algorithm used for finding minimum/maximum functional points for diverse engineering problems. Kennedy and Eberhart first established a solution to the complex non-linear optimization problem by imitating the behavior of birds in the year 1995 and later many variants are proposed by several researchers in the optimization family [22, 23]. The convergence rate of PSO is very fast with minimum computational burden. Let the position of nth organism in a n-dimensional space is p_n^i and the corresponding velocity is v_n^i. Let the local best position of each particle is p_{best} and the overall global best among all positions is g_{best}. As PSO is a population based optimized technique, the velocity of each particle is updated towards best fitness. In this process of velocity updating, the velocity of nth swarm is updated for $(i + 1)$th iteration from the ith iteration is expressed as,

$$v_n^{i+1} = \Omega v_n^i + \alpha_1\beta_1\left(p_{best_i} - p_n^i\right) + \alpha_2\beta_2\left(g_{best_i} - p_n^i\right) \tag{14}$$

where α_1 and α_2 are the acceleration constants, β_1 and β_2 are the randomly generated numbers for updating velocity in limits 0 and 1. The inertia weight factor is represented by symbol Ω. Using Eq. (14), the new position is updated as,

$$p_n^{i+1} = p_n^i + v_n^{i+1} \tag{15}$$

If the new position or solution of the swarm particle for a particular iteration yields best value than it’s previous, then the corresponding solution is updated and this process continues until the optimal position is achieved. In the process of position and velocity adjustments, the inertia weight factor is computed as,

$$\Omega_{n+1} = \Omega_n * \Omega_{damp} \tag{16}$$

where Ω_{damp} is damping ratio of inertia weight. The inertia weight factor in Eq. (16) is changed dynamically which produces better convergent results and avoids premature condition of PSO [24].

3 System studied and optimal setting of threshold

The proposed method with unique optimal threshold value is tested under 2-bus power system with 230 kV voltage operated at a frequency of 50 Hz as shown in Fig. 2. The performance of proposed method is validated by considering the relay position is at

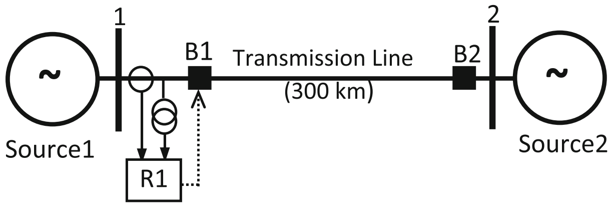


Fig. 2 Single line representation of the test system

R1. The transmission line which interlinking the both areas have per km positive and zero-sequence parameters are available in MATLAB/SIMULINK library [21, 24]. The load angle difference between the two areas is 10^0 and length of the transmission line is 300 km. For validation of proposed method, sampling frequency of 1 kHz is considered.

For the given test system, the optimal fault detection index is obtained using two processes in order to reduce computation time. In process-I, the problem is considered as a single variable problem with fault location as variable. In process-II, the problem is considered as a multi variable problem with all available constraints shown in Eqs. (11)–(13). For the process-I, the main objective function involves 11 sub optimal functions and each sub function is considered as separate function and minimum value of each function is obtained using PSO which is discussed below.

3.1 Process-I

In this case, optimal threshold setting is achieved either by 11 simultaneous or one by one PSO search processes. To set unique optimal threshold value for detection, the main objective function with 11 sub functions is considered with a single variable 'l' as described in Eqs. (8)–(10). Out of 11-PSO search processes, initially line to ground faults are considered. By considering AG-fault, minimum index of first objective function $f_1(l)$ in Eq. (8) is achieved at 209.5824 km from relay R1. The minimum threshold index value for AG-fault is 2.7309. For BG and CG faults, minimum indices are identified using PSO at critical fault locations of 270.8966 km and 276.4727 km, respectively from R1. After identification of line-to-ground fault indices, similar searching is done for all other sub functions. After identifying individual optimal indices for all possible faults occurs in transmission line system, the overall unique optimum threshold index is fixed using Eq. (8).

$$\begin{aligned} \vartheta &= min f_i(l) \\ &= \min\{2.73, 1.693, 2.794, 2.33, 4.095, 4.37, 3.33, 4.535, 4.6, 6.11, 6.09\} = 1.693 \end{aligned} \tag{17}$$

