A Novel High Impedance Fault Detection Technique in Distribution Systems With Distributed Generators

Paresh Kumar Nayak[1], *Member, IEEE*, Kumari Sarwagya[2], and Tapaswini Biswal[3]
Department of Electrical Engineering
Indian Institute of Technology (Indian School of Mines)
Dhanbad-826004, India
[1]pareshkumar.nayak@gmail.com, [2]srwgsh@gmail.com, and [3]avilipsa.biswal@gmail.com

***Abstract*— Conventional overcurrent relaying based protection scheme has limitation to detect high impedance faults in distribution systems due to random, nonlinear and low magnitude fault currents. The problem becomes further complicated in presence of distributed generators in distribution systems due to bidirectional flow of power and reduction of fault current contribution from the main grid. This paper presents a one-cycle sum of superimposed component of residual voltage based method to detect high impedance faults in distribution systems integrated with distributed generators. The performance of the scheme is evaluated for high impedance faults at different locations of a 7-node radial distribution system integrated with distributed generators. The scheme is also tested for different non-fault events like capacitor switching and load switching, which often produce similar characteristics as that of high impedance faults. PSCAD/EMTDC software is used for generating data for different test cases and the method is implemented using Matlab software. Results clearly show that the proposed scheme can assist conventional overcurrent relay in detecting high impedance faults in distribution systems integrated with distributed generators in a more reliable and faster way.**

***Keywords*— distribution systems, distributed generators, high impedance fault, overcurrent protection.**

I. INTRODUCTION

THE energized conductors in distribution systems often come in contact with poorly grounded objects, like trees, wood fences, vehicles etc. Sometimes the conductor breaks and touches the high impedance ground surfaces such as asphalt, concrete, grass, sand etc. These contacts restrict the fault current from few mA to 75A only [1]. Such low current high impedance faults (HIFs) are not detected by conventional overcurrent relaying based distribution network protection. The undetected HIFs pose a threat to human life and the arcing caused by such faults may result fire hazards. It is reported in [1] that the success rate of HIF detection in power distribution system by conventional overcurrent protection scheme is less than 20%. Detection of HIFs becomes further difficult when distributed generators (DGs) are integrated with distribution systems [2].

978-1-4799-5141-3/14/$31.00 © 2016 IEEE

Significant research has been carried out since the 1970's for modelling and detecting HIFs in distribution systems. During the initial phase, different solutions have been proposed mainly by conducting experiments on laboratory models or through staged fault studies. However, the limitation on experimental studies for HIF detection attracts researchers more towards simulation studies in the recent years. The research on HIF till 2010 is reviewed in detail in [3].

Available HIF detection techniques are either based on frequency-domain analysis, time-domain analysis, time-scale analysis or training based methods [4], [5]. Methods based on sequence components [6], phase angle difference between third harmonic current and fundamental voltage phasor [7], high frequency components [8], and interharmonic current in electric arc during HIF [9] are coming under frequency domain analysis. Power dissipation factor [10], fractal techniques [11] and signal superposition [12] are based on time domain analysis. The advantages and limitations of time-domain and frequency-domain analysis for HIF detection is discussed in [5].

Methods based on wavelet transform (WT) belong to time-scale analysis. A HIF detection scheme based on the discrete WT of residual voltage and current is proposed in [13]. Although the methods based on WT gives good simulation results, their practical implementation is difficult [9]. The training based methods such as artificial neural network [14], [15], decision tree [16] and neuro-fuzzy method [17] are used for HIF detection. However, for correct discrimination of HIFs from other similar non-fault events, generation of large number of training cases are required and also performances of these methods are system specific. Recently new algorithms are proposed in [18] based on phasor measurement units (PMU) for HIF detection. However, performances of the schemes based on PMU data are dependent on communication medium and are also more expensive.

From the above discussion it is clear that despite of significant research has been carried out for detection of HIFs in distribution systems there is a strong need for development of new algorithms which can efficiently and reliably detect HIFs in distribution systems even in the presence of DGs. This paper presents a one-cycle sum of superimposed components of residual voltage method for the detection of HIF in distribution systems considering DGs. The performance of the algorithm is

evaluated on a 7-node radial test feeder considering synchronous generator based DG. The scheme is also tested for different non-fault events like capacitor switching and load switching producing similar characteristics as that of HIF. The performance of the scheme is also found to be satisfactory for these non-fault cases.

