5
FAULT-GENERATED HIGH-FREQUENCY TRANSIENTS BASED NON-UNIT PROTECTION TECHNIQUE FOR SERIES COMPENSATED TRANSMISSION LINES USING WAVELET TRANSFORM

5.1 Introduction and Background

A perfect transmission line protection scheme is expected to differentiate the internal faults from external fault using single end measurements only. The conventional protection approaches (distance relaying) which detects and classifies the faults, based on fundamental frequency components of the fault signals mal-operates when applied for protection of series-compensated transmission line equipped with MOV especially when the faults are near towards the boundary of the protected zone [55].

The usage of fault-generated high-frequency transients in developing new relaying schemes has been first suggested in [56] - [58]. A "Non-communication" protection relay based on fault generated high frequency voltage signals has been proposed for protection of series compensated transmission line in [59]. It was shown that the relay can operate correctly under various fault conditions and system configuration. However, high-frequency voltage signal based scheme requires power line carrier equipments which would result in additional cost and consequently limits its applications to the area of power system protection.

Further studies suggested that the fault-generated high frequency current in transmission line can also be used to develop a protection scheme which does not require communication channels[60]-[62]. This transient current will travel from the fault point towards the both ends of the line. When the current signal meets the point of the discontinuity which is usually bus-bar, part of the current signal will be reflected back and rest will continue to travel along the line [60].

The bus-bar of the power system is always connected to many power system equipments. In case of bus-bar its impedance to earth is mainly determined by capacitance of these equipments (capacitive coupling) to earth. Hence, when dealing with fault-generated high-frequency signals which is traveling along the line, the bus-bar stray capacitance (between bus-bar and earth) offers these signals low impedance path due to which a large amount of generated high frequency signals (ranging from

50KHz-100 KHz) is directed to earth. On the other hand, the lower frequency signals (in the range of 1 KHz - 3 KHz) are not affected by bus-bar stray capacitance. This criterion is the key for fault generated high-frequency signals based protection scheme for deciding the two boundaries of the protected zone by the relay and has been studied in detail and presented in [61]-[64].

In [61] and [62], the authors suggested a specially designed multi-channel band pass filter to extract the transient current signals I_{f1} ,I_{f2} (two modal signals) with centre frequency at 80KHz and 1KHz respectively. Then the ratio of the energy spectrum for I_{f1} ,I_{f2} is calculated and compared with a threshold value to find out whether the fault is internal or external. The use of two modal signals to cover all kind of faults and extensive signal processing of these signals using Fourier Transform was considered to be limitations of the method.

In [63], authors presented the use of one modal current signal I_m (derived from three line currents) with signal processing being done by using Discrete Wavelet Transform (DWT), which is having obvious advantage in terms of better time-frequency localization and provision of richer problem-specific information. The spectral energy ratio of details at level 1 and level 6 of modal signal was utilized in order to discriminate the internal or external fault by comparing the ratio with a threshold for protection of series compensated transmission lines.

In [64], authors presented a approach which utilizes all the line currents and line voltages in order to develop patterns (with dimension [24 * 1] for fault detection and zone identification and with dimensions of [128 * 1] for fault classification purpose) using Discrete Wavelet Transform (DWT) and Artificial Neural Network (ANN) in order to detect, discriminate and classify the faults for the case of uncompensated line. The pattern recognition based method presented in the work[64], claims to be superior than the earlier methods which utilizes critical thresholds for obtaining the protection objectives, however it involves large amount of signal processing and large array of patterns to be stored within the relay. Additionally some questions (Whether these patterns presented for specific system parameters studied in the work will remain unchanged if system parameters are changed?, If system parameters are changed then the same set of pre-memorized patterns will be able to detect, discriminate and classify the faults for the case of series compensated transmission lines or not?) remains unanswered as authors have presented the work for the case of un-compensated lines.

Retaining the positive features of [63]-[64] (i.e. Utilizing one modal signal each for Fault generated high frequency Voltage signals and Current signals) a non-unit protection technique worked out for the protection of series compensated transmission line is proposed and discussed further in the chapter.

5.2 The Proposed scheme and its Working

Consider the typical multi-line series compensated system as shown in Figure 5.1.

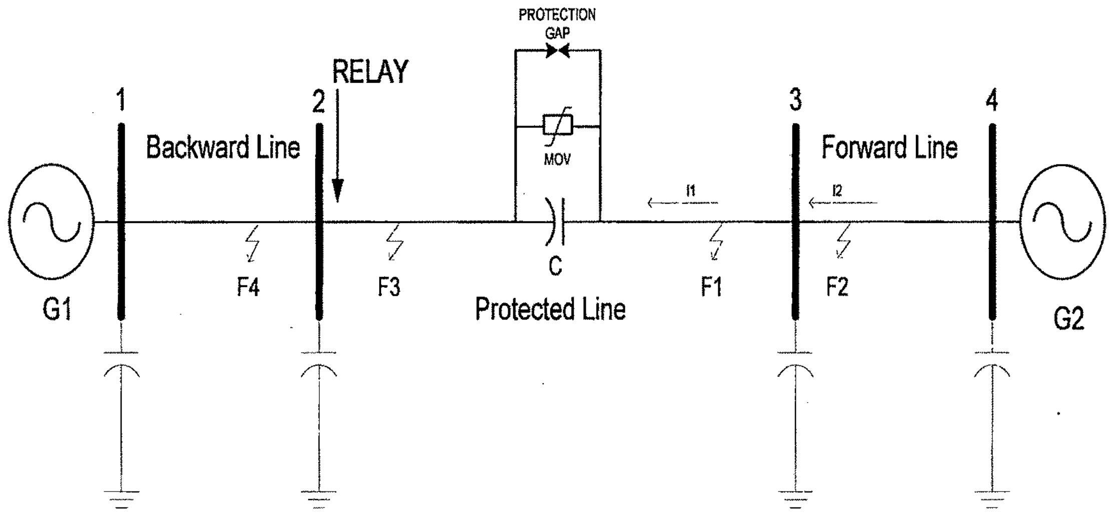

Fig.5.1 A multi-line Series-compensated System

It is assumed that the relay is installed at the bus 2 to protect the line 2–3 shown in the figure. A fault on the line will generate wideband transient voltage and current signals. The signals will travel in both directions with reflections and refractions at the discontinuity points, which are usually the bus-bars and fault loactions. The bus-bar of the power system is always connected to many power system apparatus and they usually represent the capacitance at high frequency between them and earth due to capacitive coupling. For an external fault F2 close to the bus 3, the high frequency portion of the fault current signal I2 will be shunted to earth significantly due to the bus-bar capacitance. The higher the frequency, the more significant portion of the current signal will be shunted. From the viewpoint of the relay, the magnitude of high frequency portion of the fault current signal I1 is reduced. In contrast, for the internal fault F1 close to the bus 3, the fault current of the entire frequency band can be seen by the relay. That means, if other fault conditions (fault type, fault resistance, fault angle) are identical, we can differentiate the internal fault F1 from the external fault F2 by comparing the high frequency portions of their signals. Similarly, the same method can be used to differentiate the faults at F3 and F4. Using the voltage signals, we can still differentiate faults at F1 and F2 but can not differentiate faults at F3 and F4 because the voltage measurements of the relay are obtained from bus 2.

The characteristic differences, in the post fault high frequency signals captured at relaying bus for the faults on different line sections seen by the relay at bus 2 in Figure 5.1 can be summarized as follows:

- For faults on the Protected Line, the energy of high frequency spectrum of post fault voltage and current signals are not grounded before it reaches to bus-2 where relay is placed and hence for a fault on protected line the available energy of high-frequency post fault voltage and current signal will be large.
- For faults on the backward line, the energy of high frequency portion of the post fault voltage signals available to relay at bus-2 will be large (as PT is placed on bus) while the energy of high frequency portion of the post fault current signals will be small. (as high frequency current signals will be grounded at bus-b2)
- For faults on the forward line, the energy of high frequency portion of the voltage and current signals available to relay at bus-b2 will be small.(as high frequency voltage and current signals will be grounded at bus-b3)
- Switching Transients due to switching operations irrespective of their location will be seen by relay at bus-2 containing high frequency current signals with large values for smaller period of time while high frequency voltage signals small values for smaller period of time.

It should be emphasized that the above statements are based on the assumption that all other fault parameters are the same and the "large" and "small" values are indicating relative numbers. The absolute values are dependent on fault type, fault resistance, fault angle, etc.

Based on the above key factors a non-unit protection scheme for detection, discrimination and classification of the fault for series compensated transmission line is developed. Figure 5.2. Shows flow chart for fault zone identification while, Figure 5.3 shows flow chart for fault classification of proposed scheme.

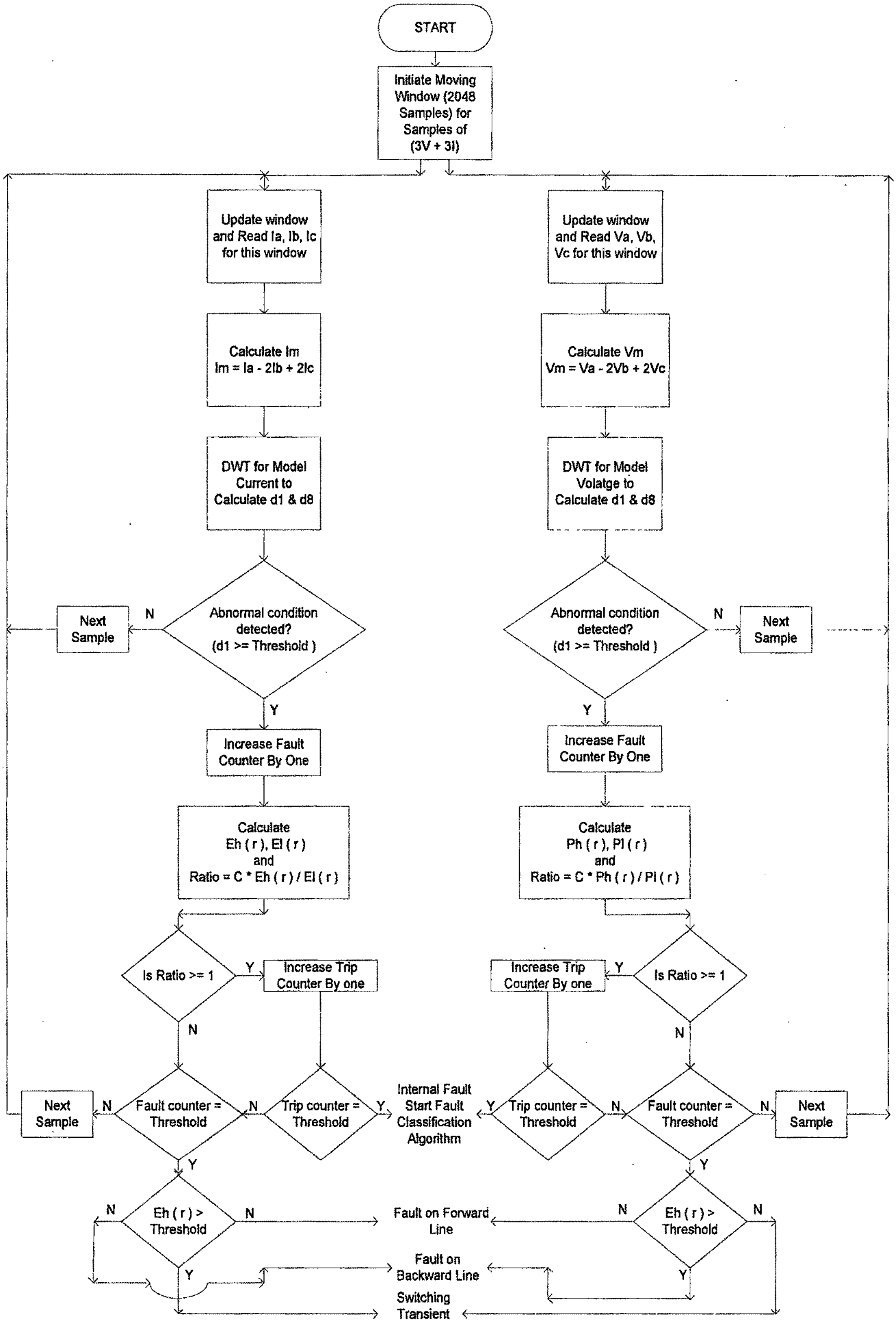

Fig.5.2 Flowchart for fault zone identification

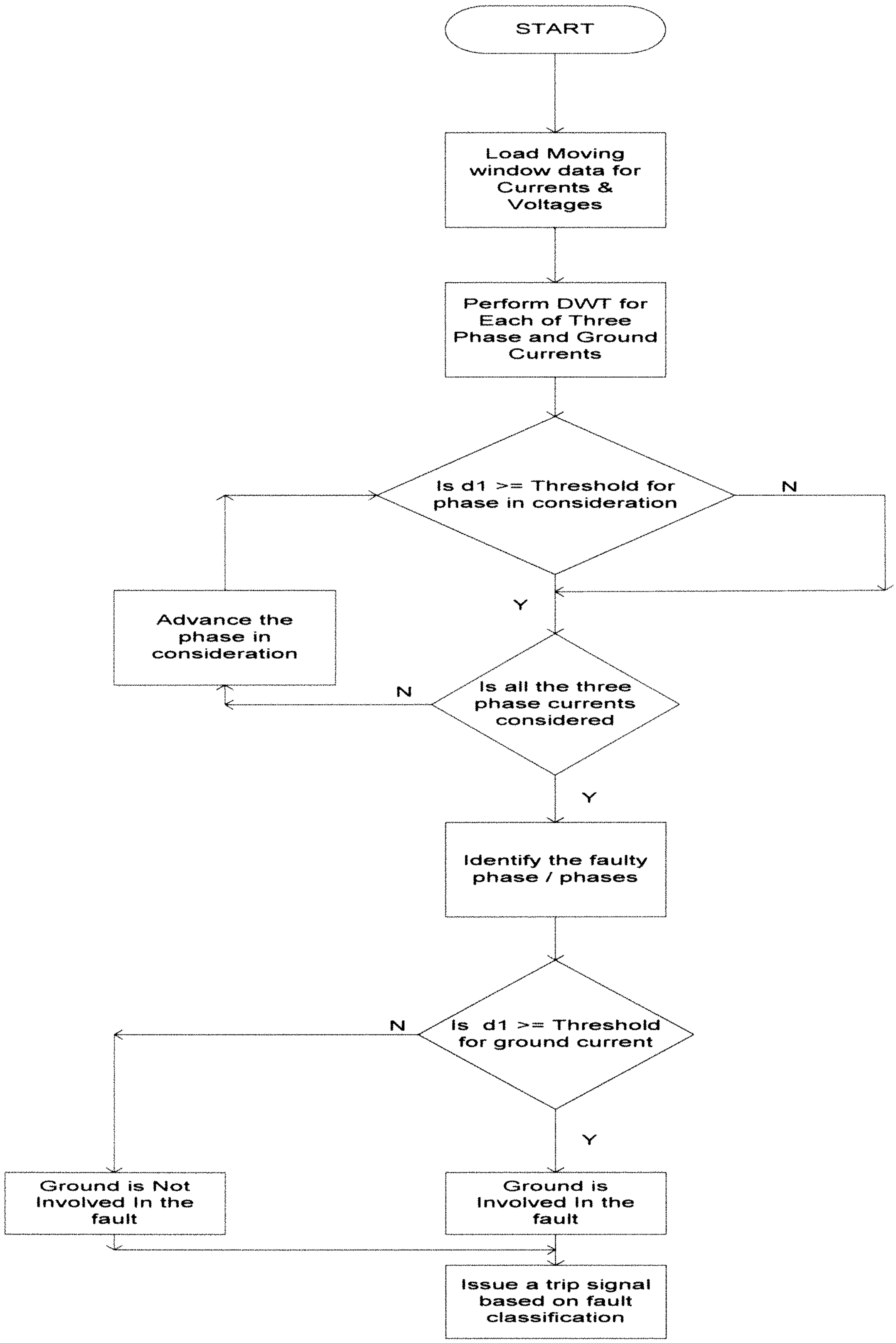

Fig.5.3 Flowchart for fault classification

As discussed in chapter-2 wavelet is a powerful tool for the analysis of transient phenomena because of its ability to extract time and frequency information from transient signals. For short and fast transient disturbances such as the case of this study db4 and db6 mother wavelet are better, while for slow transient disturbances, db8 and db10 mother wavelet are particularly good[65]. The mother wavelet used in this work is db4 for fault zone identification and classification.

5.2.1 Fault Zone Detection

The three phase currents (Ia, Ib, Ic) and voltages (Va, Vb, Vc) are combined to form the modal signals given by:

$$Im = Ia - 2Ib + 2Ic \qquad (5.1)$$

$$Vm = Va - 2Vb + 2Vc \qquad (5.2)$$

Utilizing these signals, fault types will be detected. Use of the modal signal, will eliminate any common mode signal (due to mutual coupling with adjacent circuit sharing same right of way) which will ensure immunity to all the disturbances other then those associated with the line to which the protection equipment is connected [62]. The fault generates high frequency transients of different frequency ranges, which can be observed as noise in current and voltage signals. In order to capture most of fault-generated noise, the sampling frequency is taken as 200 KHz (i.e., 4000 samples per cycle).

In [63] the authors have utilized coefficients of detail 1(d1) (50 KHz to 100 KHz) and detail 6(d6) (1.5625 KHz to 3.125 KHz) in order to discriminate between internal and external faults. But, according to studies done in [66]- "the majority of the high frequency transient signals due to switching operations in power systems lie in the range of 1 KHz to 10 KHz". Hence in order to minimize the possibility of counting of switching transients as fault transients by the proposed scheme, the scheme performs wavelet decomposition from scale 1 to scale 8 and utilizes the coefficients of detail 1(d1) and detail 8(d8), which covers frequency ranges from 50 KHz to 100 KHz and 781.25 Hz to 390.625 Hz respectively in the proposed work.

In case of external fault, such as F2 in figure 5.1, the fault generates high-frequency current and voltage signals which travel along the line. Before reaching the relaying point at bus-2, the stray capacitance of the bus-3 absorbs the high frequency components covered by detail 1, that is coefficients of detail 1 are attenuated extensively in case of external fault. In case of an internal fault such as F1 and F3 in figure 5.1, the high frequency current and voltage signals will reach the relaying point without attenuation. The coefficients of detail 8, which covers the lower frequency band, are not affected by the stray capacitance of the bus 3 because it appears as open circuit to it due to high impedance. Figure 5.4 and 5.5 shows the simulation results for the case of external and internal l-l-l-g fault.