This optimal FDI obtained for BG- fault at a critical location of 270.89 km from bus-1. In this process of searching of optimal index for threshold setting, the variation of solutions towards optimal value from initial iteration to final iteration is shown

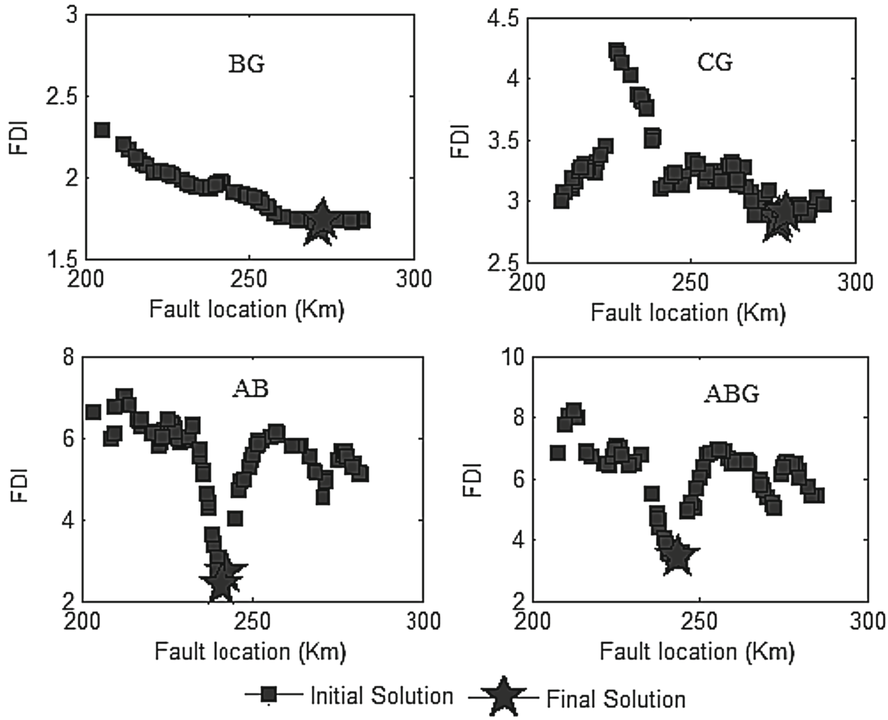


Fig. 3 Minimization of FDI as 1-dimensional using PSO algorithm via optimal search for different faults

in Fig. 3 for BG, CG, AB and ABG faults. For all 11 types of faults, the critical fault locations along with corresponding optimal indices are presented in Tables 1 and 2, respectively. The solution from process-1 is enough to set optimal threshold under normal operating conditions of faults. However, process-II is employed for more reliable detection index during extreme operating conditions as discussed below.

3.2 Process-II

Out of 11 sub functions in main objective function, $f_2(l)$ corresponding to BG fault is identified as most critical function with minimum fault detection index. Therefore, the main objective function is simplified as,

$$\vartheta = \min\{f_2(l)\} \tag{18}$$

For this objective function (18), the three constraints from Eq. (11)–(13) are imposed so that it is converted into multi-dimensional problem with objective function shown in Eq. (19),

$$\vartheta = \min\{f(l, T_{ins}, R_f)\} \tag{19}$$

Table 1 Optimal threshold indices for single-line-to-ground faults

Fault-type	Expected result from initial solution group by general scenario (km)	Actual result from final solution group by PSO (km)	Location (km)	FDI
AG	284.1720	209.9233	209.5824	2.7309
	213.3102	209.9557		
	253.3357	209.9245		
	245.9495	209.9261		
	274.7127	209.8621		
BG	257.3606	270.7473	270.8966	1.6933
	271.6666	270.8100		
	223.9467	270.7563		
	249.6411	270.7624		
	287.7388	270.8866		
CG	271.6908	276.8399	276.4727	2.7944
	216.7142	276.0502		
	209.5742	275.0283		
	251.4311	276.0735		
	210.1101	276.0484		

Table 2 Optimal indices for faults involving more than one faulty phase

Fault-type	Critical location (km)	Optimal FDI	Fault-type	Critical location (km)	Optimal FDI
AB	241.3311	2.3334	BC	268.0440	4.0955
AC	270.3228	4.3745	ABG	243.7012	3.3331
BCG	269.5341	4.5348	ACG	270.1344	4.6003
ABC	245.6008	6.1170	ABCG	245.2641	6.0911

