


Proceeding Paper

High Impedance Faults Detection and Classification in Renewable Energy-Based Distribution Networks Using Time-Varying Kalman Filtering Technique [†]

Faisal Mumtaz ^{1,*} , Muhammad Asif ¹, Haseeb Hassan Khan ^{2,3}, Shahrukh Abbas ¹, Kashif Imran ¹, Muhammad Usman Haider ¹, Muhammad Yousif ¹ and Asad Ullah ¹

¹ US-Pakistan Center of Advanced studies in Energy (USPCAS-E), National University of Science and Technology (NUST), Islamabad 44000, Pakistan

² Department of Electrical Engineering, University School for Advanced Studies (IUSS), 98122 Pavia, Italy

³ Electrical Engineering Department, University of Messina (UniME), 98122 Sicily, Italy

* Correspondence: fmumtazphd21.ces@student.nust.edu.pk; Tel.: +92-3215702584

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Abstract: In the modern world, High Impedance (HI) Faults' identification is challenging in renewable energy-based distribution networks (REBDNs) due to the low level of the fault current. In this paper, a new HI fault detection/classification strategy is presented for REBDNs, based on the time-varying Kalman Filter (TVKF). Initially, TVKF is applied to the voltage and current signal of each phase separately, in order to extract harmonic components. Secondly, the TVKF-based harmonic components are utilized to calculate the single-phase reactive power (SPRP) independently. If the SPRP of any individual phase is greater than a specific threshold value, the corresponding phase is considered faulty. Fault classification is autonomous due to phase segregation. The proposed strategy is tested on the REBDNs' test system in MATLAB/Simulink software. The results indicate that the proposed scheme detects and classifies HI faults under radial and mesh topologies.

Keywords: fault detection; fault classification; high impedance faults; renewable energy-based distribution networks; time-varying Kalman filter



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1. Introduction

Renewable energy resources, in producing green and clean energy, are the future of the modern electrical world. However, such REBDNs are small power distribution systems made up of distributed generators (DGs), energy storage devices, energy conversion devices, loads, and the necessary monitoring and protective equipment that works in grid-connected and islanded modes. However, REBDNs possess a large number of issues: high impedance faults (HIF) detection/classification is one of the most in-convenient problems in REBDNs. HIF occurs when an energized overhead (OH) line falls to the ground through a high impedance item such as high-resistance soils, dry asphalt, dry ground, dry grass, lawns, gravel, and tree limbs [1,2].

Linear Kalman filter based fault detection scheme was proposed in ref [3]. High impedance faults frequently develop, posing a serious public safety risk to humans, livestock, and the environment. Furthermore, for the power systems to operate efficiently, reliably, and safely, high impedance issues must be accurately, precisely, and quickly detected. However, due to the unpredictable, unequal, and nonlinear character of high impedance fault currents, detecting them is a difficult task because the amplitude of the fault current is significantly smaller than that of the nominal load current. Therefore, standard over-current techniques cannot identify these faults. Most of the time, over-current relays and other traditional protection systems do not detect the HIFs [4].

For HIF detection and modeling, several techniques have been presented in the literature. HIFs are detected in [5] using the low-frequency spectrum, estimated from observed currents. The authors in ref. [6] offered a technique for detecting HIFs based on the incremental variance of normalized even-order harmonics derived from current measurements. Ref. [7] proposed an inter-harmonic-based framework for modeling and detecting HIFs. HIFs are detected using a multi-resolution signal decomposition analysis and the discrete wavelet transform (DWT) in [8].

In addition, for HIFs' identification, the authors employed an algorithm based on DWT multi-resolution analysis and a windowing technique in [9,10]. Artificial neural networks are utilized to identify HIFs in [11]. Ref. [12] shows how to find HIFs using the Gabor transform with Wigner distribution. The authors of [13] describe a mathematical model based on orthogonal component decomposition. HIF detection was also proposed in [14]. These models are always being improved to enhance their accuracy and efficiency. In the case of analytical models, the advances described in [15] can still be enhanced to achieve a more accurate explanation of the HIF phenomena.

The rest of the paper is organized as follows. Section 2 explains the utilized REBDNs' test system. The mathematical principles of TVKF are explained in Section 3. The proposed HIF detection/classification design is mentioned in Section 4. Section 5 depicts the results and discussions. The paper is concluded in Section 6.