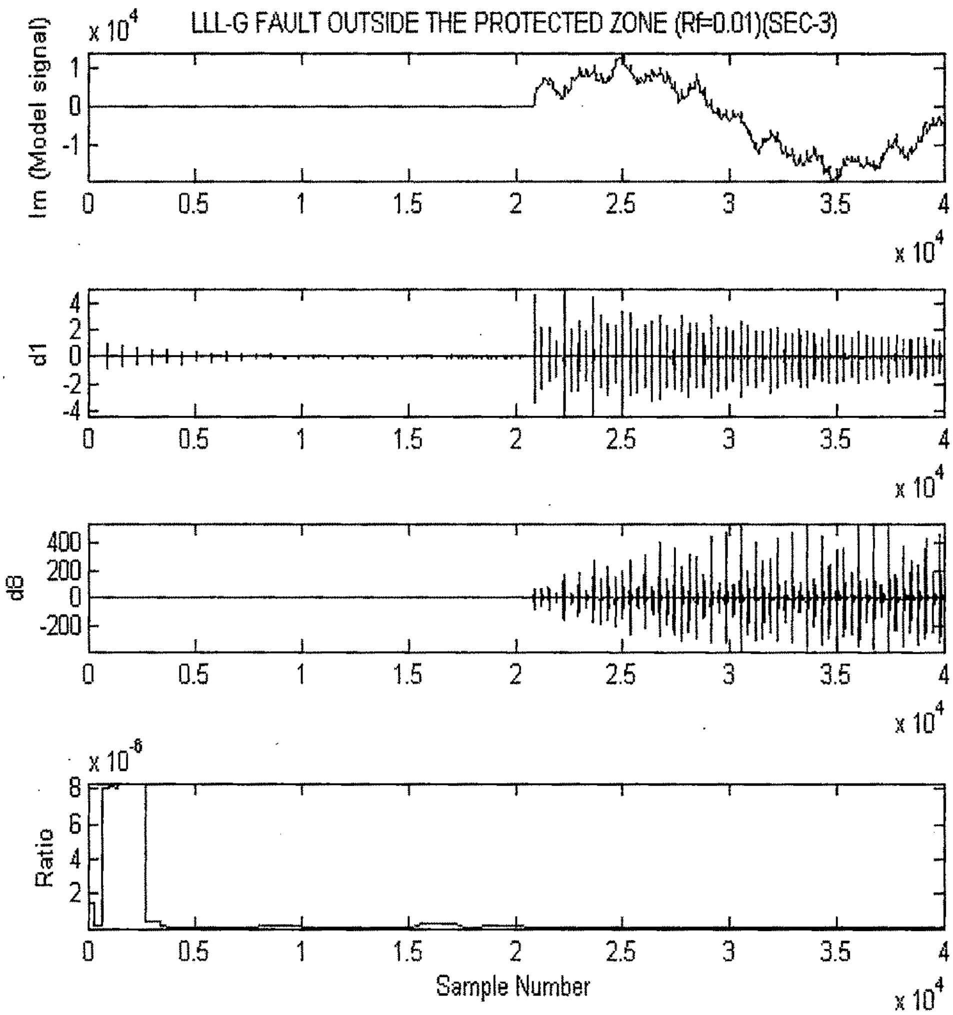

Fig.5.4 Plots showing Im:Modal signal, d1:Value of d1 coefficients and d8:Value of d8 coefficients, ratio of spectral energy for l-l-l-g External fault

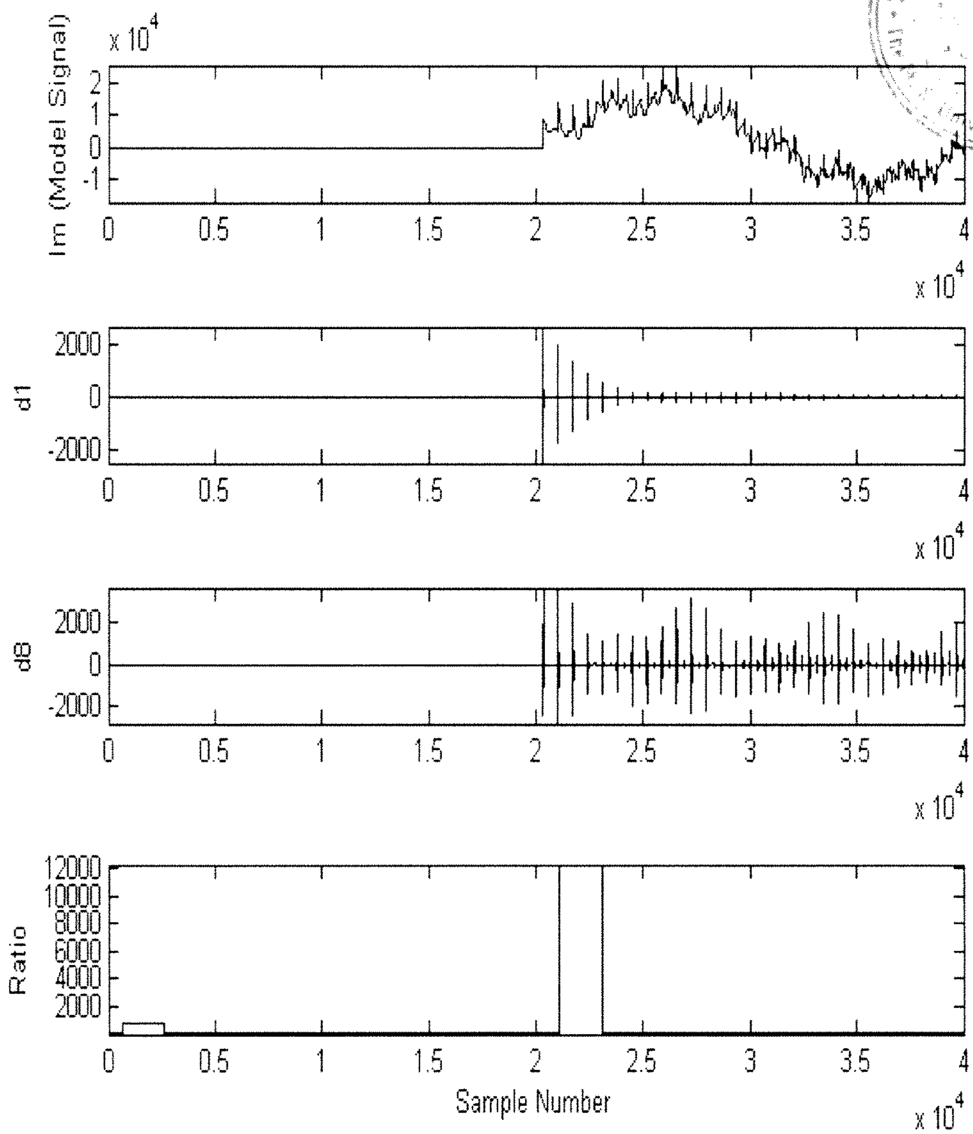

Fig.5.5 Plots showing Im: Modal signal, d1: Value of d1 coefficients and d8: Value of d8 coefficients, ratio of spectral energy for l-l-l-g internal fault

From figure 5.4 and 5.5 it can be seen that attenuation of d8 coefficients at bus-3 is quite small compared to attenuation of coefficients of d1. In other words the d8 coefficients are changing marginally while d1 coefficients are changing significantly for the external and internal fault cases. Another important observation that can be made form the figures is that before the fault inception irrespective of internal or external fault, the value of d1 coefficients are zero and their values rise sharply on fault occurrence. Hence presence of d1 coefficient higher than a preset threshold will be considered as a presence of the abnormality and will trigger the protection scheme, which will decide on the type of the fault (Internal, External-fault on forward or backward line, Switching Transient).

After detection of an abnormal condition, the scheme starts calculating the discriminating signals, based on spectral energy analysis, for detail 1 and detail 8 of the modal signals (Im,Vm) ,for every sample as per following:

$$Eh(r) = \sum_{k=n}^{r} I^2 m1(k\Delta T)\Delta T \quad (5.3)$$

$$El(r) = \sum_{k=n}^{r} I^2 m8(k\Delta T)\Delta T \quad (5.4)$$

$$Ph(r) = \sum_{k=n}^{r} V^2 m1(k\Delta T)\Delta T \quad (5.5)$$

$$Pl(r) = \sum_{k=n}^{r} V^2 m8(k\Delta T)\Delta T \quad (5.6)$$

Where,

Eh(r) - discriminating signal of high-frequency band (d1) of modal current;
El(r) - discriminating signal of low-frequency band (d8) of modal current;
Ph(r) - discriminating signal of high-frequency band (d1) of modal voltage;
Pl(r) - discriminating signal of low-frequency band (d8) of modal voltage;
Im1 – detail 1 (d1) coefficient of current modal signal;
Im8 – detail 8 (d8) coefficient of current modal signal;
Vm1- details 1 (d1) coefficient of voltage modal signal;
Vm8 - detail 8 (d8) coefficient of voltage modal signal;
ΔT – Sampling time step;
n – Fault inception sample number
r – Current sample where r > n

From equation 5.3 to 5.6 it can be seen that the energy of high frequency and low frequency signals of current and voltage transients are calculated after detection of abnormality at sample number n. With each new sample following n, the summations in these equation will be increased by one sample. After the calculation of Eh(r), El(r), Ph(r), Pl(r), the discriminating ratio is calculated at every sample as follows:

Ratio for currents spectral energy = (C * Eh(r)) / El(r) .... (5.7)

Ratio for voltages spectral energy = (C * Ph(r)) / Pl(r) .... (5.8)

Where C is normalization factor. (Taken as 150 for current signal and 1 for voltage signal.)

If the ratio is ≥ 1 for 200 samples (1 ms) for both voltage and current modal signals, the scheme decides that it is an internal fault. If the ratio is ≤ 1 for both voltage and current signal, the scheme decides it as external fault and the fault is on to forward line. If the ratio is ≥ 1 for only voltage modal signal the scheme takes as an external fault with fault on backward line. After doing the fault zone identification the scheme will look for fault classification.

5.2.2 Fault Classification

After detecting the fault and identifying its zone as internal fault, it is essential to classify the fault type. The proposed method for fault classification is shown in Figure 5.3. Detection of detail 1 coefficient higher than or equal to the threshold in phase current quantity is taken as involvement of particular phase in fault and presence of the detail 1 coefficient higher than threshold in ground current (which is obtained by summation of the phase currents) is considered as involvement of the ground in the fault. Table 5.1 gives clear idea of fault classification method used.

Table 5.1 Fault Classification

Fault Type	Value of d1 Coefficients above Threshold for Ia	Value of d1 Coefficients above Threshold for Ib	Value of d1 Coefficients above Threshold for Ic	Value of d1 Coefficients above Threshold for I0
A-g	Y	N	N	Y
B-g	N	Y	N	Y
C-g	N	N	Y	Y
A-B	Y	Y	N	N
B-C	N	Y	Y	N
A-C	Y	N	Y	N
A-B-g	Y	Y	N	Y
B-C-g	N	Y	Y	Y
A-C-g	Y	N	Y	Y
A-B-C	Y	Y	Y	N
A-B-C-g	Y	Y	Y	Y

After fault classification, a trip signal based on fault type will be issued by proposed scheme.

5.3 Performance evaluation by Simulation Studies

In order to evaluate the robustness of the proposed scheme extensive fault simulation studies are carried out on a multi line series compensated modal (as per shown in figure 5.1) using MATLAB, with a variable series compensation placed at the middle of the line. The transient fault studies are carried out using the well-known MATLAB (SIMPOWERSYSTEMS BLOCKSET) program. The performance of the proposed technique is analyzed for a large test data set (28,840) considering a wide variation in system condition along with a change in the source impedance. The simulation studies carried out in this work are based on the ideas, methods and parameters used for simulation studies in the work reported in [67].

The model used for simulation studies in MATLAB is shown in Figure 5.1.The transmission line has been represented using the distributed parameters line. The power system comprises of two sources, series capacitor (located at midpoint of the line) and its associated components. The system parameters used have been given in Table 5.2. The value of the ground capacitance of bus is taken as standard value of 0.1μF as per [61]-[62]. Individual section of multi line series capacitor model is considered of 100 Km. Hence the Protected line, Forward line and backward line section are of 100 Km each which makes the total line length of (100 * 3 = 300KM) 300KM. The voltage and current signals are captured at bus-2 in order to analyze the fault zone and fault type by the relay as per proposed scheme.

Over-voltage protection of series capacitor is provided by MOV and parallel power gap. The MOV is protected by C.B. operation against its energy dissipation capacity. The Series capacitor is designed to vary its compensation between 25% minimum to a maximum of 75%.

To test the suggested scheme the fault simulation studies have been carried out under wide variation of load angle, fault inception angle, fault resistance and fault locations. The different values of fault type, load angle, fault inception angle, fault

(i) Fault Type: a-g, b-g, c-g, a-b, b-c, c-a, a-b-g, b-c-g, c-a-g, a-b-c/a-b-c-g

(ii) Load angle: 10°, 20°, and 30°

(iii)Fault inception angle: 0°,45°, 80°, 115°

(iv) Fault resistance: 0.01Ω, 1Ω, 50Ω, 100 Ω.

(v) Fault Locations: 20% (on the backward line),
40% & 60% (on the protected line) &
80% (on the forward line)

Table 5.2 System Parameters

Line Length	300 KM
Voltage	400 KV
Compensation degree	25% to 75%
Location of Series Capacitors	150 KM
Positive Sequence Impedance of Line	8.25 + j94.5 Ω
Zero Sequence Impedance of Line	82.5 + j308 Ω
Positive Sequence Capacitance of Line	13 nF/KM
Zero Sequence Capacitance of Line	8.5 nF/KM
System Frequency	50 HZ
Positive Sequence Impedance of the G1-G2	1.31 + j15 Ω
Zero Sequence Impedance of the G1-G2	2.33 + j 26.6 Ω

Table 5.3 Range of Parameter Variation for test Data generation

Case No	ZG1 (%)	ZG2 (%)	Xc (%)
1-3	100	100	25,50,75
4-6	100	75	25,50,75
7-9	100	125	25,50,75
10-12	75	100	25,50,75
13-15	125	100	25,50,75

Thus, 10×3×4×4×4 =1920 combinations of above mentioned parameters have been selected for a single compensation level (Xc) with a fixed value of source impedance ZG1 and ZG2 at two ends of the transmission line. A total of 15 different cases have been generated by varying the said two parameters. Hence, 1920×15=28800 test cases are simulated. Table 5.3 shows different values of parameters used in generation of 15 cases. (In other words 10×3×4×4×15 = 7200 test cases are generated and studied for forward and backward line each while 10×3×4×4×15×2=14,400 test cases are generated and studied for protected line section)

The performance of the proposed scheme has been checked for test cases so generated by simulation studies. It is to be noted that for each and every fault simulation study simulation parameters as per Table 5.4 have been performed.

Table 5.4 Simulation Parameters

Simulation Time	0.2 Sec (Ten Cycles)
Sampling Frequency	200 KHZ
Simulation Starts	T=0 Sec (0'th Sample)
Fault is applied at	T=0.1 Sec (20,000'th Sample)
Simulation Ends	T=0.2 Sec (40,000'th Sample)

Next section will be demonstrating some case studies of fault simulations done considering the suggested scheme. The relay with the proposed scheme is at Bus-B2.

5.3.1 Some case studies and related discussions

(1) Xc=50%, ZG1=100%,ZG2=100%, A-g Fault at 60KM from Bus-B1, Rf=1 Ω (fault on backward line)

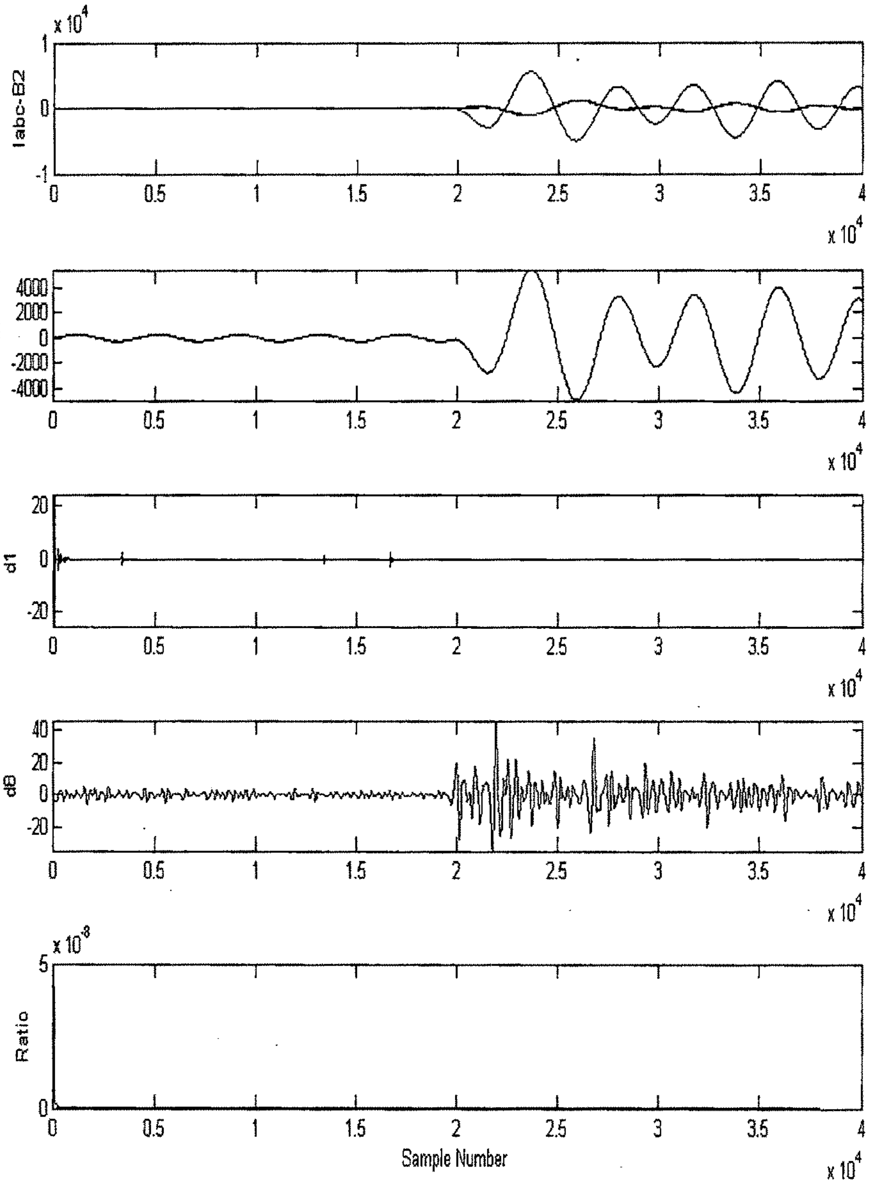

Fig.5.6 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,

d1: Value of d1coefficients, d8: Value of d8 coefficients,

Ratio of spectral energy for A-g fault on backward line section (Rf = 1 ohm)