For the above objective functions, the constraints are chosen as follows:

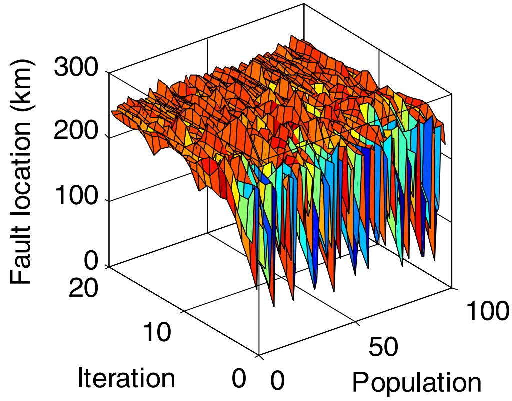
$$1 \leq l \leq 299 \tag{20}$$

$$0.03 \leq T_{ins} \leq 0.05 \tag{21}$$

$$0.01 \leq R_f \leq 30 \tag{22}$$

By using PSO, the optimal solution is arrived at 291.8602 km from relay R1 with fault initiation time of 0.0376 s. The fault resistance corresponding to optimal index is 92.6794 Ω. Finally, the optimal index which is used as threshold for the given test system is obtained at 0.9683. The pattern of variation of variables for initial iteration to final iteration of PSO is shown in Fig. 4 and corresponding FDI search is shown in Fig. 6. In the initial iteration the surface pattern is clumsy where as in final iteration it is converged to uniform because of optimality.

Fig. 4 Variation of fault location using PSO algorithm from initial iteration to final iteration



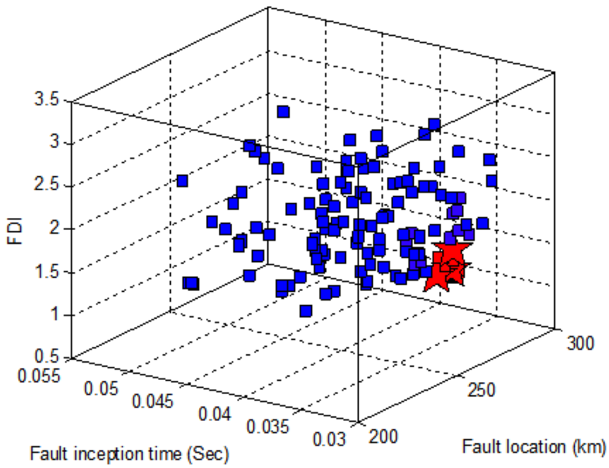


Fig. 5 Minimization of FDI as 2-dimensional using PSO algorithm via optimal search

However, without taking fault resistance into consideration, the problem is two dimensional in nature whose minimization of FDI is shown in Fig. 5. The variations of FDI from the initial iteration to final iteration for all the particles (population) are presented in Fig. 6.

4 Performance evaluation of proposed method through simulation results

Using the optimal threshold value obtained with help of PSO, several case studies are investigated on test system presented in Sect. 3 using proposed method by randomly varying fault location, fault inception angle, fault resistance and type of fault etc.

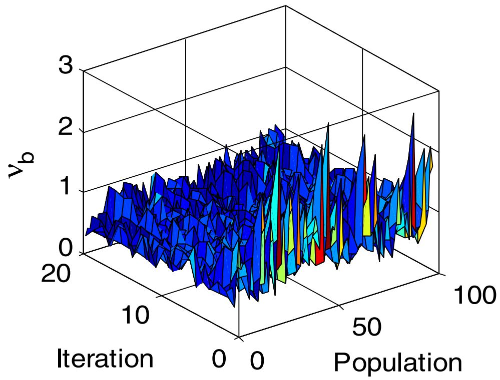


Fig. 6 Variation of FDI using PSO algorithm from initial solution to final solution