The rest of the paper is organized as follows. The physical characteristics, the mathematical modelling and the PSCAD/EMTDC simulation results for the typical HIF is provided in section-II. The detail description of the proposed method is provided in Section-III. The simulation results of the proposed method are provided in Section-IV. Finally, the paper is concluded in Section-V.

II. SYSTEM MODELING

A. Modelling of Distribution System with DG

The test system studied in the present work is a three phase, 11 kV, 7-node, radial distribution system with DG integrated at node-3. Distribution line positive-sequence impedance = 0.3 + j 0.25 Ω/km. The distance between each node is 2 km. The schematic diagram of the test feeder is shown in Fig.1. A linear load of each 0.667 MVA at a p.f. of 0.95 per phase are connected to nodes 1, 3, 5 and 7 and another load of each 1.667 MVA at a p.f. of 0.95 per phase is connected to nodes 2, 4 and 6. The DG connected to the feeder in this study is a synchronous generator. The DG provides about 20% of the feeder load. Such type of DG contributes a significant fault current. As a result the grid contribution to the fault current reduces. These types of generators are used in combined heat and power plants [19].

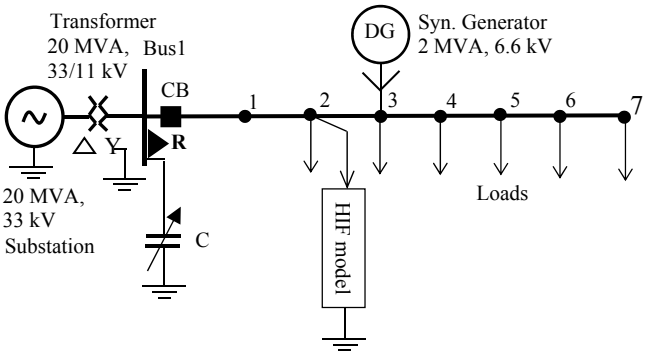

Fig.1. Single line diagram of a 7-node test feeder.

B. HIF Modeling

High impedance faults are mostly associated with electric arc which introduces some peculiarities to fault currents such as asymmetry, nonlinearity, build up, shoulder and intermittence [20]. HIFs are also characterised by the presence of harmonics and high frequency components [17]. Several methods are available in the literature to model HIF [4], [20]-[22]. In this paper, the HIF model chosen for study is similar to [4]. The circuit diagram of the HIF model is shown in Fig. 2. The HIF model is connected between one phase and ground of the distribution feeder. The model consists of two parallel branches. A dc voltage source V_p, a diode D_p and a variable resistor R_p are connected in series in one branch and in the other branch voltage source V_n, a diode D_n and a variable resistor R_n are connected in series. The dc voltage sources are of unequal magnitude and their values are set according to the phase voltage of the study system. When $V_{ph} > V_p$, the fault current flows towards ground and the current reverses when $V_{ph} < V_n$. No current flows during $V_n < V_{ph} < V_p$. In the present study, the values of V_p and V_n are set at 3 kV and 1.5 kV respectively. During HIF, the values of the resistors R_p and R_n are varied randomly between 300 Ω and 400 Ω at every 2 ms interval in such a manner that the magnitude of fault current through HIF branch remains always less than 5% of the rated load current of the test feeder. Random variation in resistor value introduces asymmetry in the fault current.

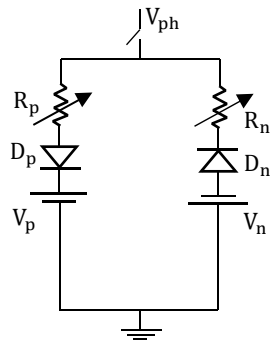

Fig. 2. HIF model.