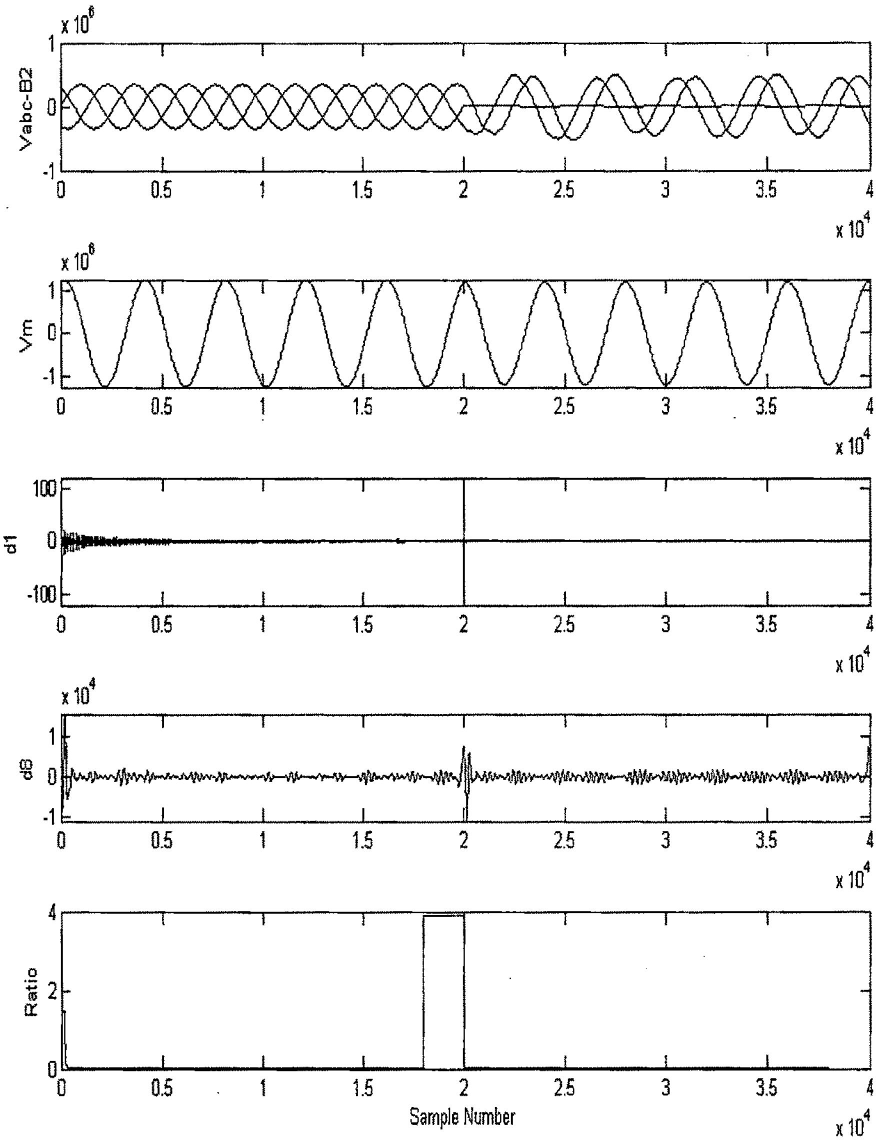

Fig.5.7 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Volatge Signal,
d1: Value of d1coefficients, d8: Value of d8 coefficients,
Ratio of spectral energy for A-g fault on backward line section (Rf = 1 ohm)

As the ratio of spectral energies remains lower than threshold for modal current signal(Fig. 5.6), the scheme detects it as an external fault, further the ratio of spectral energies for modal voltage signal exceeds the threshold (Fig. 5.7), the scheme detects the fault is on backward line section.

(2) Xc=50%, ZG1=100%,ZG2=100%,A-g Fault at 60KM from Bus-B1, Rf=0.01 Ω (fault on forward line)

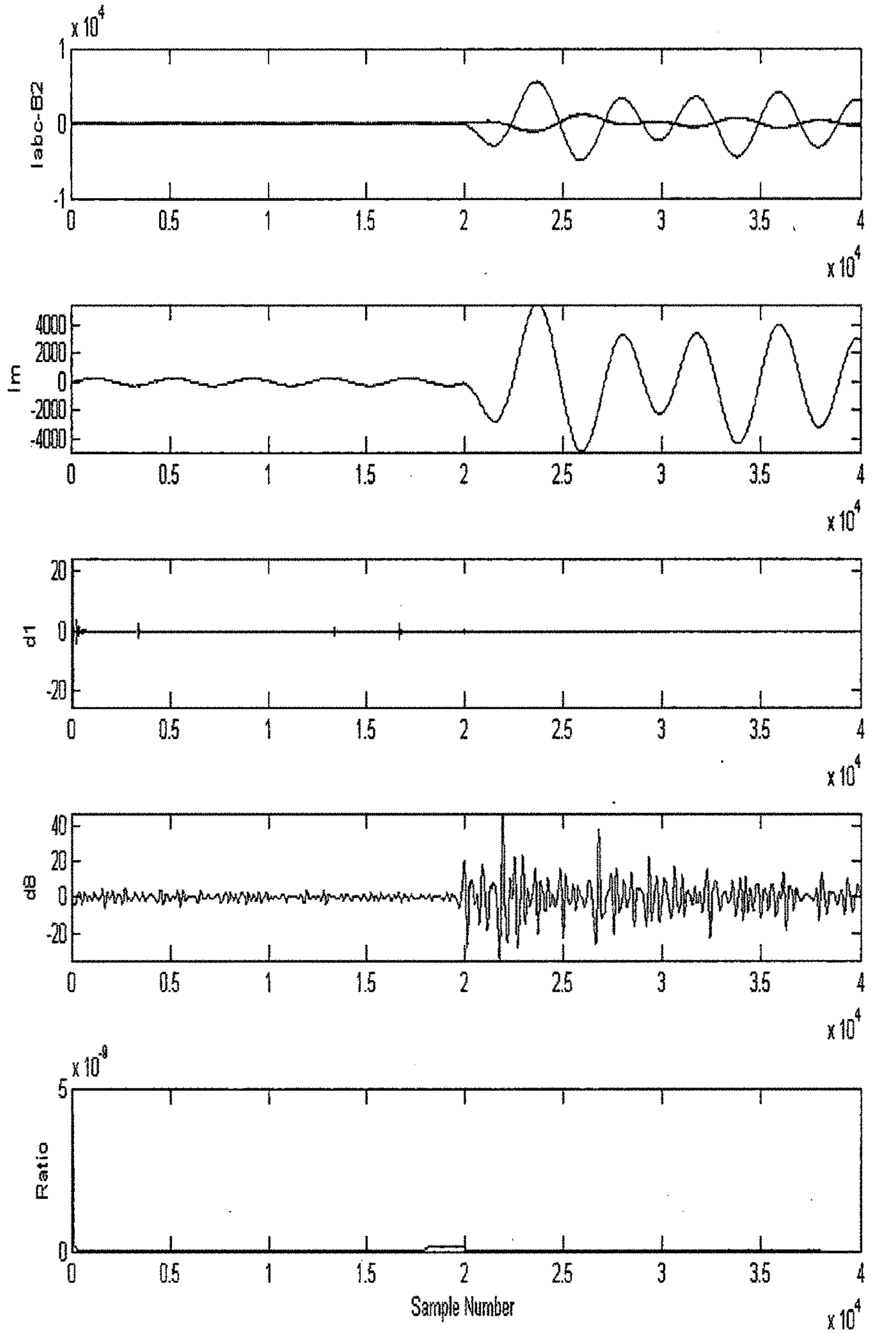

Fig.5.8 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,

d1: Value of d1coefficients, d8: Value of d8 coefficients,

Ratio of spectral energy for A-g fault on backward line section (Rf=0.01 ohm)

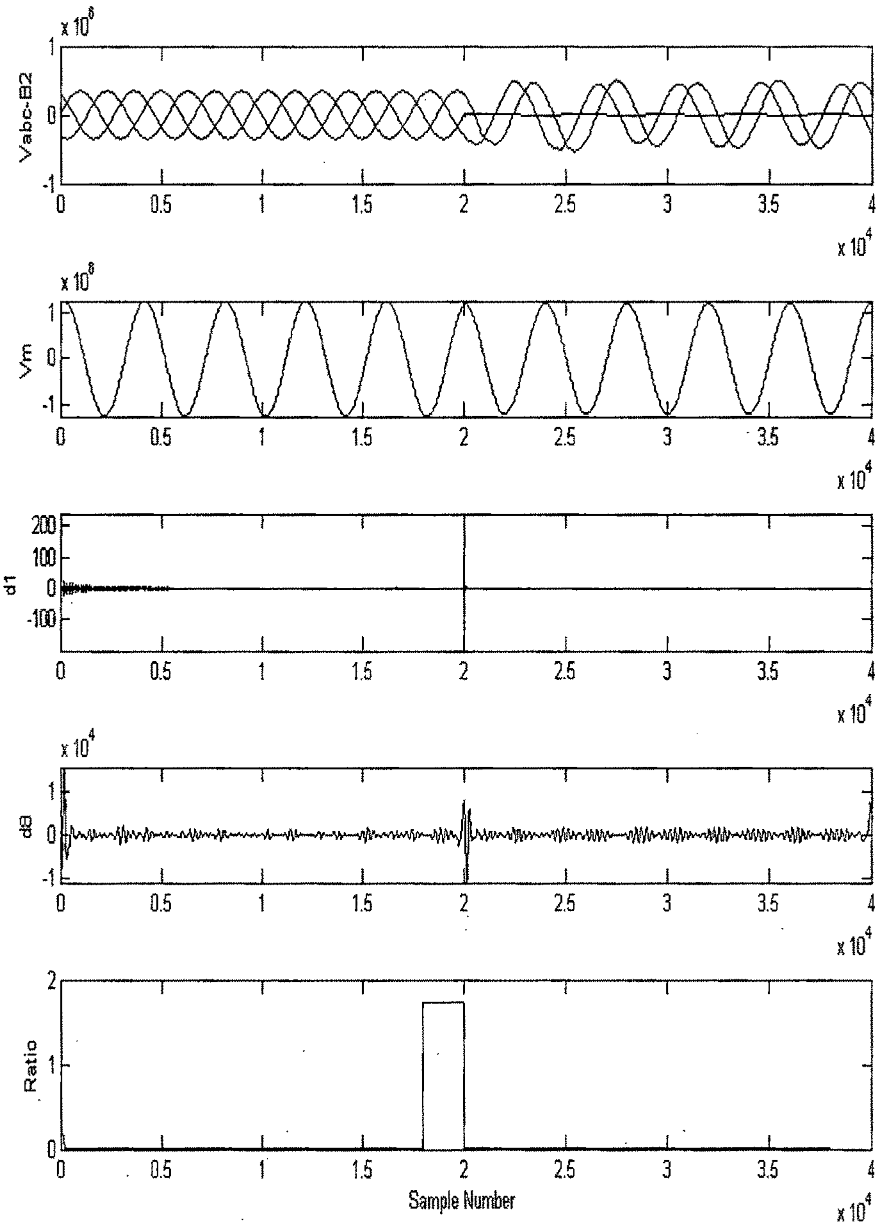

Fig.5.9 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, ratio of spectral energy for A-g fault on backward line section (Rf=0.01ohm)

As the ratio of spectral energies remains lower than threshold for modal current signal(Fig. 5.8), the scheme detects it as an external fault, further the ratio of spectral energies for modal voltage signal exceeds the threshold (Fig. 5.9), the scheme detects the fault is on backward line section.

(3) Xc=50%, ZG1=100%,ZG2=100%,A-B-g Fault at 120KM from Bus-B1, Rf=0.01 Ω (fault on protected line)

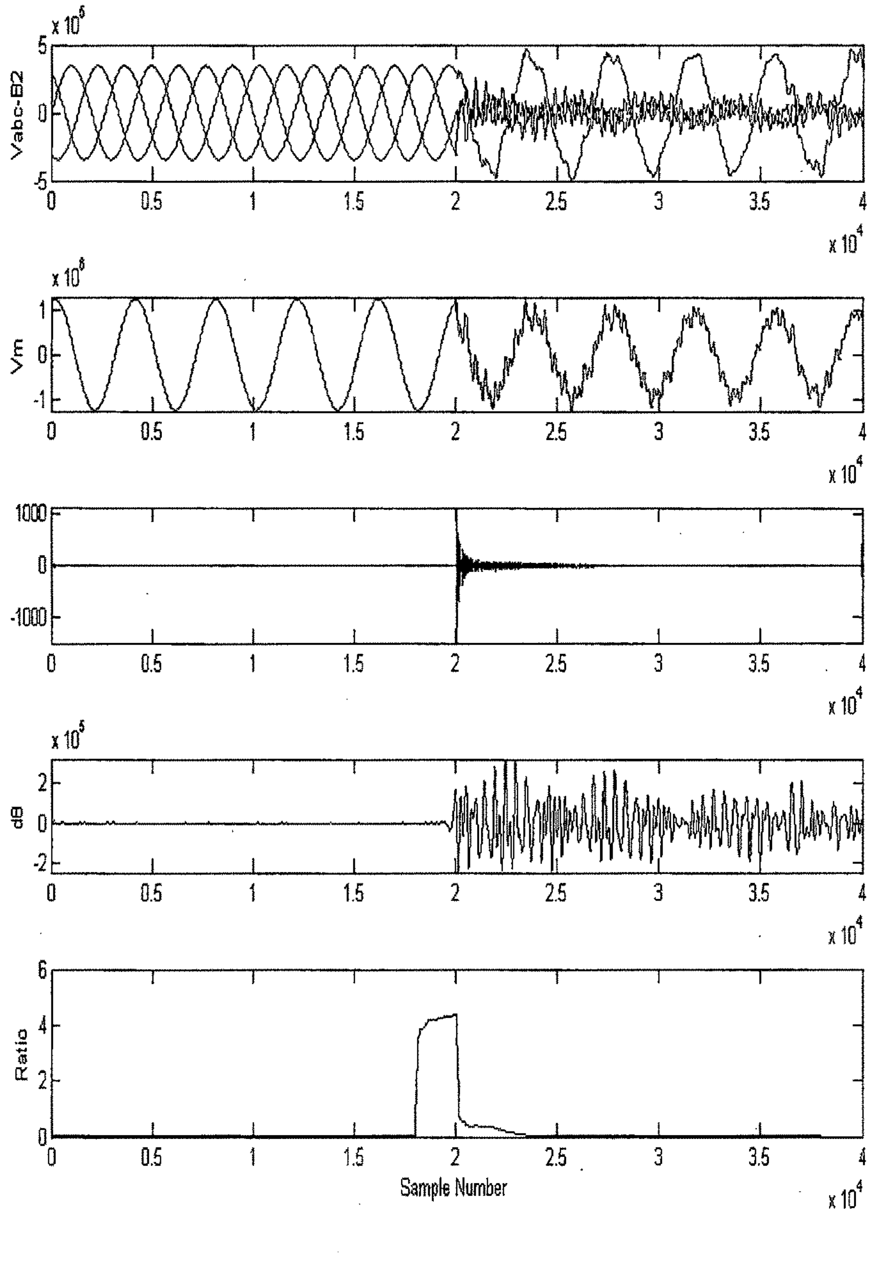

Fig.5.10 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-B-g fault on protected line section (Rf=0.01 ohm)

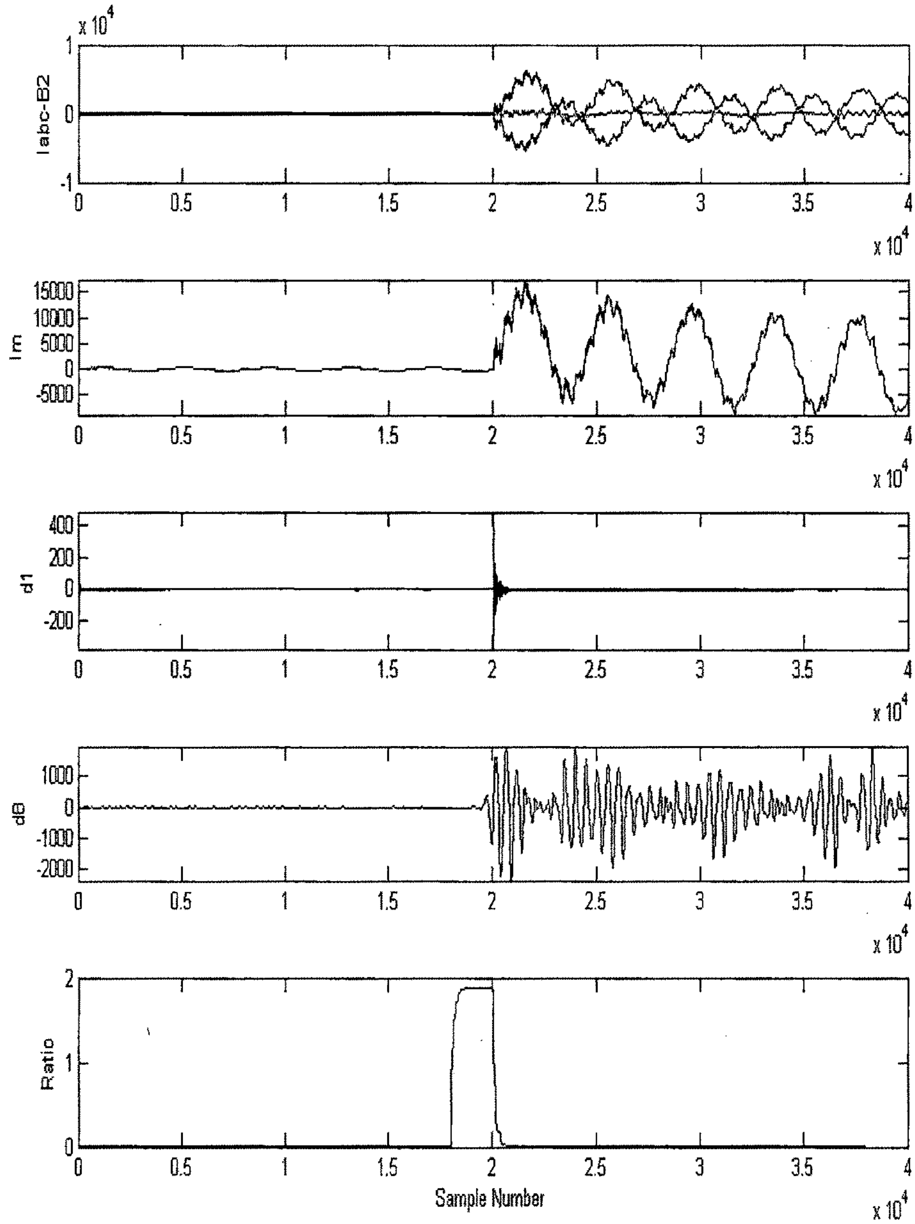

Fig.5.11 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1 coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-B-g fault on protected line section (Rf=0.01ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.10, 5.11), the scheme detects the fault as a fault on protected line section or internal fault.