4.1 Performance evaluation during unsymmetrical faults

With the help of swarm intelligence assisted unique threshold value, the reliability of proposed method is tested initially with most common occurring unsymmetrical faults. When AG-fault occurring on transmission lines at 200 km from relay point R1 with a fault inception time of 0.05 s (50th sample for 1 kHz sampling frequency), the detection plots are presented in Fig. 7a. As observed from the figure, when there is no fault in transmission line, the value of FDI is low and is less than the threshold value. With the inception of the fault at 50th sample, the FDI rises to a high value and crosses the optimal threshold value just in 2 ms. Thus, the AG-fault is detected by the proposed method in 2 ms. The subplots in Fig. 7 show the variation of actuation quantities, the fault detection index (FDI) and trip signal generated from the algorithm. Similar testing is done for all other unsymmetrical faults and detection plots of CG, AB and ACG faults presented in Fig. 7b–d, respectively. As the FDI involves three phase frequency coefficients, the detection indices for line-to-ground faults are comparatively low with other unsymmetrical faults involving more than one phase in fault. However, irrespective of type of fault, the proposed method detects them within 4–5 ms. From Fig. 7a–d, for all the unsymmetrical faults, the location and inception angle of fault is maintained constant. Here low fault resistance of 1 Ω is considered.

4.2 Performance evaluation during symmetrical faults

The relative fault detection index for symmetrical faults is large compared to unsymmetrical faults as it involves three faulty phase currents in the process of calculation of FDI. The detection plots for three-phase faults occurring at 0.07 s are provided in Fig. 8. As observed from the figure, FDI values of three-phase faults are large and they are easily detected whenever the corresponding indices cross the optimal threshold value by generating a trip signal within 5 ms.

4.3 Performance evaluation of proposed method for remote end faults

Detection of remote end faults is not possible with conventional distance relaying schemes but the proposed method reliably detects all type of faults which occurs

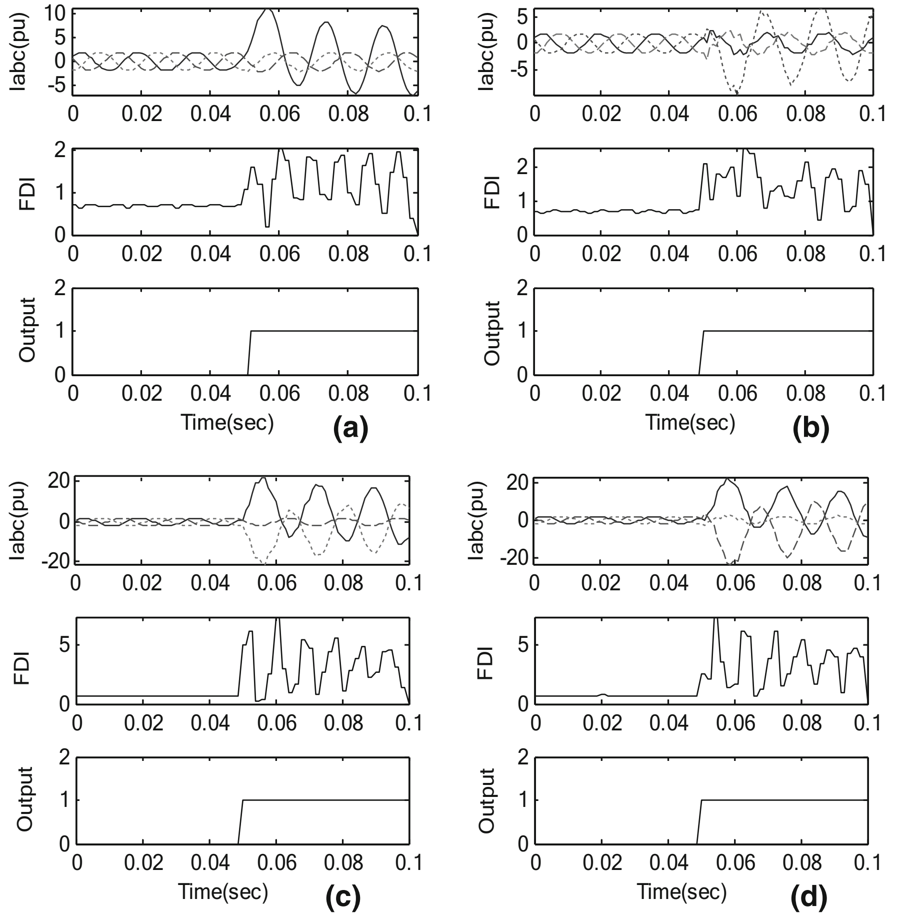


Fig. 7 Performance evaluation of proposed method, **a** AG fault, **b** CG fault, **c** AB fault, **d** ACG faults of location 200 km from relay R1 with fault inception at 0.05 s

beyond 80% of transmission line network. Performance of proposed method during the occurrences of an AG-fault and an ABCG-fault at 290 km (96.67% of transmission line) from relay R1 is shown in Fig. 9. Here the magnitude of FDI is reduced compared to previous cases. But using the swarm intelligence assisted optimal threshold even critical remote end faults can be detected in a very fast manner which is clearly observed from the figures.