The measured voltage and current waveforms at the fault point during a HIF between phase-a and ground at node-7 of Fig. 1 is shown in Fig. 3. It is clearly seen from Fig. 3(b) that the current waveform obtained at the fault point during HIF is random in nature and also have unequal positive and negative half cycles. The interruption near zero crossing in the current waveform shows temporary arc extinction. The $v - i$ characteristic at the fault point during HIF is shown in Fig. 4. The current waveform (Fig 3(b)) and the $v - i$ characteristic (Fig. 4) obtained during HIF using the model (Fig. 2) matches well with those obtained from lab experiments, on actual distribution system and from the different high impedance arc models reported in the literature [4]. This shows that the HIF model chosen for the study (Fig. 2) can faithfully represent the randomness, asymmetry and nonlinearity in the fault current and intermediate arc extinctions. For the HIF case discussed above, the voltage and current waveform at the relay bus is shown in Fig. 5. From the figure it is observed that as the fault is far away from the relay point, the influence of the HIF on relay bus voltage and current is not significant, because the system still draws sinusoidal load currents. This imposes difficulty in HIF detection.

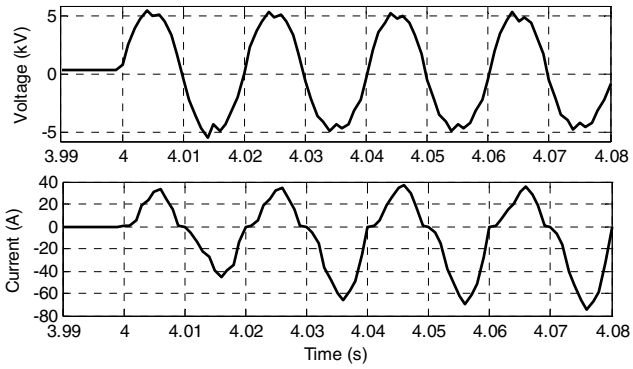

Fig.3. Arc voltage and current waveform at fault point during HIF at node-7.

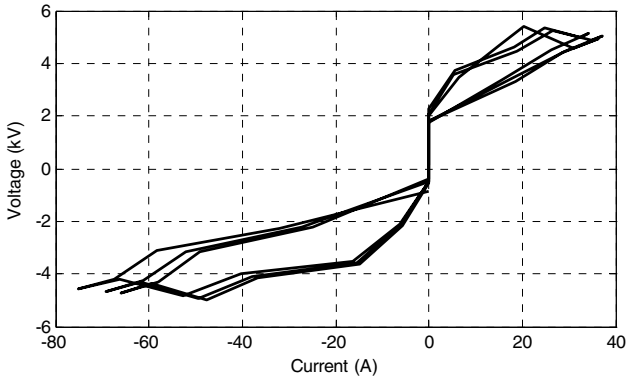

Fig.4. $v - i$ characteristics during HIF at node-7.

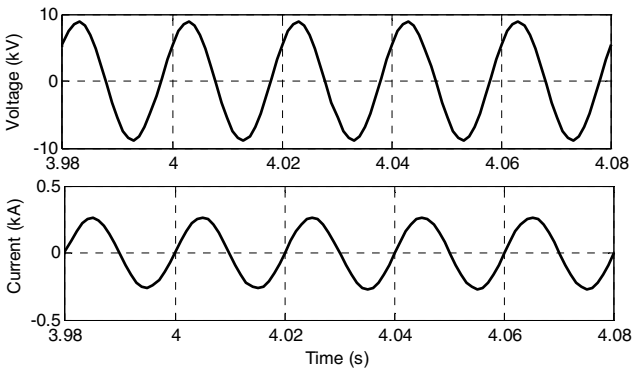

Fig.5. Voltage and current waveform at relay bus-1 during HIF at node-7.

III. PROPOSED METHOD

The different methods available in the literature either use current or both current and voltage waveforms as input features for HIF detection. During HIF as the increase of current with respect to the pre-fault current is very less (in this study it is kept < 5%), the distortions and irregularities in the current waveform at the relay location is insignificant which is clearly evident from Fig. 5(a). However, the voltage waveforms are less dependent on pre-fault loading conditions. HIFs are mostly single-line-to-ground type. Occurrences of such faults introduce unbalance into the system and can produce significant percentage of residual current with respect to the positive-sequence current in case of a grounded distribution system. However, significant percentage of residual voltage with respect to the positive-sequence voltage exists both for grounded and isolated grounded distribution system. In the present work, residual voltage is considered as a feature for the detection of HIF. The detail computational steps of the proposed method are provided below.