(4) Xc=50%, ZG1=100%,ZG2=100%,A-B-C-g Fault at 120KM from Bus-B1, Rf=100 Ω (fault on protected line)

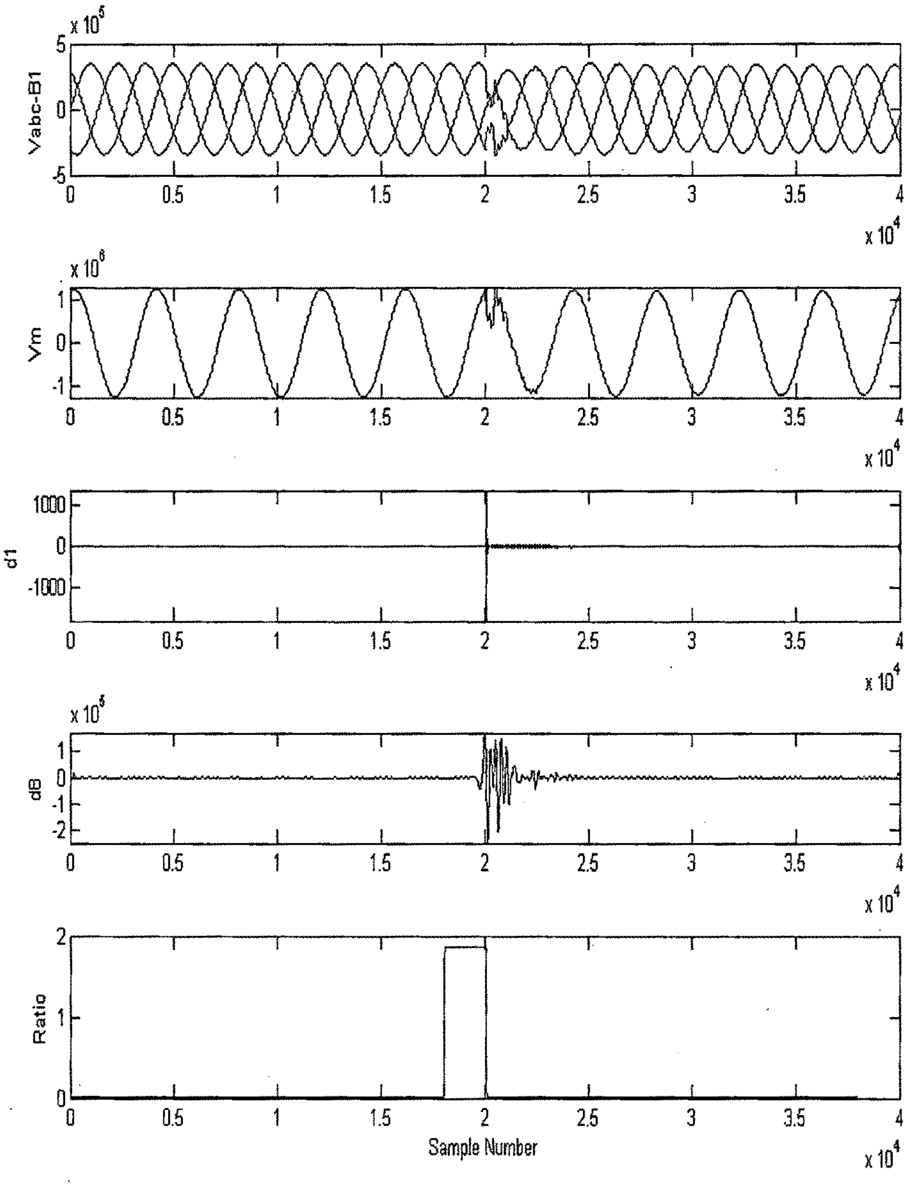

Fig.5.12 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients,

Ratio of spectral energy for A-B-C-g fault on protected line section (Rf=100 ohm)

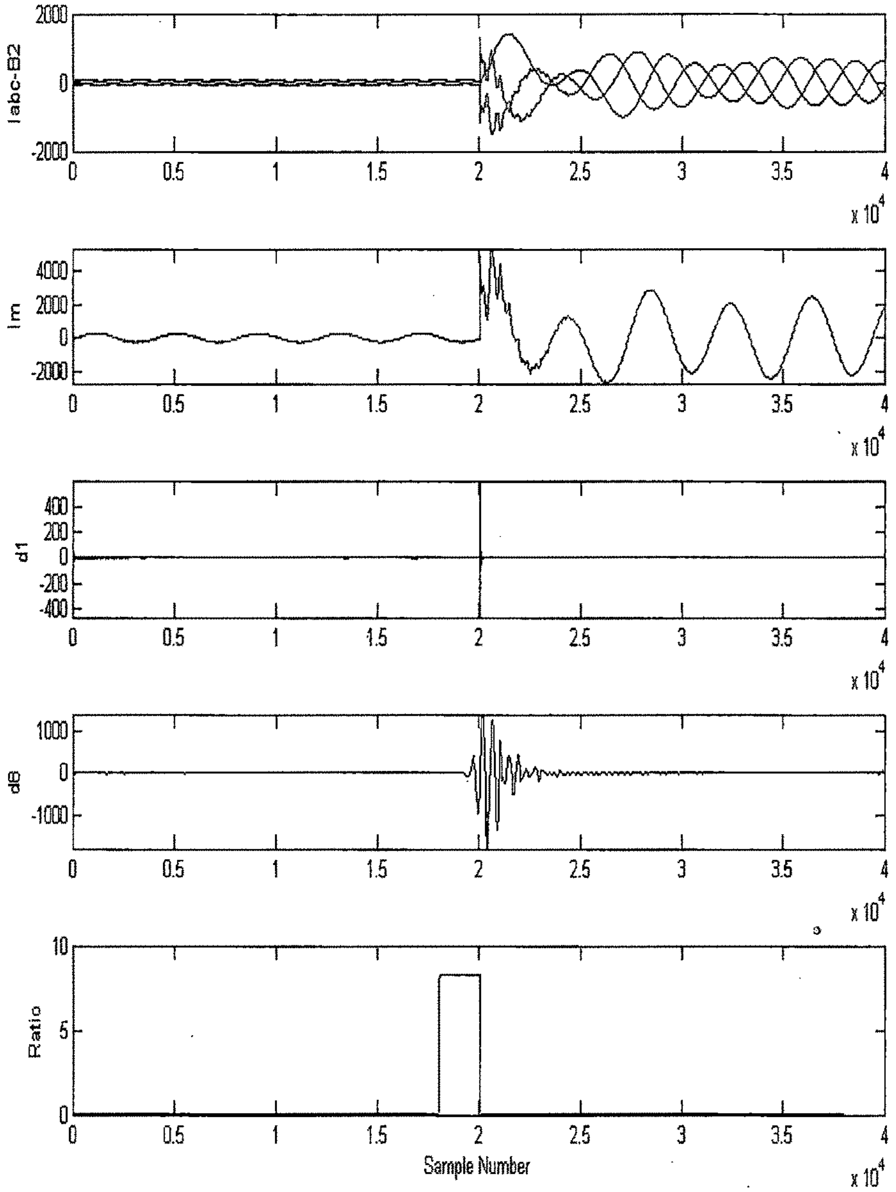

Fig.5.13 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,
d1: Value of d1coefficients, d8: Value of d8 coefficients,
Ratio of spectral energy for A-B-C-g fault on protected line section (Rf=100 ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.12, 5.13), the scheme detects the fault as a fault on protected line section or internal fault.

(5) Xc=75%, ZG1=100%,ZG2=100%,B-C Fault at 120KM from Bus-B1, Rf=1 Ω (fault on protected line)

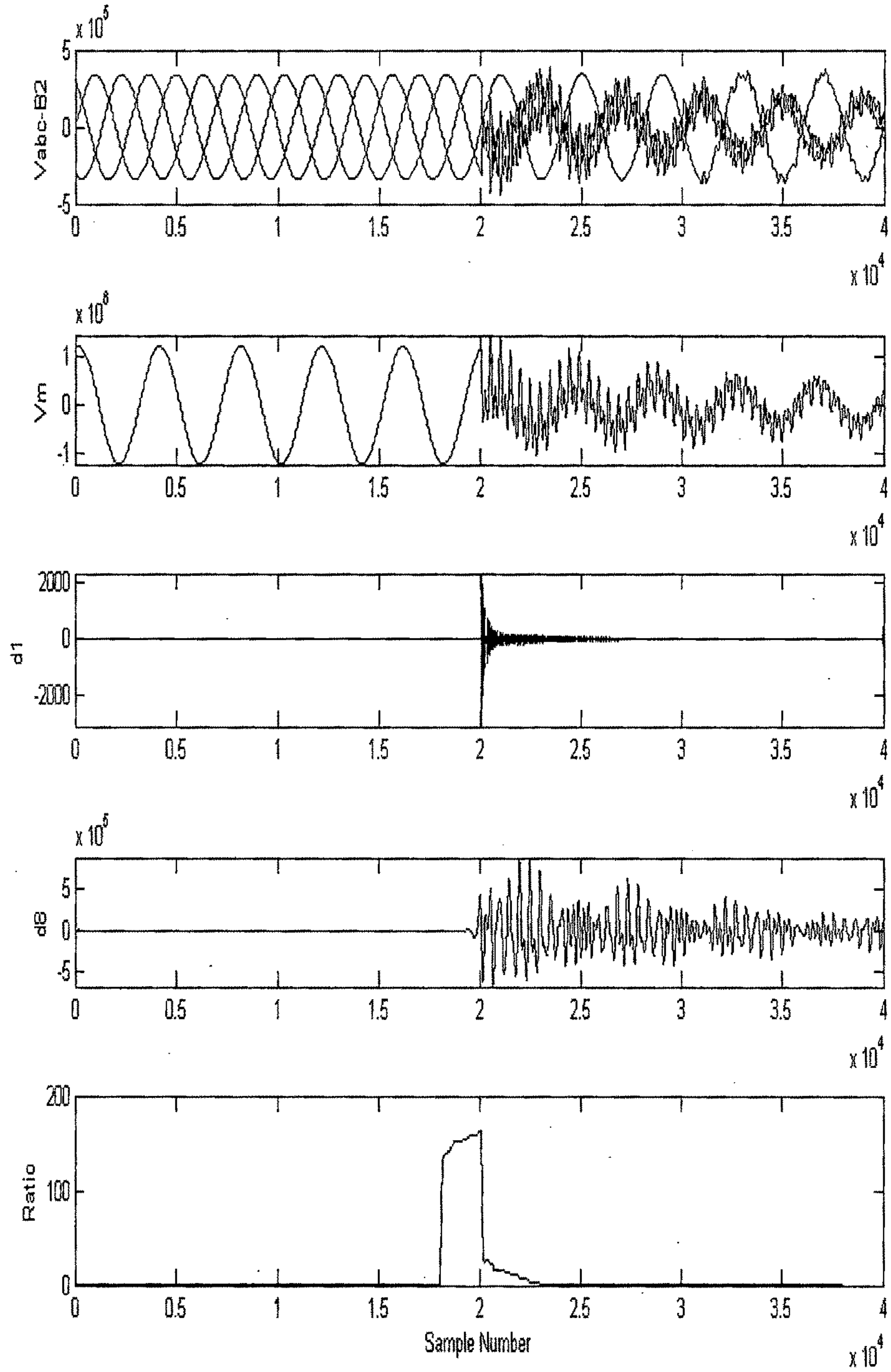

Fig.5.14 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal,

d1: Value of d1coefficients, d8: Value of d8 coefficients,

Ratio of spectral energy for B-C fault on protected line section (Rf=1 ohm)

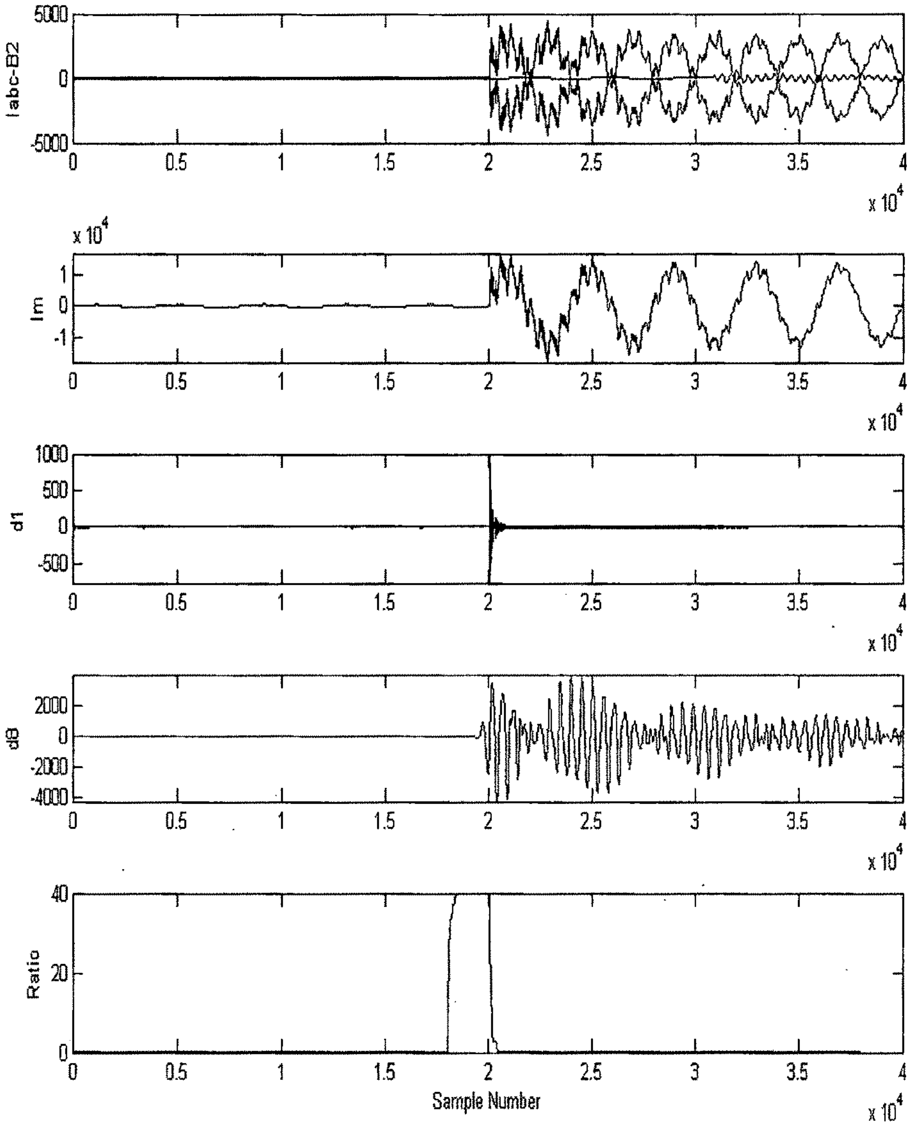

Fig.5.15 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for B-C fault on protected line section (Rf=1 ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.14, 5.15), the scheme detects the fault as a fault on protected line section or internal fault.

(6) Xc=75%, ZG1=100%,ZG2=100%,B-g Fault at 120KM from Bus-B1, Rf=50 Ω (fault on protected line)

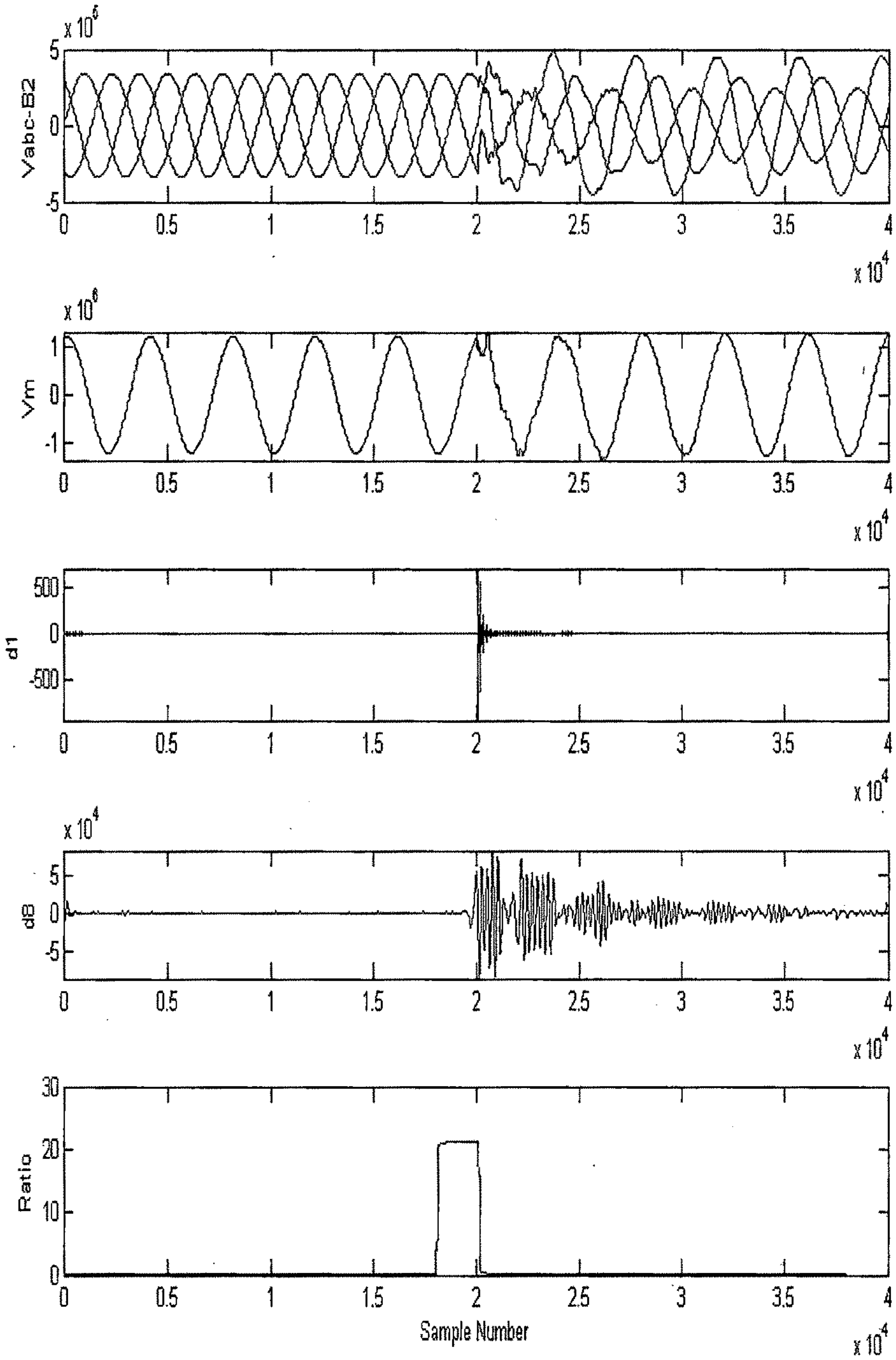

Fig.5.16 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for B-g fault on protected line section (Rf=50 ohm)