4.4 Performance evaluation of proposed method for various faults with high fault resistance

Detection of high resistance faults is another shortcoming of existing distance relaying scheme. But the proposed method detects several faults with high impedances because of usage of wavelet transform. For example, BG type fault occurs in transmission line

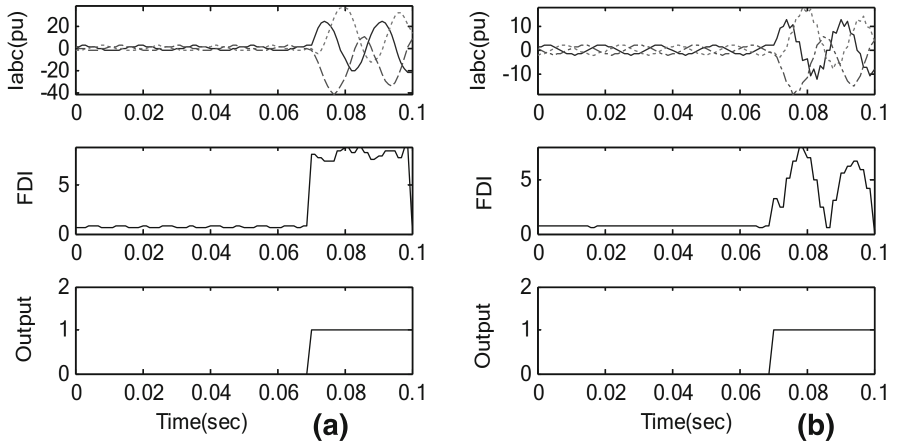


Fig. 8 Performance evaluation of proposed method, **a** ABC-fault located at 120 km from R1, **b** ABCG fault located at 280 km from relay point 1

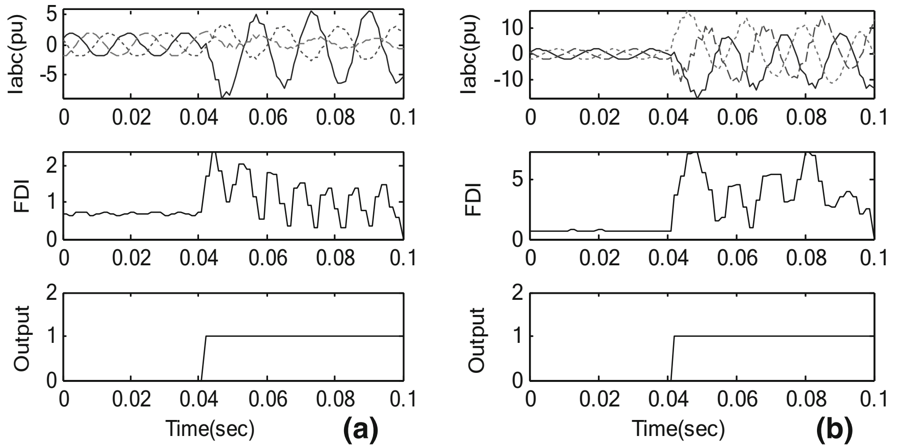


Fig. 9 **a** Performance of proposed method for AG fault at 290 km, **b** performance of proposed method for ABCG fault at 290 km

at 220 km from relay R1 with fault resistances of 20 Ω, 60 Ω, 100 Ω and 150 Ω whose detection responses are shown in Fig. 10a–d, respectively. Increase of fault resistance reduces current magnitude which obviously affects the fault detection index. However, in this case, high resistance fault can be easily detected by proposed method up to 250 Ω when the fault location is below 50% of the line section and above it varies in between 120 and 200 Ω.