The three-phase voltages are collected at the relay bus at 1 kHz sampling rate for a 50 Hz power system. The residual voltage e_{rk} computed at k^{th} instant is given as,

$$e_{rk} = v_{ak} + v_{bk} + v_{ck} \tag{1}$$

where, v_{ak}, v_{bk}, and v_{ck} are the voltages of phase-a, phase-b and phase-c respectively at k^{th} instant of. The one-cycle superimposed components of the residual voltage is computed as below which has ability to measure the randomness, non-periodicity and the presence of non-harmonic components in a signal and is suitable in the characterisation of HIFs. The one-cycle difference of residual voltage is given as,

$$e_{rk\_diff} = e_{rk} - e_{rk-N} \tag{2}$$

where, N is the number of samples per cycle. Further the absolute sum of e_{rk_diff} over one-cycle is computed to obtain a better index for discriminating HIFs from other non-fault events having similar characteristics as that of HIFs and is given in (3) as,

$$g_k = \sum_{k-N}^{k} \left(e_{rk\_diff} \right) \tag{3}$$

The algorithm will detect a fault if,

$$g_{k+t_{wait}} > g_{th} \tag{4}$$

The fault detector index g_k is zero during normal operating condition (including both balanced and unbalanced loading). At the inception of a fault (for both short circuit fault as well as HIF) or any other non-fault events (e.g. load switching, capacitor switching etc.), the value of g_k increases from zero to higher value in all cases and again returns to zero within two-cycle (40 ms) in all cases except HIF. In case of HIF, the value of g_k remains high till it persists. This is happened due to the presence of distortions and irregularities in the residual voltage during HIF. In the present study t_{wait} is fixed at 0.1 s. Though, the criterion, $g_{k+t_{wait}} > 0$ can be able to discriminate HIF from any other non-fault transients, a small threshold g_{th} greater than zero is considered for ensuring security in HIF detection. For better understanding the proposed scheme is provided in the flow chart as shown in Fig. 6.

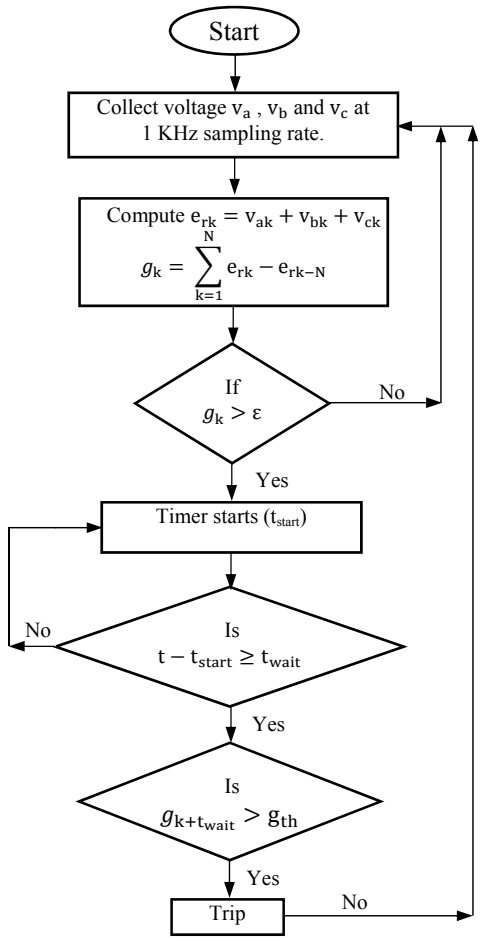

Fig. 6. Flow chart of the proposed scheme.

IV. Results and Discussions

The proposed method is tested by creating HIFs at different locations of the test feeder of Fig. 1. EMTDC/PSCAD simulation software is used for data generation. The data sampling rate is maintained at 1 kHz. Performance of the proposed method is also tested for different non-fault events such as balanced and unbalanced load switching and capacitors switching which also produce similar characteristics as that of HIF. The results obtained for different cases are elaborated below.