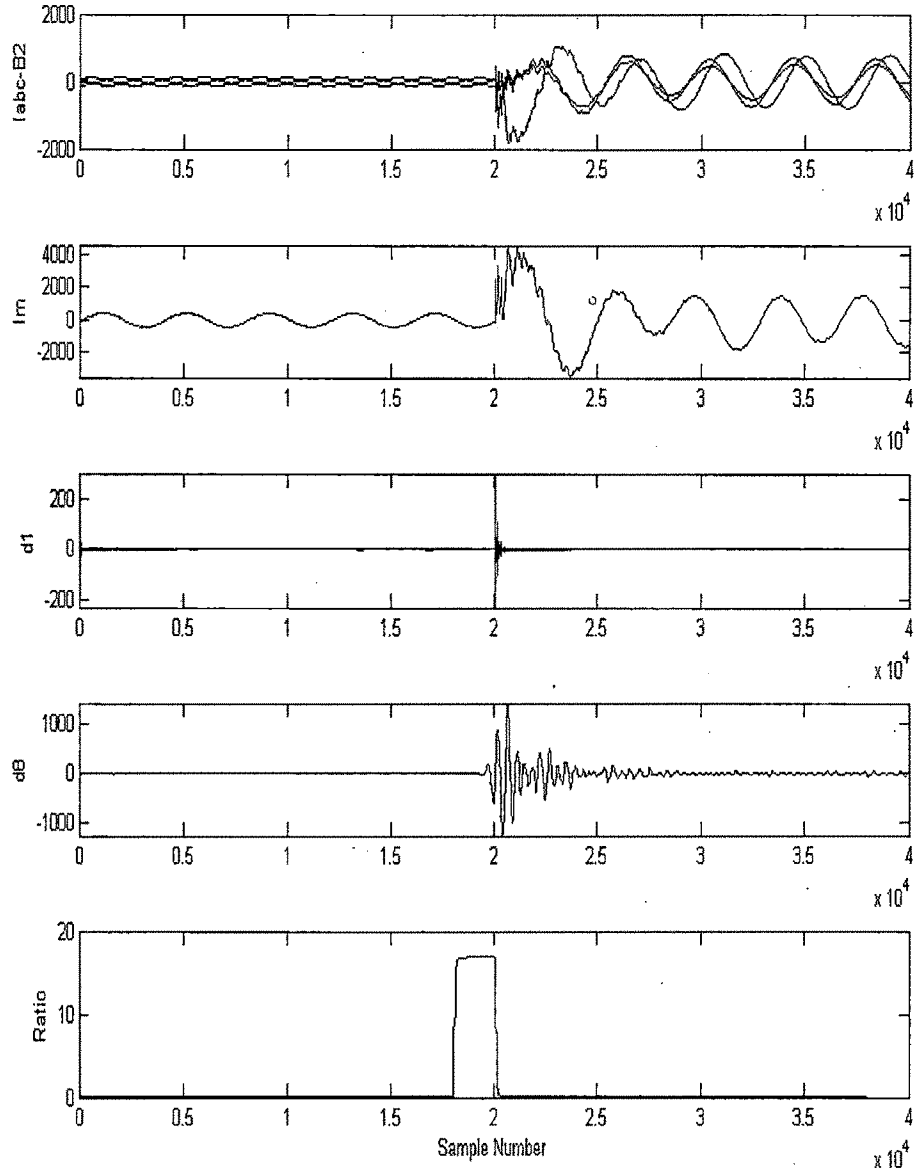

Fig.5.17 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,

d1: Value of d1coefficients, d8: Value of d8 coefficients,

Ratio of spectral energy for B-g fault on protected line section (Rf=50 ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.16, 5.17), the scheme detects the fault as a fault on protected line section or internal fault.

(7) Xc=25%, ZG1=100%,ZG2=100%,A-B-C Fault at 180KM from Bus-B1, Rf=100 Ω (fault on protected line)

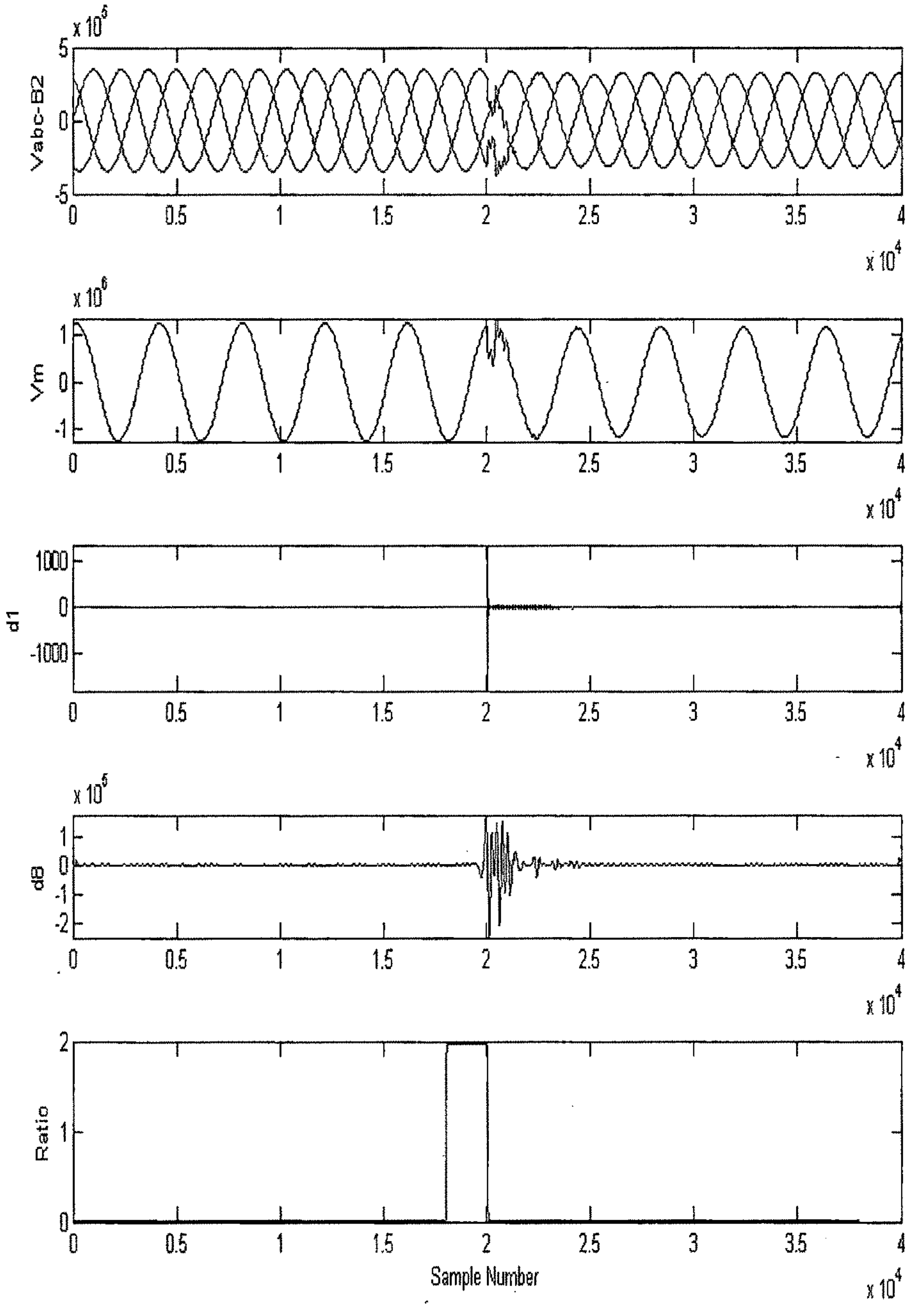

Fig.5.18 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-B-C fault on protected line section (Rf=100 ohm)

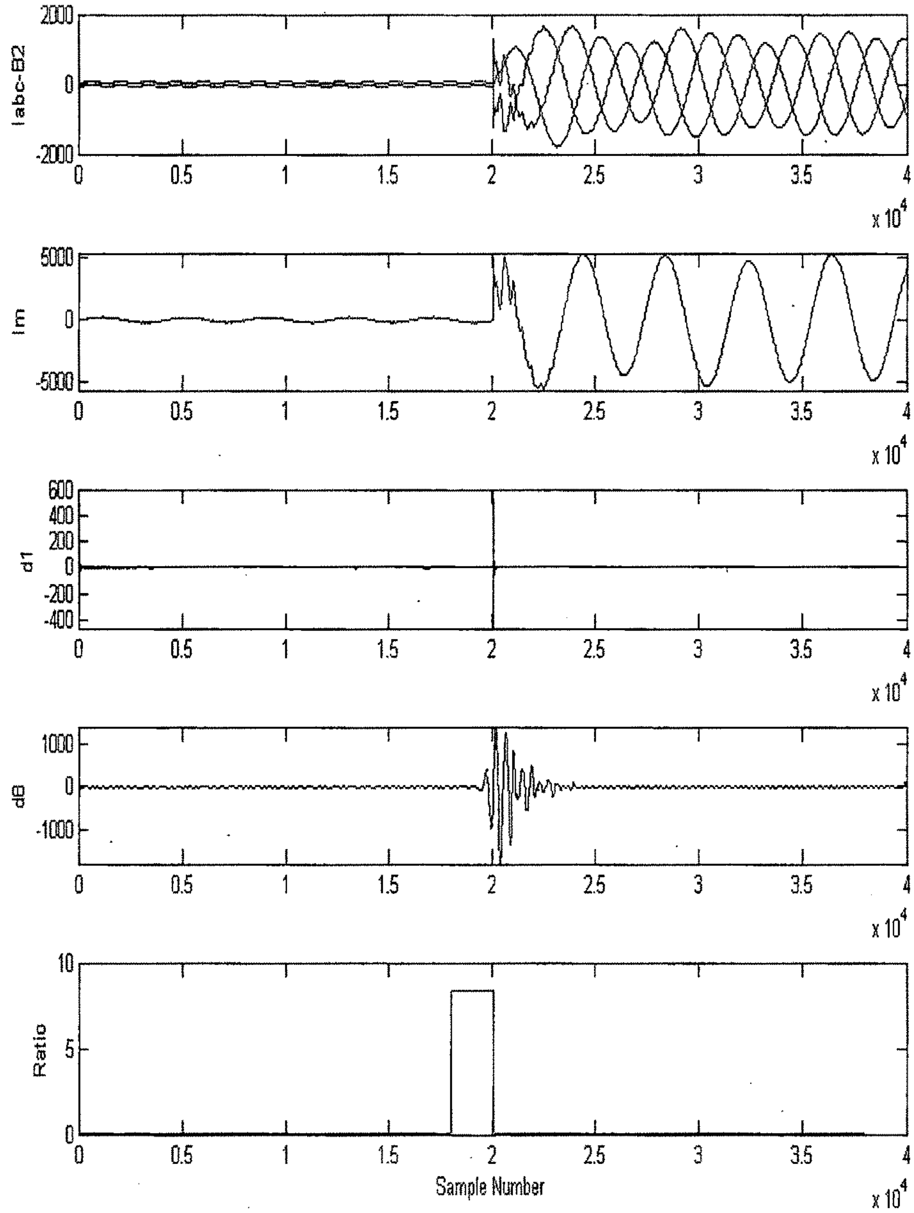

Fig.5.19 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,
d1: Value of d1coefficients, d8: Value of d8 coefficients,
Ratio of spectral energy for A-B-C fault on protected line section (Rf=100 ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.18, 5.19), the scheme detects the fault as a fault on protected line section or internal fault.

(8) Xc=25%, ZG1=100%,ZG2=100%,A-B-g Fault at 180KM from Bus-B1, Rf=0.01 Ω (fault on protected line)

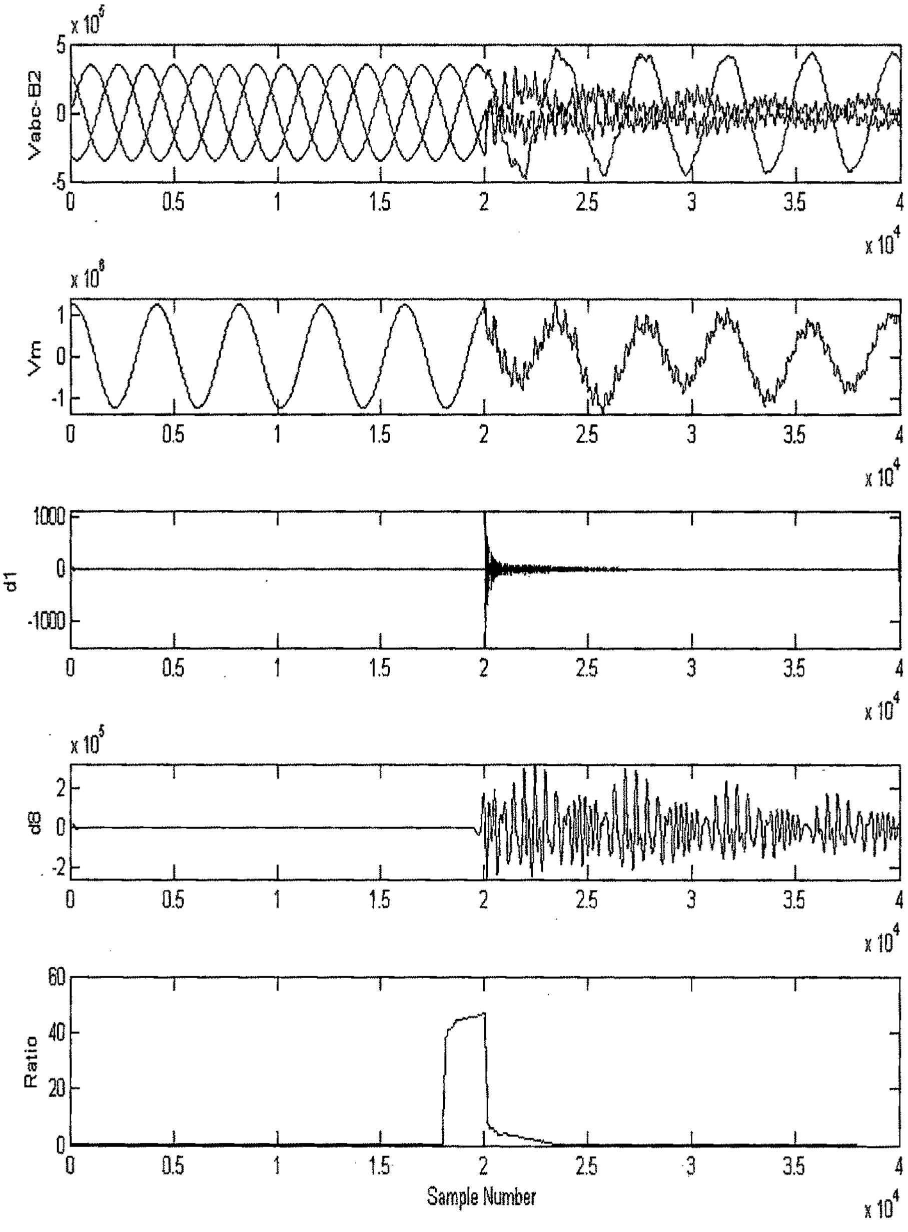

Fig.5.20 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-B-g fault on protected line section (Rf=0.01 ohm)

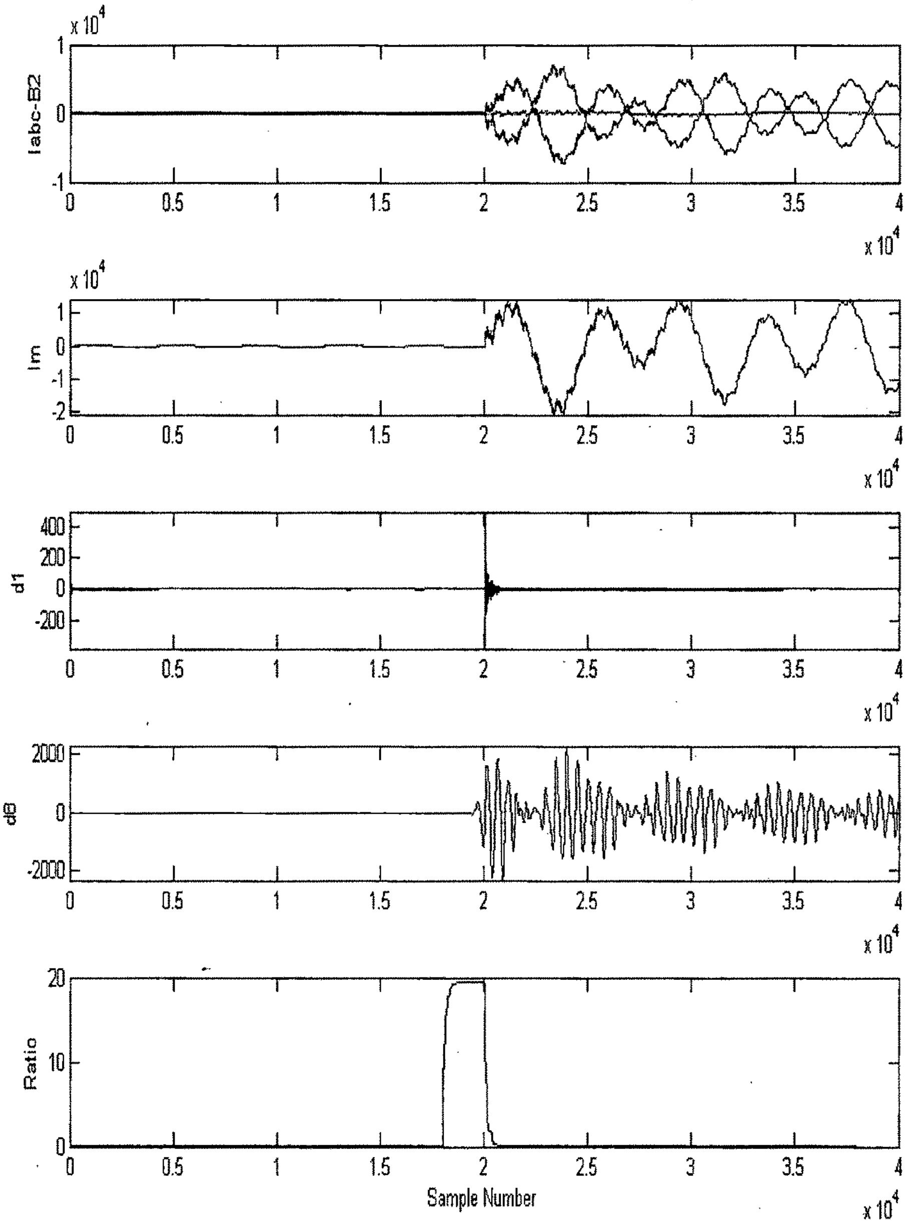

Fig.5.21 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-B-g fault on protected line section (Rf=0.01 ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.20, 5.21), the scheme detects the fault as a fault on protected line section or internal fault.