4.5 Performance of proposed method during generalized variable parameters

From case 4.1–4.4, various fault cases are tested on a 2-bus test system by varying parameters such as inception angle/time of fault, location of fault, fault resistance etc.

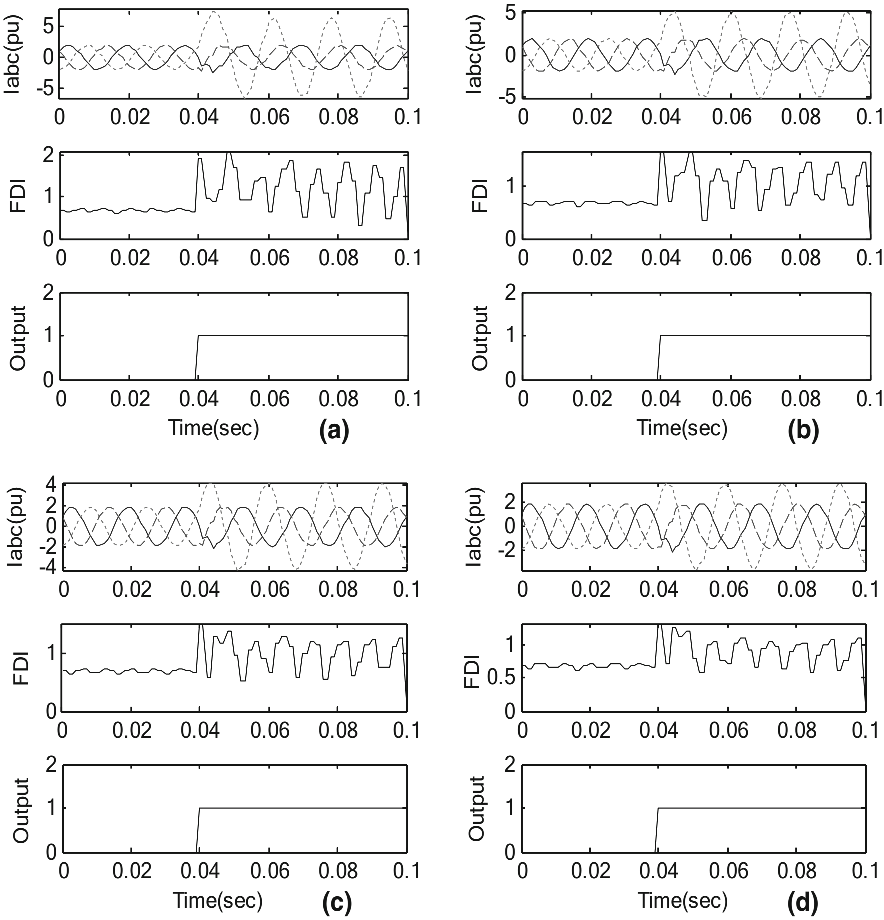


Fig. 10 Performance of proposed method for BG fault at 220 km with **a** fault resistance of 20 Ω, **b** fault resistance of 60 Ω, **c** fault resistance of 100 Ω, **d** fault resistance of 150 Ω

A total of 275,000 cases are tested by PSO technique to set threshold value by varying location, type of fault. In this process of setting, inception and fault resistance are kept constant. But while evaluating the algorithm, all four parameters are randomly varied and found the method is accurate to detect various faults listed in Tables 3 and 4. For the above-mentioned fault cases although the peak detection time is large but even with that also the fault can be detected at a very early stage i.e. within 4 ms. Achieving quick detection for all cases as presented in Tables 3 and 4 is one of the advantages of the proposed method.

4.6 Results for multi terminal test systems

The method is further tested on multi-machine, multi-terminal systems [25, 26] and results are discussed below. The three terminal transmission line network (TTL) [25]