2. Utilized REBDNs' Test System

To test the effectiveness of the created approach, the REBDNs were constructed in MATLAB/Simulink software. However, the scheme has also been tested on the IEEE-9 bus system. A single-line schematic of the REBDNs' test system is shown in Figure 1. The test system is made up of six buses and four DGs, three DGs are inverter-based and one is synchronous. For the validation of the proposed approach, four HI faults, Fault-1 to Fault-4, are produced at various places on separate lines.

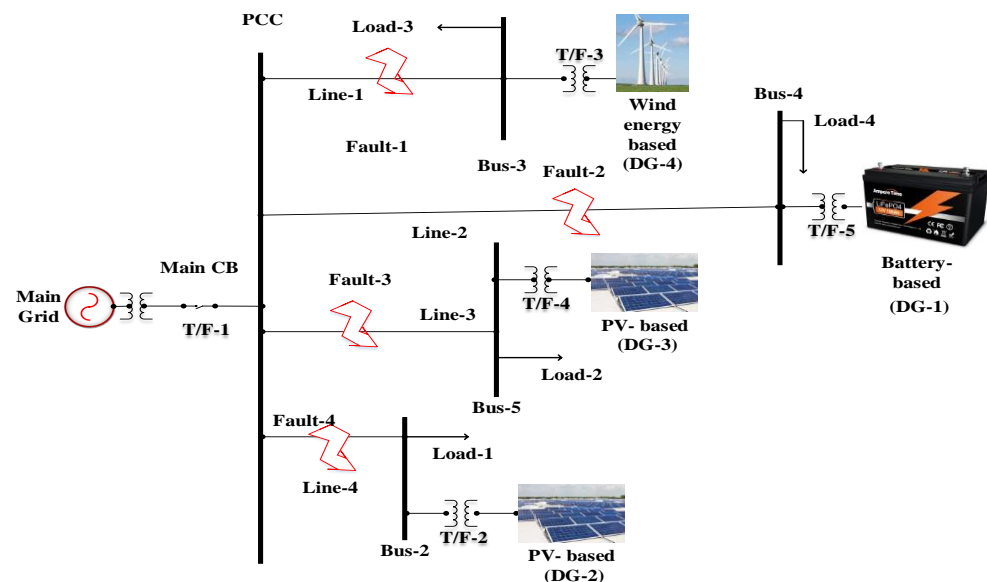


Figure 1. Utilized REBDNs' test system under study.

3. Mathematical Principles of Time-Varying Kalman Filter

The TVKF is a state estimation and time-dependent algorithm, whose complete workings are depicted in Figure 2. However, the TVKF is primarily used for State Estimation, and it allows filtering in the time domain, which reduces the challenge of managing a large dimensionality in state-space vectors. Apart from that, the TVKF efficiently handles

non-linear data, eliminating the requirement for conversion [16,17]. Furthermore, the TVKF can identify HIF more precisely and quickly than previous methods could.

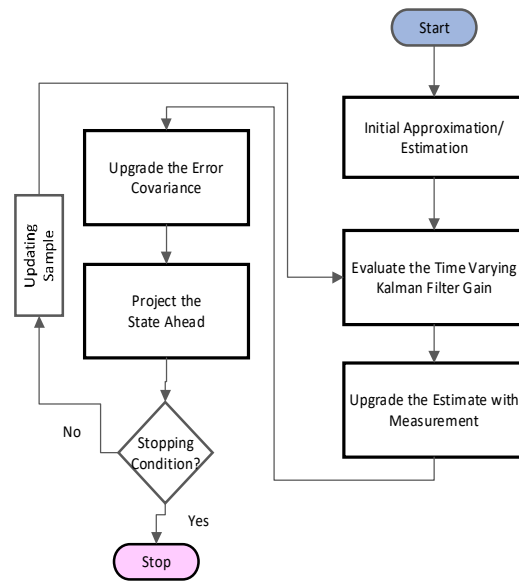


Figure 2. (TVKF) Algorithm.