(9) Xc=50%, ZG1=100%, ZG2=125%, B-g Fault at 180KM from Bus-B1, Rf=1 Ω (fault on protected line)

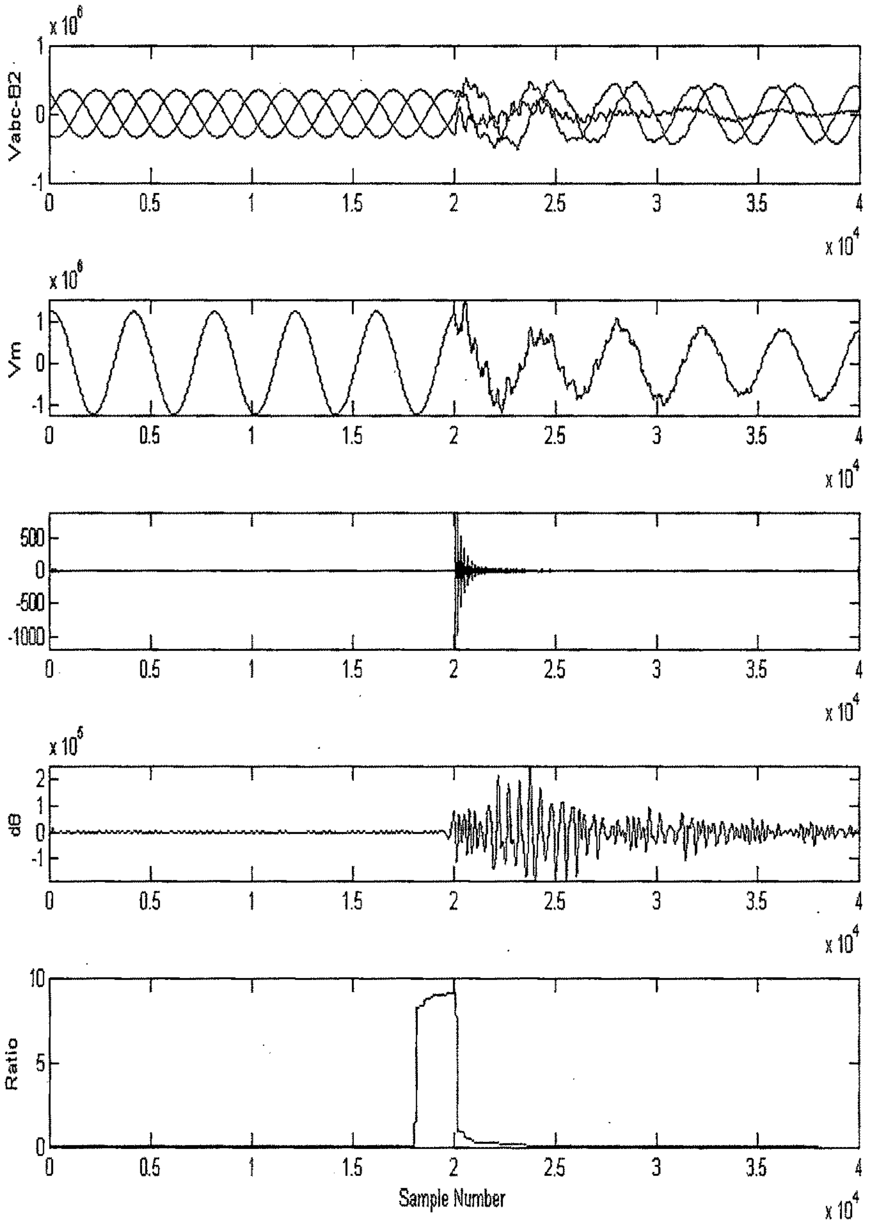

Fig.5.22 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for B-g fault on protected line section (Rf=1 ohm)

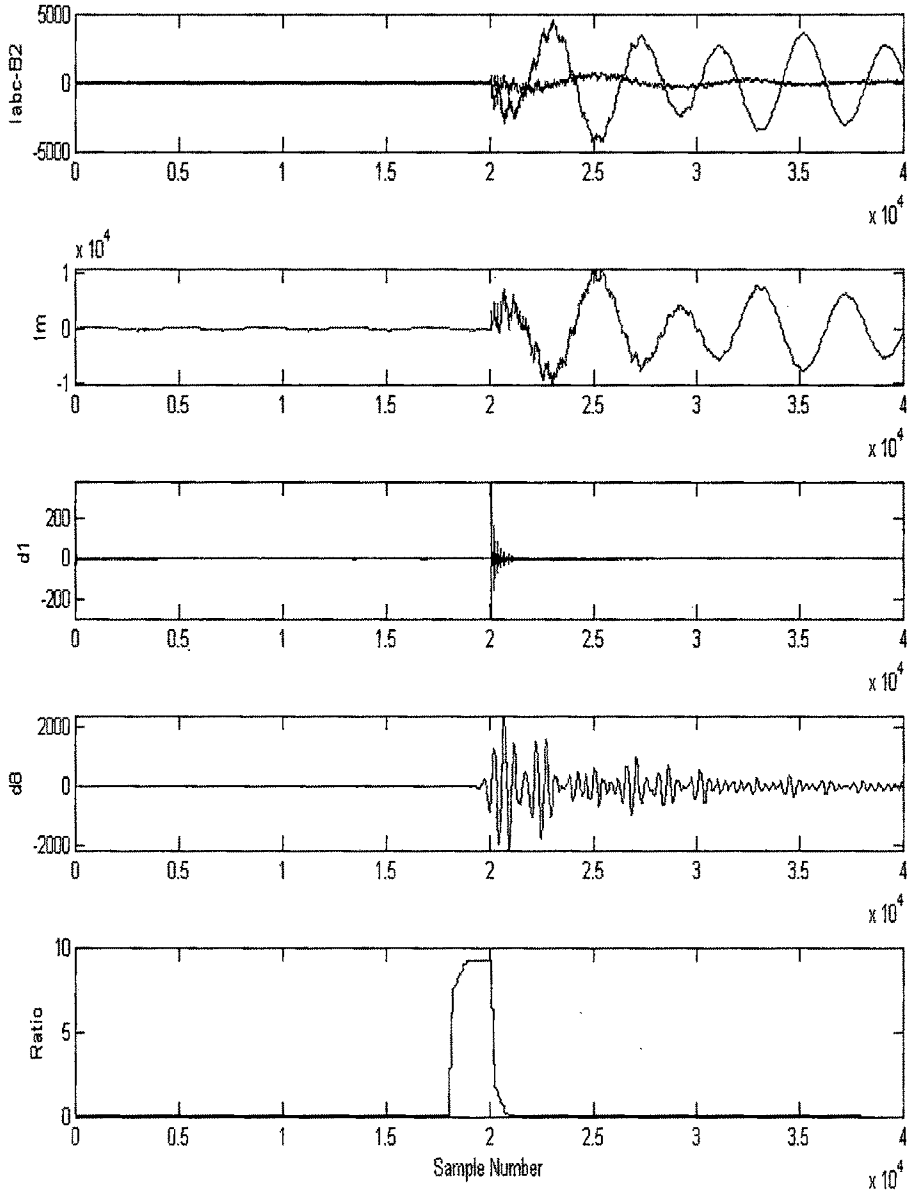

Fig.5.23 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for B-g fault on protected line section (Rf=1 ohm)

As the ratio of spectral energies exceeds the threshold for both modal signals (Fig. 5.22, 5.23), the scheme detects the fault as a fault on protected line section or internal fault.

(10) Xc=50%, ZG1=75%, ZG2=100%, B-C Fault at 180KM from Bus-B1, Rf=50 Ω (fault on protected line)

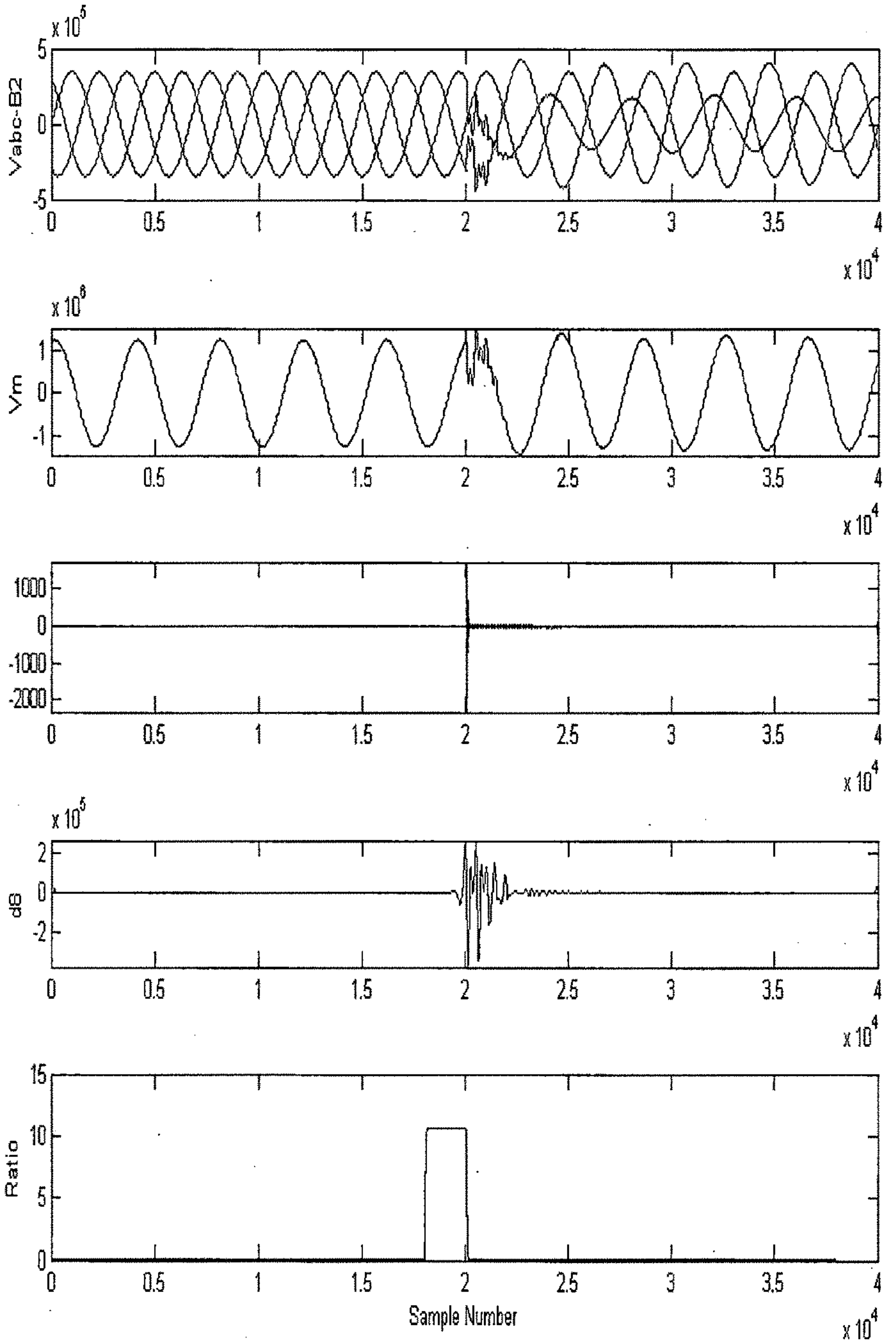

Fig.5.24 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for B-C fault on protected line section (Rf=50 ohm)

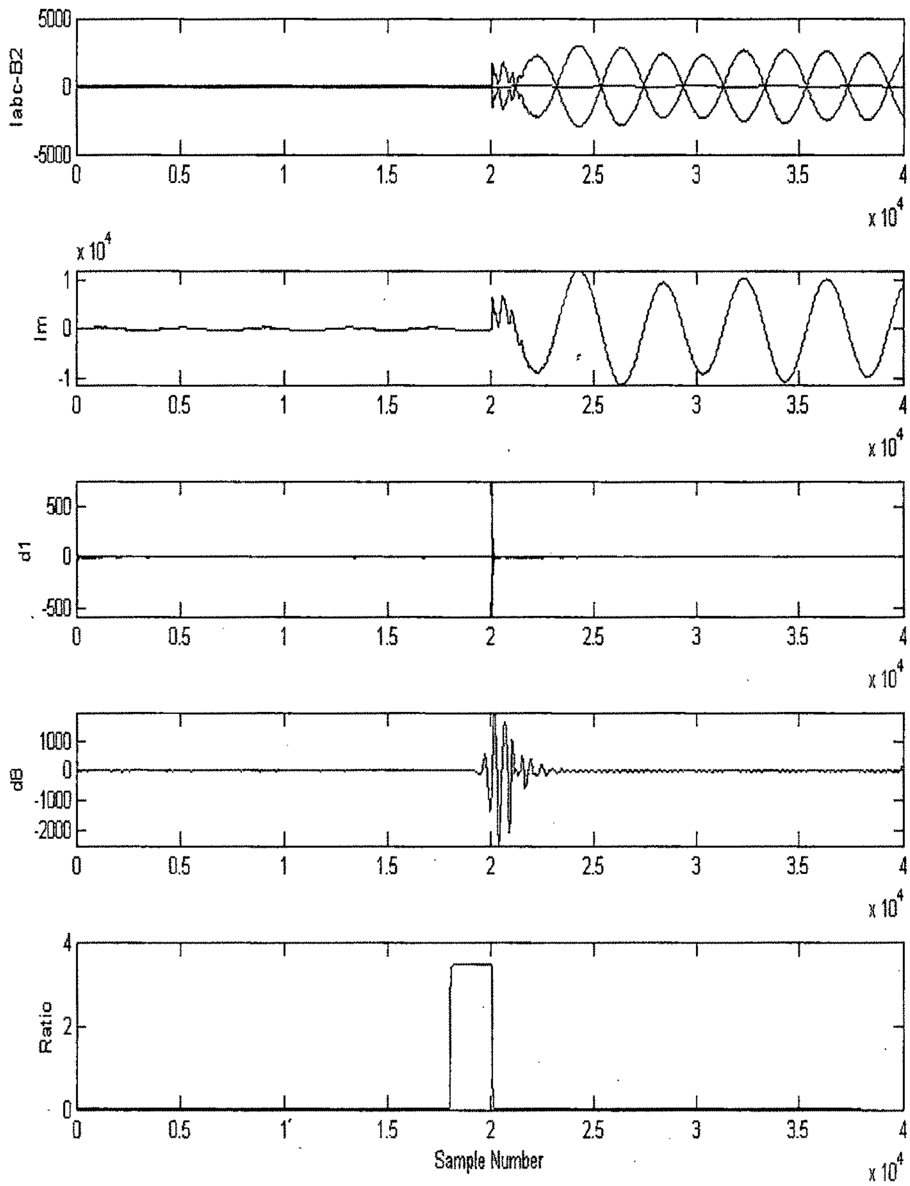

Fig.5.25 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for B-C fault on protected line section (Rf=50 ohm)

As the ratio of spectral energies exceeds the threshold for both model signals (Fig. 5.24, 5.25), the scheme detects the fault as a fault on protected line section or internal fault.

(11) Xc=50%, ZG1=100%, ZG2=100%, A-B-C-g Fault at 240KM from Bus-B1, Rf=0.01 Ω (fault on forward line)

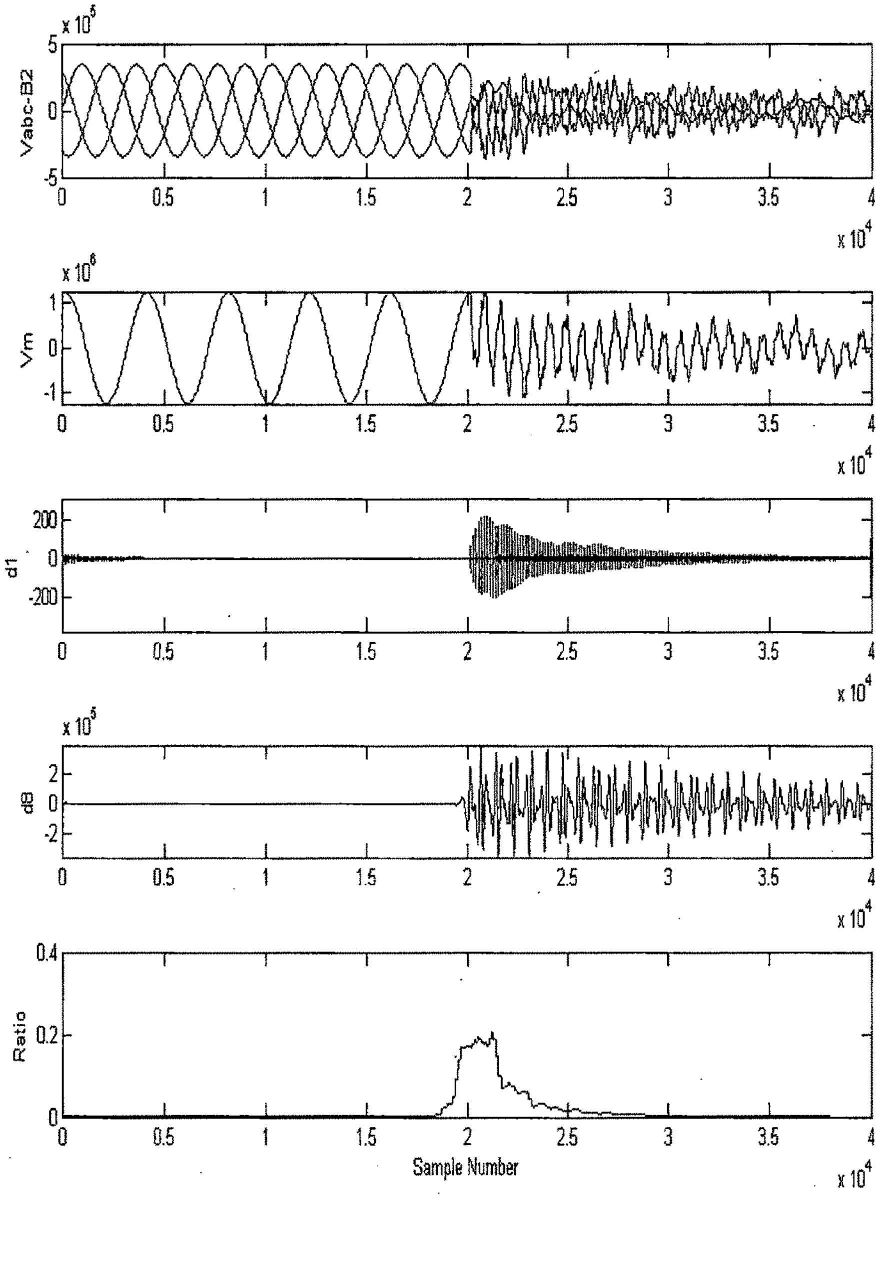

Fig.5.26 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-B-C-g fault on forward line section (Rf=0.01 ohm)