A. Performance for HIF at Node-1

A HIF is created at 4 s at node-1 of Fig. 2 which is close to the relay bus. The performance of the proposed scheme is shown in Fig. 7. The HIF current shown in Fig. 7(a) has high resemblance with the staged fault thus validate the simulation study. Fig. 7(b) shows the three phase voltages at relay bus-1. From the figure it is clear that even if the fault is close to the relay bus, the change in voltage from pre-fault to fault is

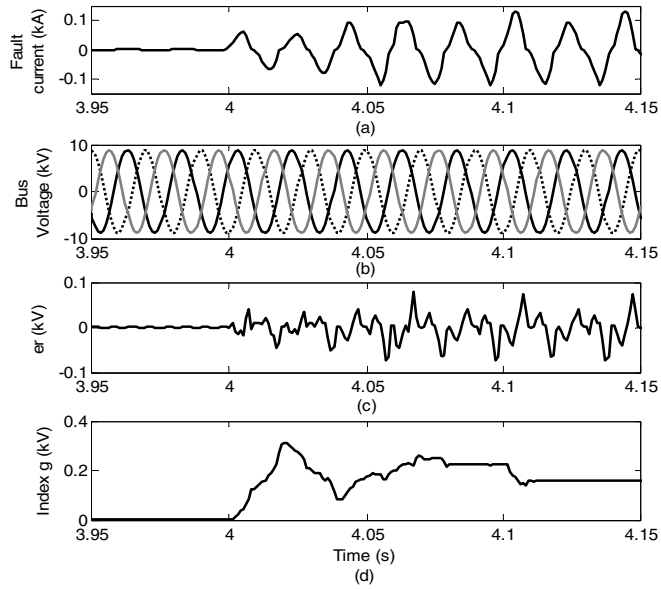

Fig. 7. Performance for HIF at node-1, (a) Current at fault point, (b) Three-phase voltages at relay bus, (c) Residual voltage at relay bus-1 and (d) Fault detector index g.

insignificant as the HIF current is kept below 5% of the full load. However, a distorted residual voltage is observed during HIF (Fig. 7(c)). The presence of irregularities in the residual voltage during HIF helps to obtain a distinguishable index g which is zero during normal operation. The value of index g remains almost constant after 0.1 s of the fault inception. Hence, using the proposed method, HIF can be detected in 0.1 s.

B. Performance for HIF at Node-7

Another HIF is created at 4 s at node-7 (Fig. 2) to test the performance of proposed scheme for HIF at different location of the feeder. The performance of the proposed scheme is shown in Fig. 8. Here also the HIF current shown in Fig. 8(a) has high resemblance with the staged fault. Fig. 8(b) shows the three phase voltages at relay bus-1. Since the fault is initiated far away from the relay bus, there is no change in voltage from pre-fault to fault. Even if there is no change in voltage magnitude certain distortion observed in the residual voltage after the initiation of HIF (Fig. 8(c)). The presence of irregularities in the residual voltage during HIF helps to obtain a distinguishable index g. Here also the index g remains almost at a constant value 0.1 s after the fault inception. Thus it is possible to detect the HIF by the present method irrespective of the location of the fault.

C. Performance for HIF During Single-Phase Loading

In India, the typical distribution systems supplying electricity to urban and rural areas are 3-phase, 4-wire with multiple–grounded neutral. Most of the distribution transformers are three-phase transformers connected in delta-star. However, there are few single-phase transformers are also installed in rural areas. The connection of single-phase loads introduce significant percentage of residual current and voltage with

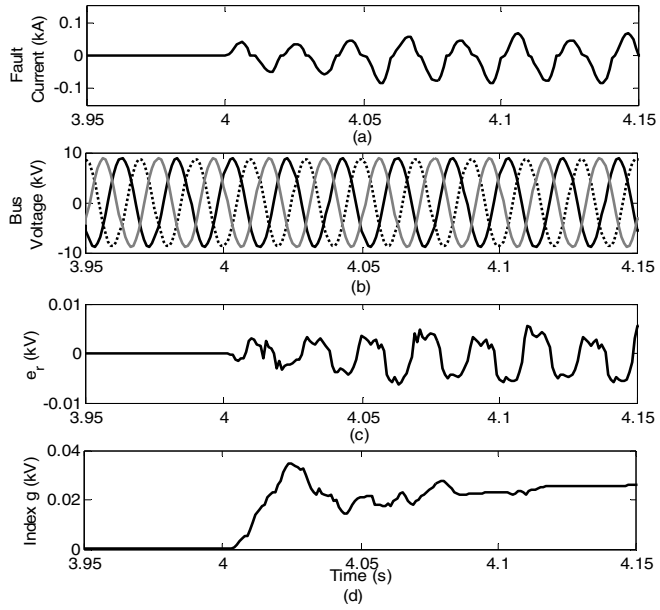

Fig. 8. Performance for HIF at node-7, (a) Current at fault point, (b) Three-phase voltages at relay bus-1, (c) Residual voltage at relay bus-1 and (d) Fault detector index g.