Table 3 Early detection times for various faults using proposed method

Type of fault	Location of fault (km)	Inception time (s)	Peak magnitude	Peak detection time (ms)	Early detection time (ms)
AG	20	0.03	10.81	14	2
BG			10.67	12	2
CG			11.12	08	2
AB			28.01	13	2
BC			29.95	11	2
AC			27.62	02	2
ABG			28.37	12	2
BCG			30.16	10	2
ACG			27.44	03	2
ABCG			34.21	12	2
AG	150	0.06	2.692	11	2
BG			3.911	05	2
CG			2.610	12	2
AB			7.387	02	2
BC			7.509	14	2
AC			6.543	12	2
ABG			7.455	02	2
BCG			7.817	14	2
ACG			7.172	12	2
ABCG			8.066	11	2
AG	280	0.045	2.179	03	2
BG			2.189	20	2
CG			1.786	12	2
AB			7.263	15	2
BC			4.716	13	2
AC			5.888	18	2
ABG			5.875	17	2
BCG			4.801	12	2
ACG			6.034	18	2
ABCG			7.958	15	2

and Western System Coordinating Council (WSCC) 9-bus test system [26] are considered for the study. The system details are provided in [25, 26]. For three-terminal transmission line system, threshold is obtained at 0.9873 when the proposed relay placed at bus-1. For WSCC 9-bus system, optimal threshold is obtained at 0.5786 at bus-7. The corresponding results from PSO are presented in Table 5. For performance assessment of the proposed method with the optimal threshold for three-terminal network, a fault case is generated and results are presented in Fig. 11. In this case, AG fault is created at 80 km from relay location at 0.045 s with a fault resistance of 30 Ω. The

Table 4 Early detection time during LG faults with different fault resistances

Type of fault	Location (km)	Fault resistance (Ω)	Peak magnitude	Peak detection time (ms)	Early detection time (ms)
AG	180	10	2.206	20	5
	180	40	1.943	20	5
	180	80	1.699	18	8
	180	140	1.595	09	9
BG	100	10	3.408	11	2
	100	40	2.456	09	2
	100	80	2.089	17	2
	100	140	1.793	02	2
CG	240	10	2.958	07	2
	240	40	2.879	05	2
	240	80	2.743	05	2
	240	140	2.352	04	2

Table 5 Optimal indices for different systems using PSO

Type of system	References	Bus	Critical fault location	Optimal index
Two terminal	[24]	1	270.8966	1.6933
TTL	[25]	1	186.7922	0.9873
WSCC-9 bus	[26]	7	193.4451	0.5786

fault is detected by the proposed method after 3 ms of fault inception which is evident from trip command generated from the algorithm. Similarly, ABG fault is created at 170 km from bus-7 location with a fault resistance of 120 Ω on WSCC9-bus system and corresponding detection plots of the proposed method are shown in Fig. 12. Even the fault is high resistance type; the proposed optimal index-based technique is able to detect it in 8 ms from fault initiation. These results show the effectiveness of the PSO application in threshold setting.

4.7 Statistical analysis of PSO assistance

As PSO assistance for threshold setting is a new attempt in relaying applications, a statistical analysis is required to validate optimum solution. This is a systematic approach for threshold setting to improve the overall reliability and security of the fault detection technique. In this paper, the fault detection algorithm is designed with unique threshold value with the help of 11 sub functions. Each sub optimal function represents the objective function of optimal threshold setting considering a fixed type of fault among all possible 11 types of faults (AG, BG, CG, AB, BC, CA, ABG BCG, CAG, ABC and ABCG). The optimal indices and critical fault locations where these optimal indices occur are already presented in Sect. 3. For initial iterations of optimal threshold search using PSO, the statistical measures in terms of mean, variance and

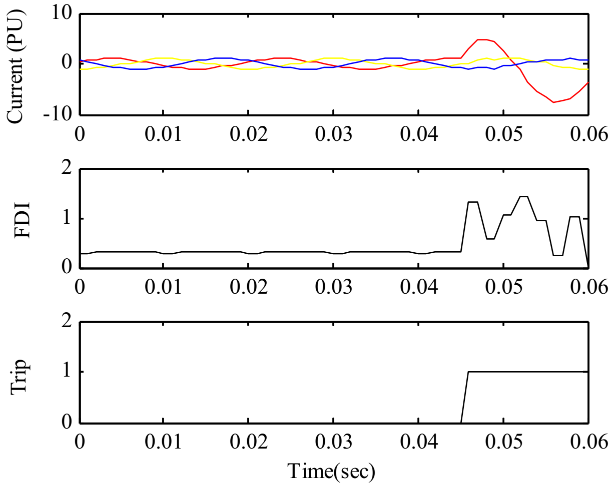


Fig. 11 Performance of proposed method on TTL system for AG fault at 80 km with a fault resistance of 30 Ω and a fault inception time of 0.045 s