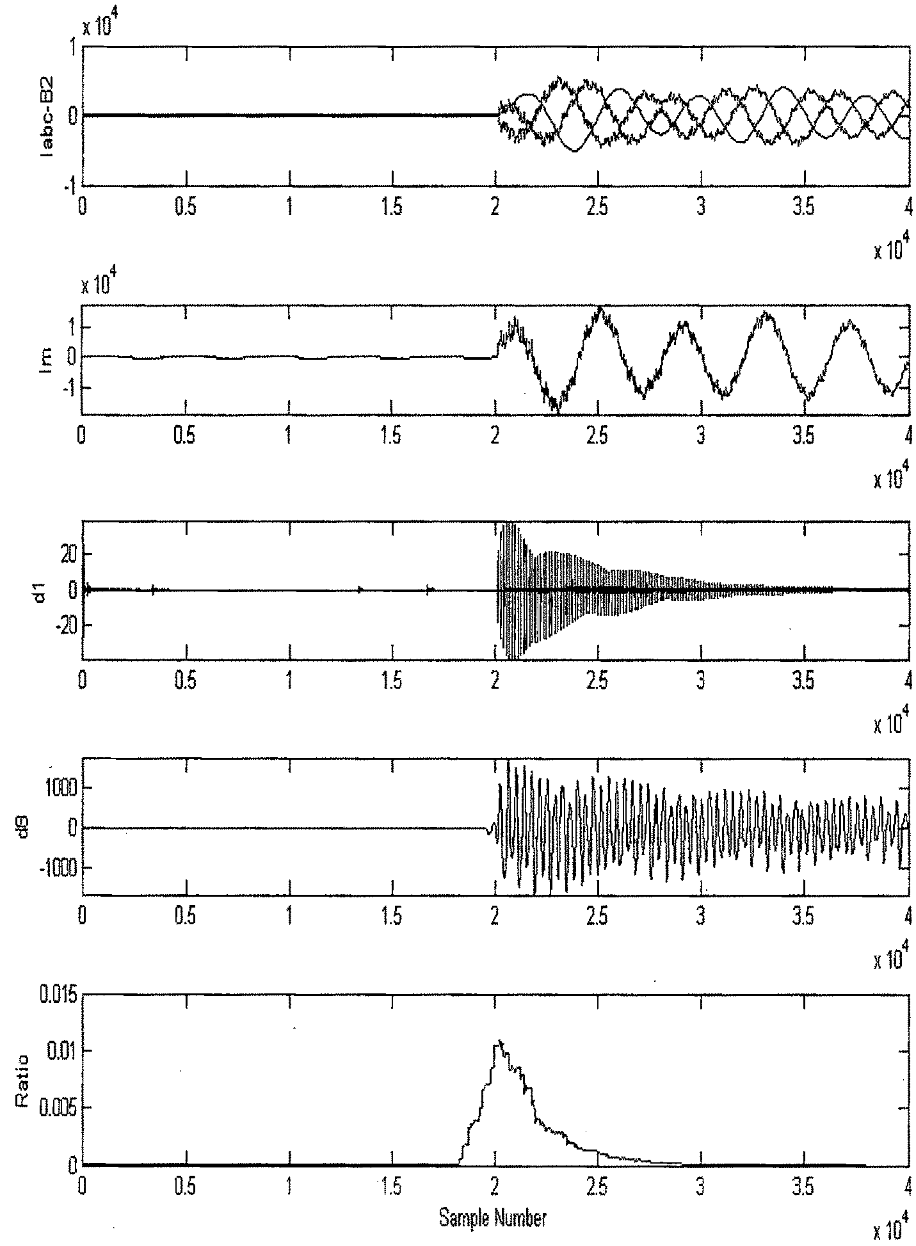

Fig.5.27 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,
d1: Value of d1coefficients, d8: Value of d8 coefficients,
Ratio of spectral energy for A-B-C-g fault on forward line section (Rf=0.01 ohm)

As the ratio of spectral energies remains lower than threshold for both model signals (Fig. 5.26, 5.27), the scheme detects the fault as a fault on forward line section or external fault.

(12) Xc=50%, ZG1=100%, ZG2=100%, A-C Fault at 240KM from Bus-B1, Rf=1 Ω (fault on forward line)

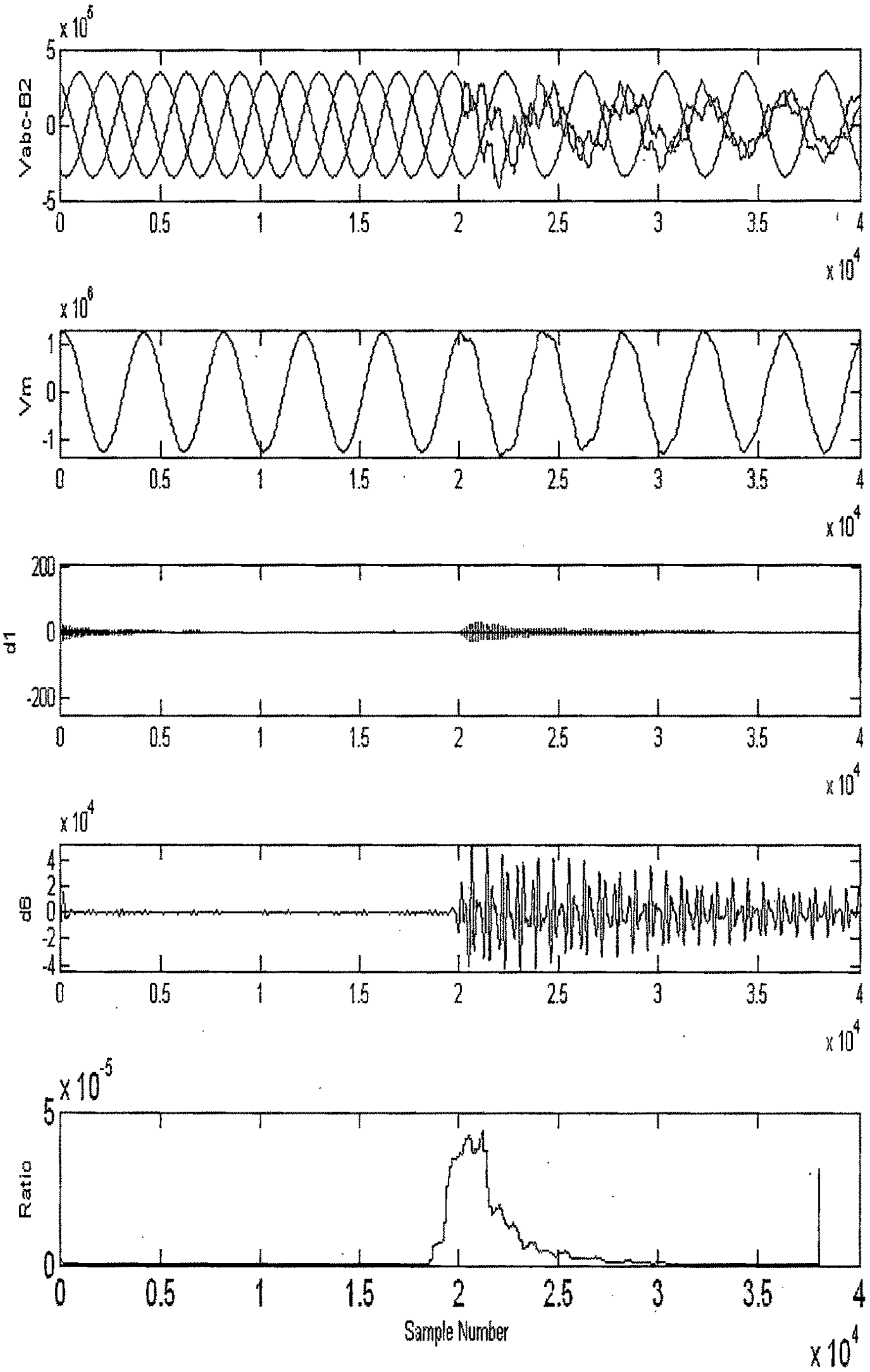

Fig.5.28 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-C fault on forward line section (Rf=1 ohm)

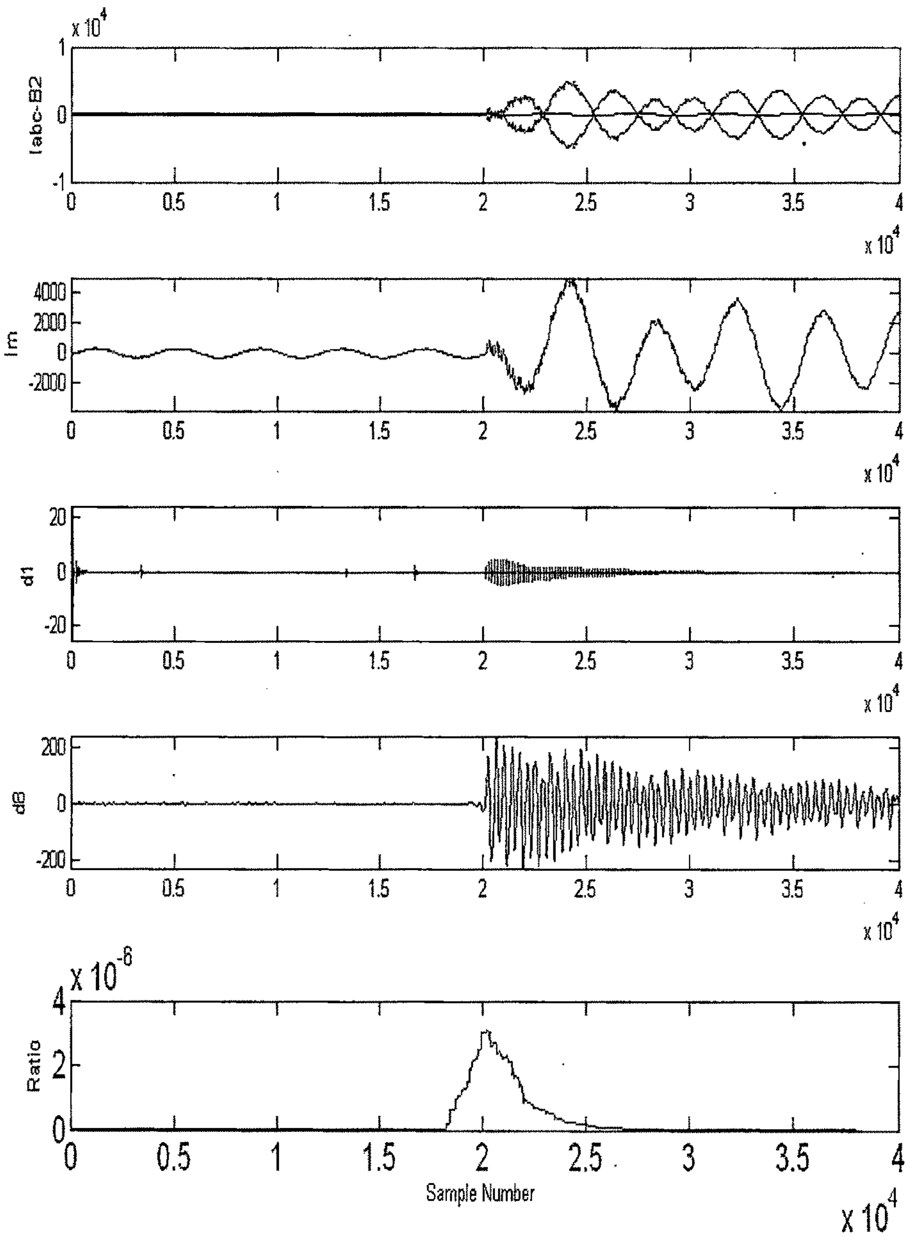

Fig.5.29 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for A-C fault on forward line section (Rf=1 ohm)

As the ratio of spectral energies remains lower than threshold for both model signals (Fig. 5.28, 5.29), the scheme detects the fault as a fault on forward line section or external fault.

(13) Xc=75%, ZG1=100%, ZG2=100%, C-g Fault at 240KM from Bus-B1, Rf=100 Ω (fault on forward line)

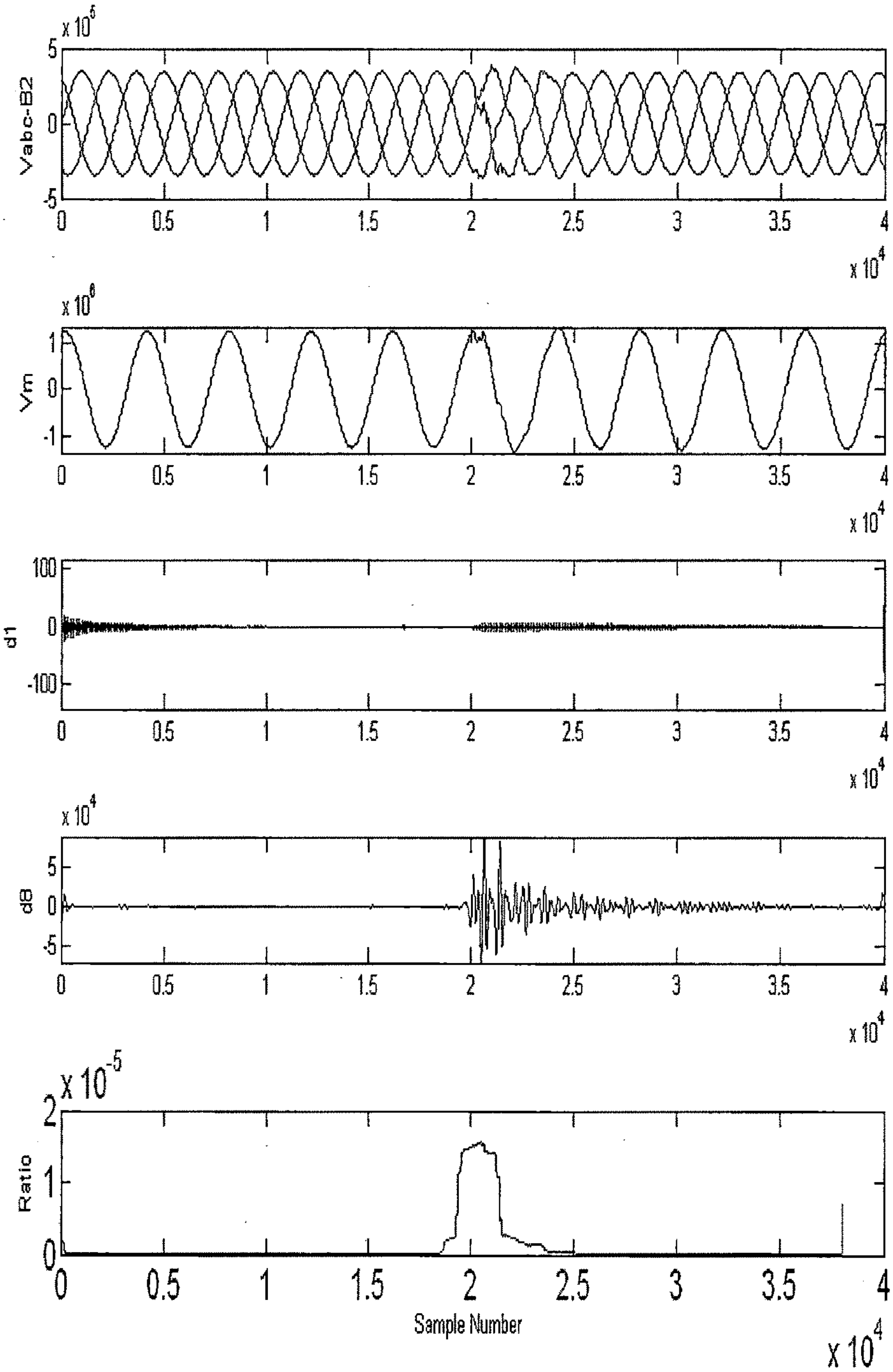

Fig.5.30 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal,
d1: Value of d1coefficients, d8: Value of d8 coefficients,
Ratio of spectral energy for C-g fault on forward line section (Rf=100 ohm)

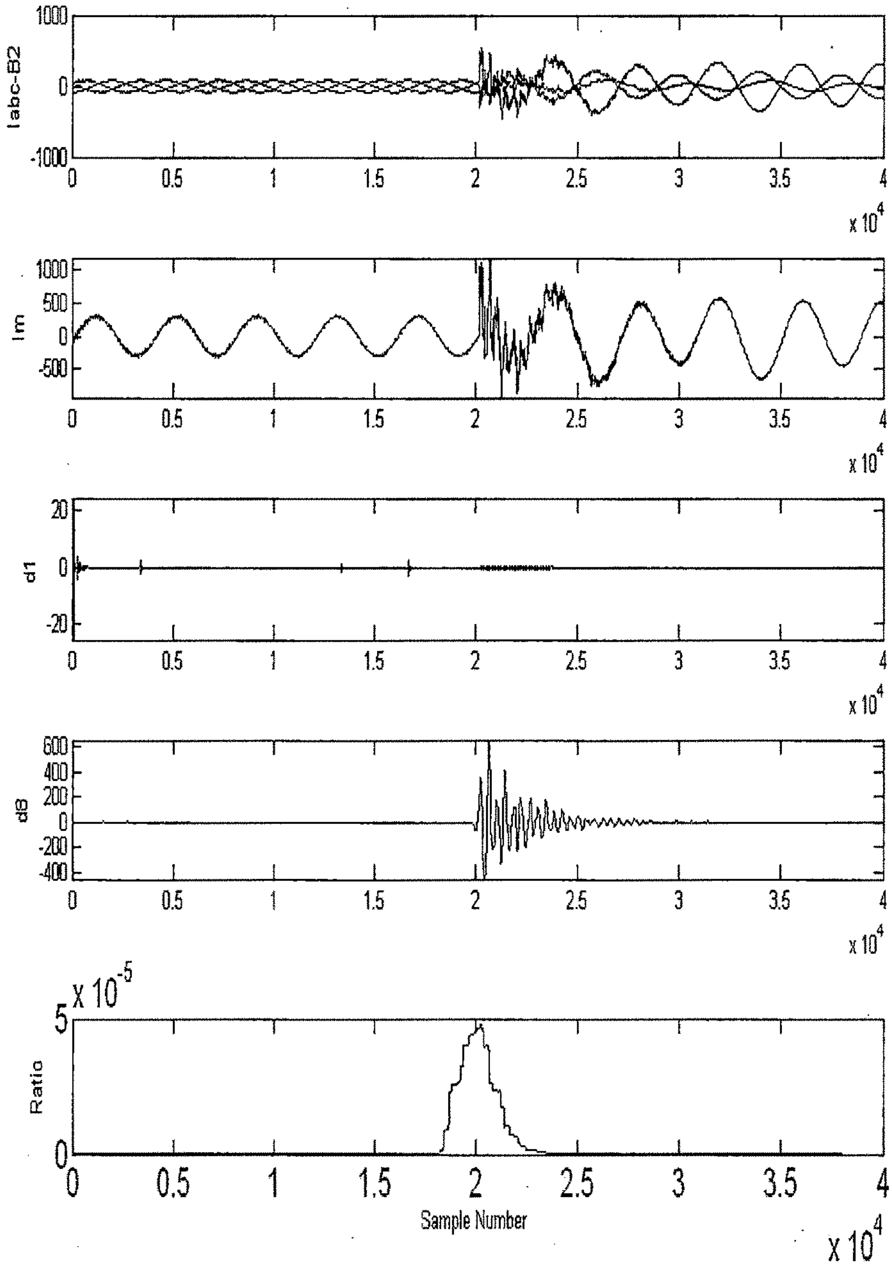

Fig.5.31 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal,
d1: Value of d1coefficients, d8: Value of d8 coefficients,
Ratio of spectral energy for C-g fault on forward line section (Rf=100 ohm)

As the ratio of spectral energies remains lower than threshold for both model signals (Fig. 5.30, 5.31), the scheme detects the fault as a fault on forward line section or external fault.