respect to the fundamental component current and voltage respectively. The present method being based on residual voltage needs to be tested under single-phase loading condition. A HIF is created at 4 s at node-5 (Fig. 2) while a single-phase load is at node-3. The result for the test case is shown in Fig. 9. From Fig. 9(c) it is evident that single-phase loading at node-4 introduces significant residual voltage during normal operating condition. However, the residual voltage is sinusoidal in nature. As a result the fault detector index g remains zero during normal condition despite of single-phasing. As soon as a HIF is initiated at 4 s, a significant distortion appears in the residual voltage and the index g increases to a higher value from zero and can be able to detect the HIF. This shows the strength of the proposed method for HIF detection even occurring during single-phase loading condition.

D. Performance During Single-Phase Load Switching

Single-phase load switching acts like an unbalanced load to the distribution system. This might give rise to frequency spectra or harmonic contents similar to those resulting from HIFs. One of the phases of a three-phase load (0.667 MVA, operating at 0.95 p.f.) is switched off at node-3 at 3 s. The results are demonstrated in Fig. 10. From Fig. 10(b), it is seen that single- phase load switching at 3 s introduces unbalance into the system resulting significant residual voltage. Due to the momentary transient in the system, the fault detector index g rises from zero to a higher value and remains only for 50 ms and after that it disappears. As the proposed scheme takes decision only if the index g exists after 0.1 s, so in this case the proposed method will treat such phenomena as a non-fault event and will remain silent. Thus, the proposed scheme is immune to single-phase load switching.

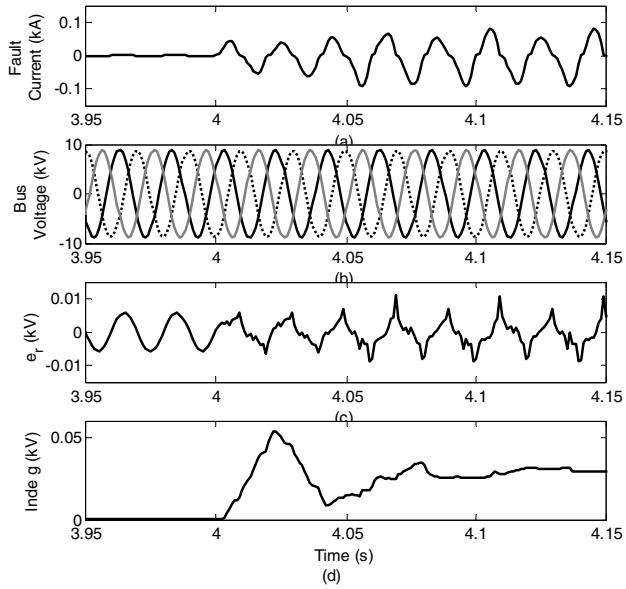

Fig. 9. Performance for HIF at node-6 with single-phase load at bus-4, (a) Current at fault point, (b) Three-phase voltages at relay bus, (c) Residual voltage at relay bus and (d) Fault detector index g.