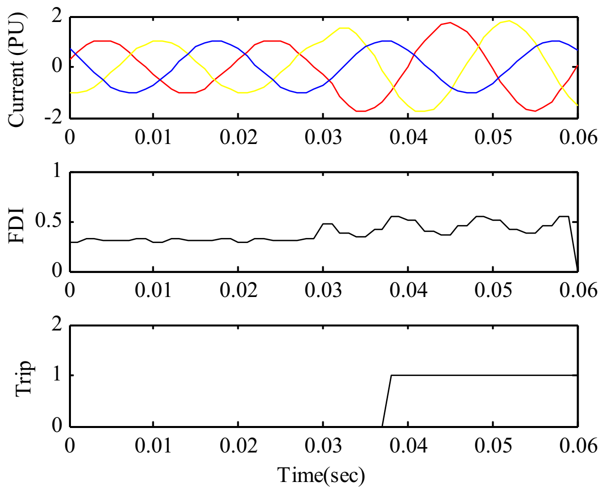


Fig. 12 Performance of proposed method on WSCC-9 bus system for ABG fault at 170 km with a fault resistance of 120 Ω and a fault inception time of 0.03 s

standard deviation are very large and distinct from actual expected values. However, after fixed number of iterations, the solution approached towards optimum value. At the end of final iteration, these statistical parameters reduce and optimum solution is achieved which is evident from variance and standard deviation calculated from iterative solutions and presented in Table 6. For setting optimal threshold in fault detection studies, PSO is more suitable and it converges quickly. In earlier studies, the setting of threshold is taking place with the help of extensive case studies in which the optimal value may escape. But here, using PSO, extensive case studies are tested

Table 6 Statistical analysis of initial and final iterations of the PSO

Fault-type	For initial iteration			For final iteration		
	Mean	STD	Variance	Mean	STD	Variance
AG	250.9717	21.8480	477.3337	209.9150	0.0310	0.0010
BG	261.9792	26.2499	689.0562	270.7875	0.0523	0.0027
CG	240.0133	27.8955	778.1562	276.0300	0.0680	0.0046
AB	239.7058	17.5818	309.1203	241.4975	0.0397	0.0016
BC	259.0741	23.1075	533.9562	268.9802	0.0765	0.0059
AC	250.1574	24.0682	579.2798	270.7439	0.2151	0.0463
ABG	241.8526	30.8864	953.9668	243.2477	0.2989	0.0894
BCG	256.9408	28.8809	834.1038	269.5326	0.0549	0.0030
ACG	265.1070	27.5387	758.3802	271.0108	0.5118	0.2620
ABC	248.6631	27.2912	744.8101	245.1246	0.2960	0.0876
ABCG	245.2606	21.0842	444.5418	245.0028	0.2116	0.0448

Table 7 Reliability of proposed method

Fault-type	No. of iterations	No of optimal indices	Population size	No of trails	Total simulations	No of failure cases	% reliability
AG	50	1	100	5	25,000	0	100
BG	50	1	100	5	25,000	0	100
CG	50	1	100	5	25,000	0	100
AB	50	1	100	5	25,000	0	100
BC	50	1	100	5	25,000	0	100
AC	50	1	100	5	25,000	0	100
ABG	50	1	100	5	25,000	0	100
BCG	50	1	100	5	25,000	0	100
ACG	50	1	100	5	25,000	0	100
ABC	50	1	100	5	25,000	0	100
ABCG		1	100	5	25,000	0	100
11					**275,000**	**0**	**100**

All 11 possible fault cases are provided together in the last column of Table 7 represented in bold

in systematic approach to find optimal threshold value and reliability of this way of setting is presented in Table 7.

5 Conclusions

A unique PSO assisted wavelet-based fault detection technique is presented in this paper first time for protection of power transmission networks. The direct extraction of the actuating signal components by using Haar wavelets with PSO tuned unique optimal threshold value reduces the computational burden of the detection algorithm. Unlike the usage of higher computational logics or techniques, detection is achieved by direct comparison between particular frequency components of the sampled signal with optimal threshold index. The test results on a wide variety of fault and non-fault cases confirms that using the proposed method a very fast and accurate detection of faults in transmission lines can be performed.

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