(14) Switching Operation at Bus-B3 (300MW,0.8 p.f. Load)

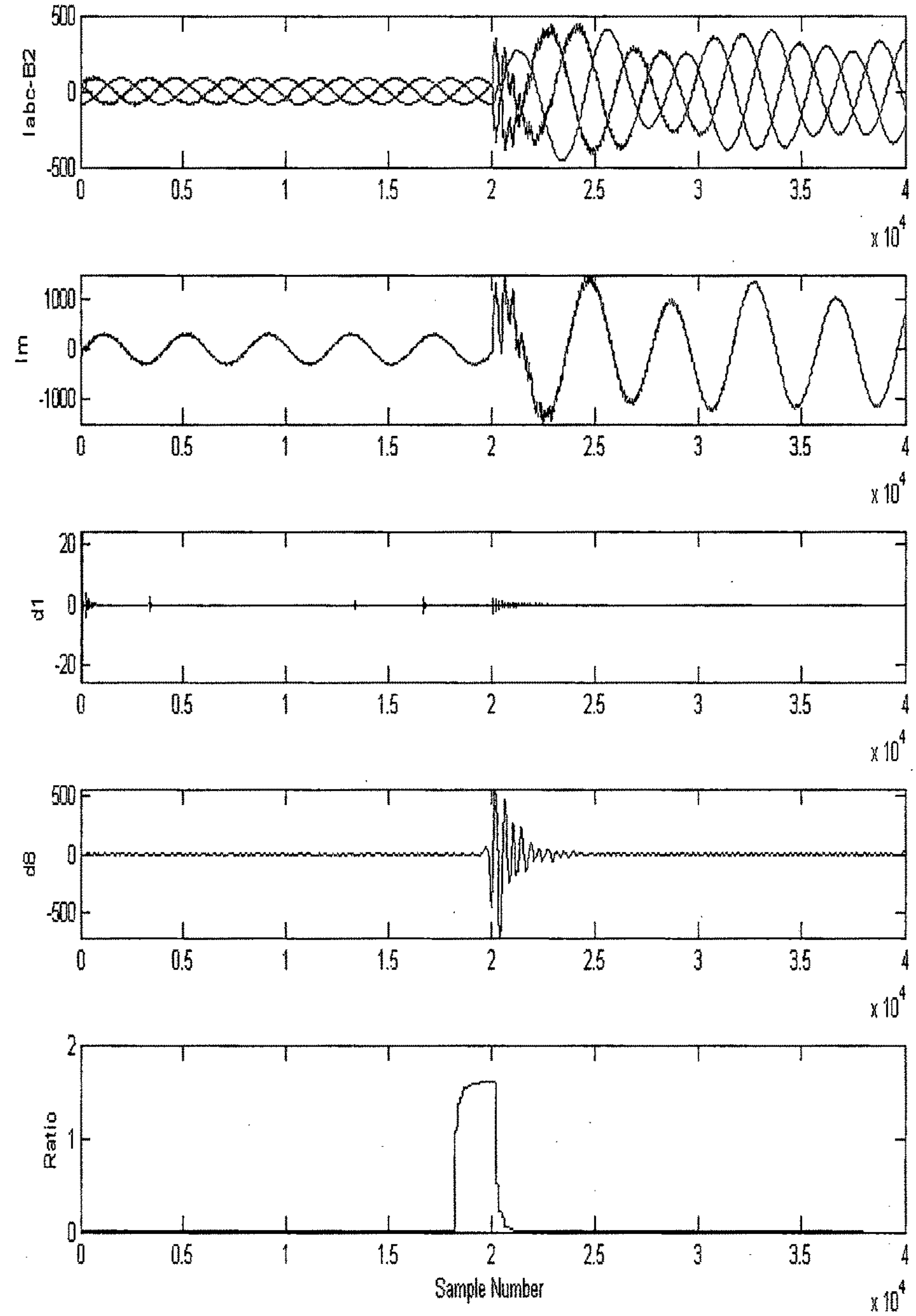

Fig.5.32 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for Switching Operation at Bus-B3

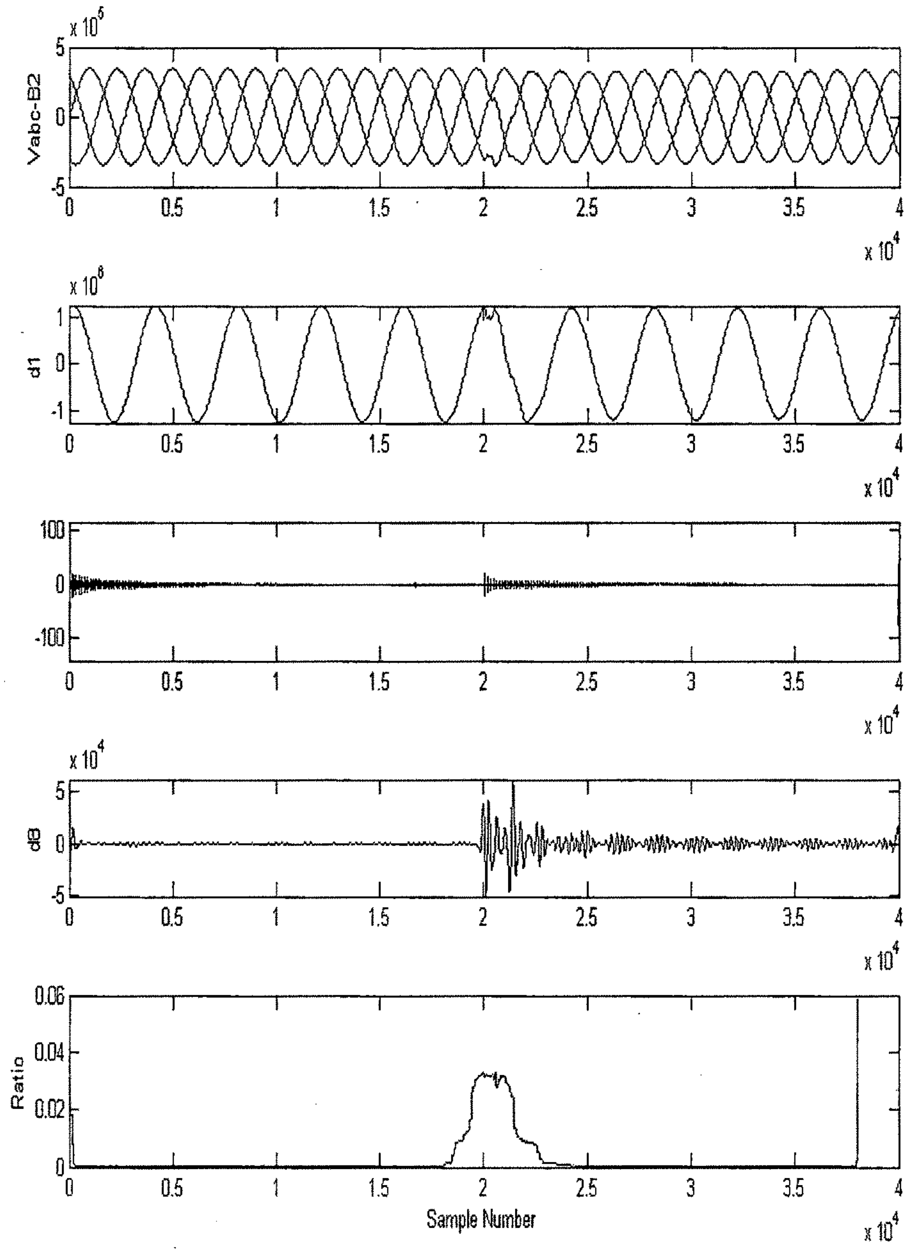

Fig.5.33 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for Switching Operation at Bus-B3

As the ratio of spectral energies, remains lower than threshold for Voltage Modal Signal (Fig. 5.33) and remains higher than threshold for Current Modal Signal (Fig. 5.32), the Scheme detects the abnormality as switching operation.

(15) Switching Operation at Bus-B2 (300MW,0.8 p.f. Load)

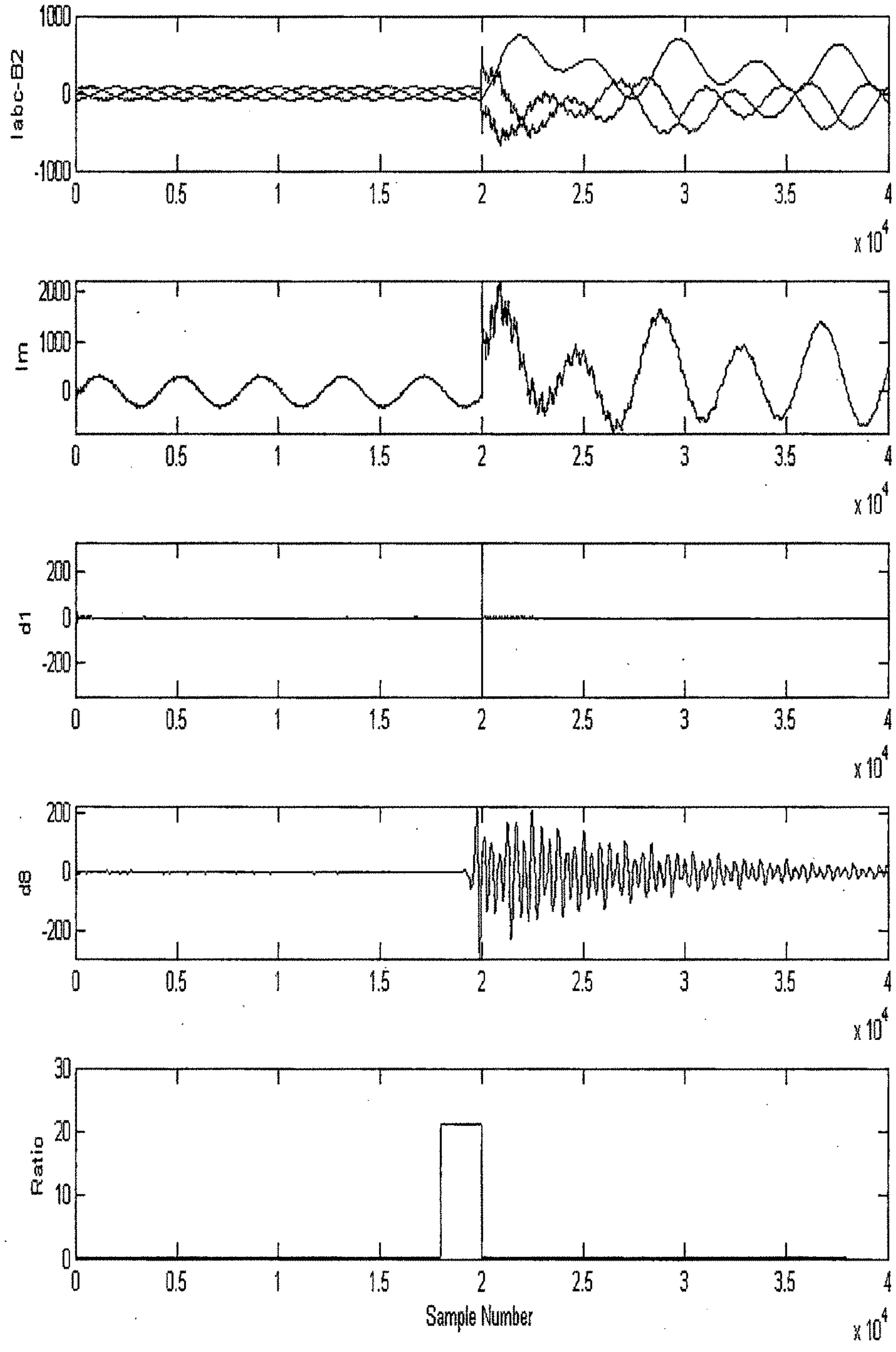

Fig.5.34 Plots showing Iabc-B2: Three Phase currents, Im: Modal Current Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for Switching Operation at Bus-B2

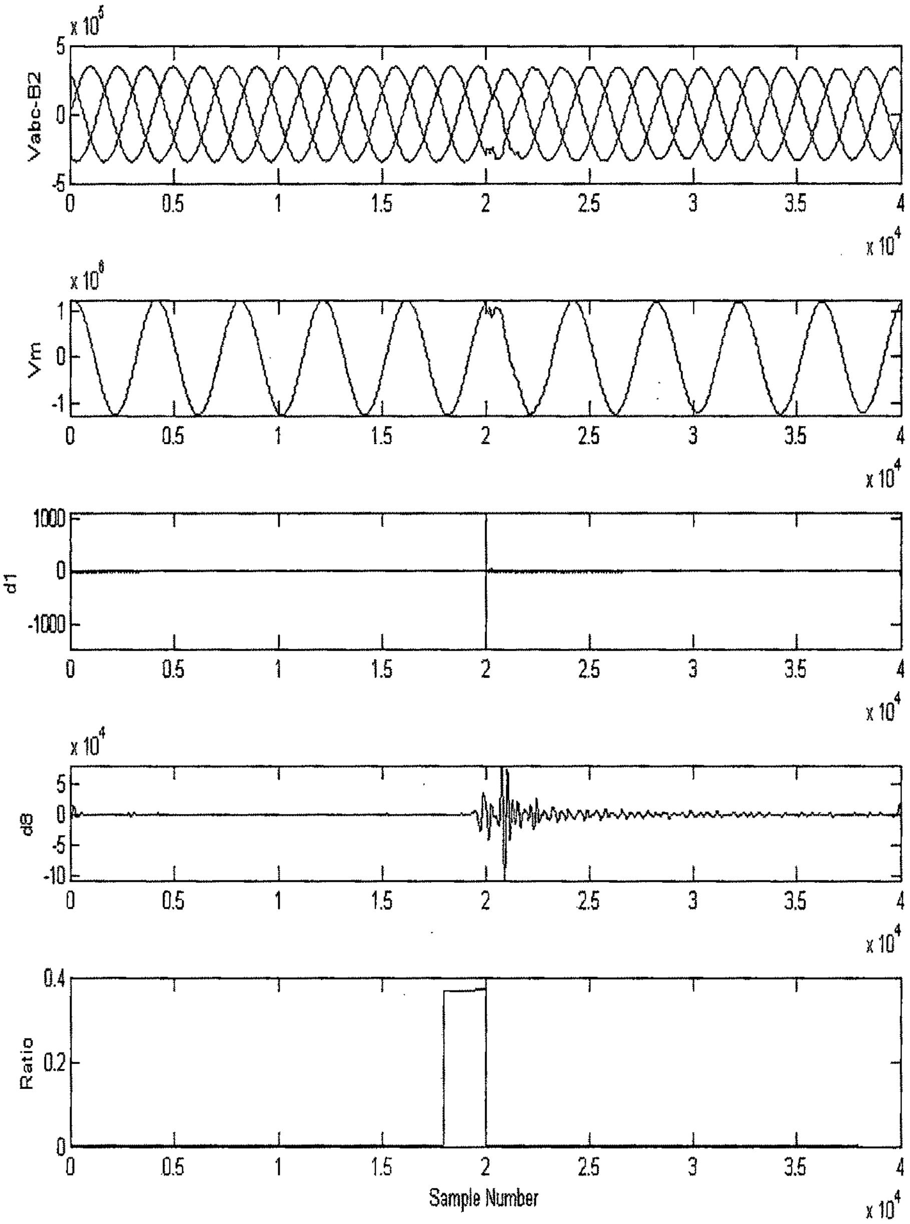

Fig.5.35 Plots showing Vabc-B2: Three Phase voltages, Vm: Modal Voltage Signal, d1: Value of d1coefficients, d8: Value of d8 coefficients, Ratio of spectral energy for Switching Operation at Bus-B2

As the ratio of spectral energies remains lower than threshold for Voltage Modal Signal (Fig. 5.35) and remains higher than threshold for Current Modal Signal (Fig. 5.34), the Scheme detects the abnormality as switching operation.

5.4 Summary of Simulation Results

The proposed scheme has been extensively tested by carrying out fault simulation studies under wide variation of load angle, fault inception angle, fault resistance and fault locations, compensation levels and variation of source impedance. Total 28,840 simulation cases (7200 test cases are generated and studied for forward and backward line each while 14,400 test cases are generated and studied for protected line section) has been tested using suggested scheme. The scheme is also tested for its robustness against switching transients by doing switching operations at all the four buses.

Table 5.5 Performance of Proposed Scheme with Different Parameters

Case No.	Xc %	ZG1 %	ZG2 %	Energy Ratio of Detail Coefficients	Threshold For d1 coefficients Line currents	Threshold For d1 coefficients ground current	No. of Test Cases	True Relaying Decision	Incorrect Relaying Decision	Accuracy (%)
1	50	100	100	1	0.5	0.00001	1920	1900	20	98.58
2		75	100	1	0.5	0.00001	1920	1910	10	99.47
3		125	100	1	0.5	0.00001	1920	1906	14	99.27
4		100	75	1	0.5	0.00001	1920	1912	08	99.58
5		100	125	1	0.5	0.00001	1920	1896	24	98.75
6	25	100	100	1	0.3	0.00001	1920	1895	25	98.69
7		75	100	1	0.3	0.00001	1920	1905	15	99.21
8		125	100	1	0.3	0.00001	1920	1890	30	98.43
9		100	75	1	0.3	0.00001	1920	1902	18	99.06
10		100	125	1	0.3	0.00001	1920	1888	32	98.33
11	75	100	100	1	0.8	0.00001	1920	1913	07	99.63
12		75	100	1	0.8	0.00001	1920	1916	04	99.79
13		125	100	1	0.8	0.00001	1920	1901	19	99.01
14		100	75	1	0.8	0.00001	1920	1909	11	99.42
15		100	125	1	0.8	0.00001	1920	1900	20	98.58
16	Switching Operations at Various Buses						40	39	01	97.500
Total							28840	28582	258	99.10

Table 5.5 gives the thresholds selected for energy ratio for fault zone identification and thresholds selected of d1 coefficients for fault classification through heuristic approach for various compensation levels with variation of source impedances. It also shows the accuracy of the proposed scheme with different parameters. From Table 5.5 it can be said that the proposed technique is quite effective in case of wide variations in the source impedance along with the change in compensation level. It is also observed from the table 5.5 that, the cases which limits the accuracy of the proposed technique are having very high value of source impedance which makes the system weak (reduces fault current feed capacity), ultimately reducing the high frequency transients results due to fault inception.

The simulation studies also indicated that the proposed technique has a very high degree of accuracy in fault detection, fault zone identification and fault classification. The technique is robust and does not respond spuriously to switching operations.