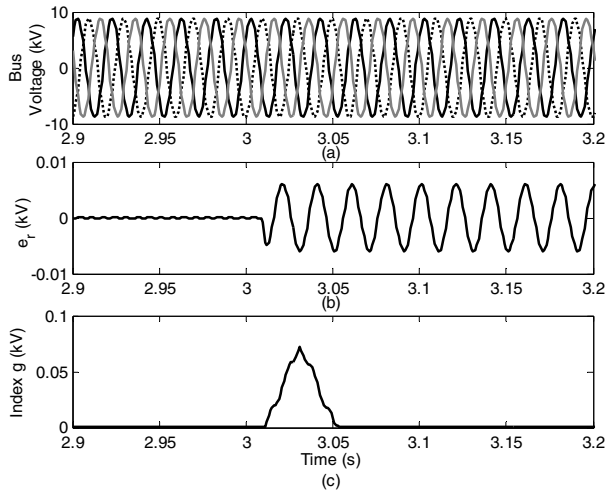

Fig. 10. Performance during single-phase load switching at node-3, (a) Three-phase voltages at relay bus, (b) Residual voltage at relay bus-1 and (d) Fault detector index g.

E. Performance During Capacitor Switching

Switching on/off of shunt capacitors are often done for maintaining voltage profile within tolerable limits in distribution system. However, capacitor switching can introduce harmonics similar to those resulting from HIFs. Thus it is necessary to test the performance of the proposed scheme for such switching event. To test the performance of the proposed scheme a capacitor bank of 400 kVAR is switched on at bus-1 at 2 s. The results for the switching case are provided in Fig. 11. From the Fig. 11(a), it is clearly seen that capacitor switching at 2 s introduces transient to voltage waveforms. However, there is no residual voltage is observed (Fig. 11 (b)). Hence the fault detector index g remains almost zero during the

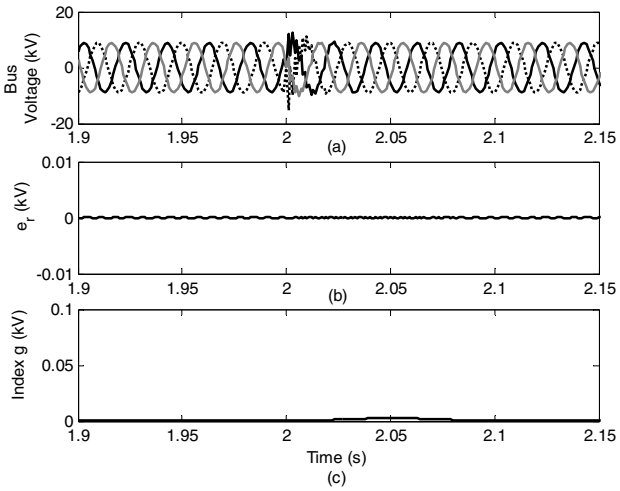

Fig. 11. Performance during capacitor switching at bus-1, (a) Three-phase voltages at relay bus, (b) Residual voltage at relay bus-1 and (c) Fault detector index g.

event (Fig. 11 (c)). Thus, such phenomena will be treated by the proposed scheme as a non-fault event.

V. Conclusion

A superimposed component of residual voltage based technique is proposed in this paper for detecting HIFs in distribution systems installed with distributed generators. The method is tested for HIFs initiated at different locations of the feeder. Performance of the scheme is also tested for different non-fault events such as unbalanced loading, single-phase load switching and capacitor switching which can sometimes also produce similar characteristics as that of HIFs. The results show that using proposed scheme HIFs can be detected with high accuracy in 0.1 s after the inception of the fault. The computational burden of the proposed scheme is also very less.

References

[1] J. Tengdin, R. Westfall, and K. Stephan, "Impedance fault detection technology", Mar. 1996, Report of PSRC Working Group D15. [Online]. Available: http://www.pes-psrc.org/Reports/High_Impedance_Fault_Detection_Technology.pdf.

[2] E. Sortomme, S. S. Venkata, and J. Mitra, "Microgrid protection using communication assisted digital relays," *IEEE Transactions on Power Del.*, vol. 25, no. 4, pp. 2789-2796, 2010.

[3] M. Sedighizadeh, A. Rezazadeh, and N. I. Elkalashy, "Approaches in high impedance fault detection a chronological review," *Adv. Elect. Comput. Eng.*, vol. 10, no. 3, pp. 114–128, 2010.

[4] S. Gautam and S. M. Brahma, "Detection of high impedance fault in power distribution systems using mathematical morphology," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 1226–1234, May 2013.

[5] A. Ghaderi, H. A. Mohammadpour, H. L. Ginn, and Y. J. Shin, "High-impedance fault detection in the distribution network using the time-frequency-based algorithm," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1260–1268, June 2015.

[6] D. Yu and S. Khan, "An adaptive high and low impedance fault detection method," *IEEE Trans. Power Del.*, vol. 9, no. 4, pp. 1812–1821, Oct. 1994.

[7] K. -Y. Lien, S. -L. Chen, C. -J. Liao, T. -Y. Guo, T. -M. Lin, and J. -S. Shen, "Energy variance criterion and threshold tuning scheme for high impedance fault detection," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 810–817, Jul. 1999.

[8] Detection of Arcing Faults on Distribution Feeders, Texas A & M Univ., EPRI Report EL-2757, Dec. 1982.

[9] J. R. Macedo, J. W. Resende, C. A. Bissochi Jr, D. Carvalho, and F. C. Castro, "Proposition of an interharmonic-based methodology for high-impedance fault detection in distribution systems," *IET Gener., Transm., Distrib.*, vol. 15, Iss. 16, pp. 2293–2601, Aug. 2015.

[10] K. K. Li and W. L. Chan, "Novel methods for high impedance grounding fault protection in low voltage supply systems," *Elect. Power Compon. Syst.*, vol. 31, pp. 1133–1150, 2003.

[11] A. V. Mamishev, B. D. Russell, and C. L. Benner, "Analysis of high impedance faults using fractal techniques," *IEEE Trans. Power Syst.*, vol. 11, no. 1, pp. 435–440, Feb. 1996.

[12] I. Zamora, A. J. Majon, K. J. Sagastabeitia, and J. J. Zamora, "New method for detecting low current faults in electrical distribution systems," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2072–2079, Oct. 2007.

[13] N. I. Elkalashy, M. Lehtonen, H. A. Darwish, I. Taalab, and M. A. Izzularab, "DWT-based detection and transient power direction-based location of high-impedance faults due to leaning trees in unearthed MV networks," *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 94–101, Jan. 2008.

[14] S. R. Samantaray, B. K. Panigrahi, and P. K. Dash, "High impedance fault detection in power distribution networks using time-frequency transform and probabilistic neural network," *IET Gener., Transm., Distrib.*, vol. 2, no. 2, pp. 261–270, Mar. 2008.

[15] M. Michalik, M. Lukowicz, W. Rebizant, S. -J. Lee, and S. -H. Kang, "New ANN-based algorithms for detecting HIFs in multigrounded MV networks," *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 58–66, Jan. 2008.

[16] Y. Sheng and S. Rovnyak, "Decision tree-based methodology for high impedance fault detection," *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 533–536, Apr. 2004.

[17] A. H. Etemadi and M. Sanaye-Pasand, "High-impedance fault detection using multi-resolution signal decomposition and adaptive neural fuzzy inference system," *IET Gener., Transm., Distrib.*, vol. 2, no. 1, pp. 110–118, Jan. 2008.

[18] M.G.M. Zanjani, H.K. Kargar, and M.G.M. Zanjani: 'High impedance fault detection of distribution network by phasor measurement units'. Proc. of 17th Conf. on Electrical Power Distribution Networks (EPDC), Tehran, Iran, pp. 1–5, 2012.

[19] N. Jenkins, R. Allen, P. Crossley, D. Kirschen, and G. Strbac, *Embedded Generation*. Series 31, 2nd edn, IEE Power & Energy, London, 2000.

[20] F. B. Costa, B. A. Souza, N. S. D. Brito, J. A. C. B. Silva, and W. C. Santos, "Real-time detection of transients induced by high-impedance faults based on the boundary wavelet transform," *IEEE Trans. Industry Applications*, vol.51, no. 6, pp. 5312–5323, Nov./Dec. 2015.

[21] N. Elkalashy, M. Lehtonen, H. A. Darwish, M. A. Izzularab, and A. M. I. Taalab, "Modeling and experimental verification of high impedance arcing fault in medium voltage networks," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 14, no. 2, pp. 375–383, Apr. 2007.

[22] S. R. Nam, J. K. Park, Y. C. Kang, and T. H. Kim, "A modelling method of a high impedance fault in a distribution system using two series time-varying resistances in EMTP," in *Proc. Power Engineering Society Summer Meeting, 2001*, 2001, vol. 2, pp. 1175–1180.