The following recursive equation gives the time-varying Kalman filter for the REBDNs' system model:

Measurement's update:

$$\hat{x}(k|k) = \hat{x}(k|k-1) + M(k)(y_v(k) - C\hat{x}(k|k-1)) \tag{1}$$

$$M(k) = P(k|k-1)C^T(R(k) + CP(k|k-1)C^T)^{-1} \tag{2}$$

$$P(k|k) = (I - M(k)C)P(k|k-1) \tag{3}$$

Time updates:

$$\hat{x}(k+1|k) = A(k)\hat{x}(k|k) + Bu(k) \tag{4}$$

$$P(k+1|k) = A(k)P(k|k)A^T + GQ(K)G^T \tag{5}$$

$$Q(K) = \mathbb{E}(w(k)w(k)^T) \tag{6}$$

$$R(K) = \mathbb{E}(v(k)v(k)^T) \tag{7}$$

$$P(K|K) = \mathbb{E}[\{x(k) - \hat{x}(k|k)\}\{x(k) - \hat{x}(k|k)\}^T] \tag{8}$$

$$P(K|K-1) = \mathbb{E}[\{x(k) - \hat{x}(k|k-1)\}\{x(k) - \hat{x}(k|k-1)\}^T] \tag{9}$$

$\hat{x}(k|k-1)$ is the assessment of $x(k)$ given the past value of up to $(y_v(k-1))$. Besides, $\hat{x}(k|k)$ is the revised assessment based on the last measurement $(y_v(k))$. In the measurement and time update steps [18], the following definitions should be utilized. We assume the beginning circumstances to build a time-varying Kalman filter $\hat{x}(1|0) = 0$ and $P(1|0) = BQB^T$.

4. Proposed HIF Detection/Classification Scheme

The accurate and precise fault detection and classification of HIF are crucial in REBDNs. Therefore, the reliable threshold value is chosen in this paper for a timely detection and precise fault classification. Hence, a constant threshold value of 1×10^{-5} for the SPRP is chosen for abnormal conditions, and if the SPRP of any phase is greater than the re-

spective threshold values, the relevant phase is considered faulty. The proposed HIF detection/classification strategy is shown in Figure 3.

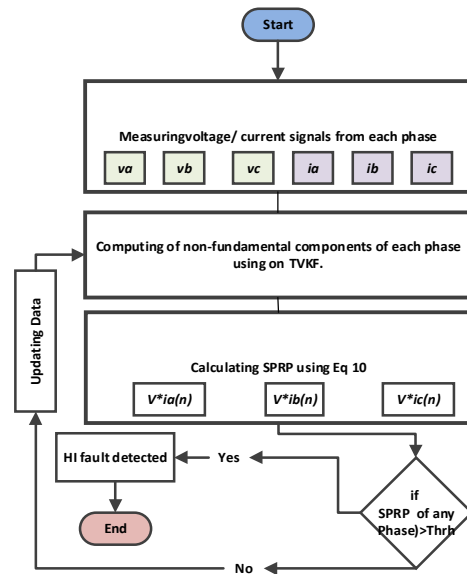


Figure 3. Proposed HIF detection/classification scheme.

Initially, the three-phase voltage and current signals are measured from the CT and PTs of an individual bus. Then, the measured current and voltage signals are preprocessed using an antialiasing filter to remove higher-order odd harmonics. Thereafter, these analog voltage signals are then converted into digital signals by using an analog-to-digital converter (ADC).

Secondly, the ADC converted discrete voltage and current signals are then utilized at the input of TVKF to extract the features by state estimation. Furthermore, the calculated non-fundamental feature of the voltage and current are utilized to calculate the single-phase reactive power, as mentioned in Equation (10).

$$SPRP = VI \sin \theta \tag{10}$$

At the third stage, the SPRP is compared by the suitable pre-chosen threshold value, and if the measured value of SPRP is greater than the threshold value, the system detects and classifies HIF in a timely manner. This system is classification-autonomous because every phase is segregated, and based on the reactive power, every phase fault is detected separately due to classification autonomy.

5. Results and Discussion

As shown in the the result in Figure 4a, there is a three-phase HIF fault with a fault resistance $R = 200$ ohm occurring at 0.2 s, so the SPRP of the faulty phases A, B, and C exceeds the threshold limits, and the corresponding relay senses the fault-1. In another case, the result of fault-2 is shown in Figure 4b: the fault is a single-phase HIF with a fault resistance $R = 100$ ohm occurring at 0.15 s. Hence, the faulty phase B is detected and classified based on the SPRP because the SPRP of B is higher than the threshold value and the relays sense the fault. In the fault-3 case shown in Figure 4c, there is a double-phase HIF with a fault resistance $R = 250$ ohm initiated at 0.3 s, the SPRP is greater than the threshold limits, and the relay detects and classifies the faulty phases B and phase C in a timely manner. The result of the last case is shown in Figure 4d, where fault-4 is a single-phase HIF with a fault resistance $R = 150$ ohm occurring at 0.2 s; thus, the faulty phase C is detected and classified based on the SPRP.

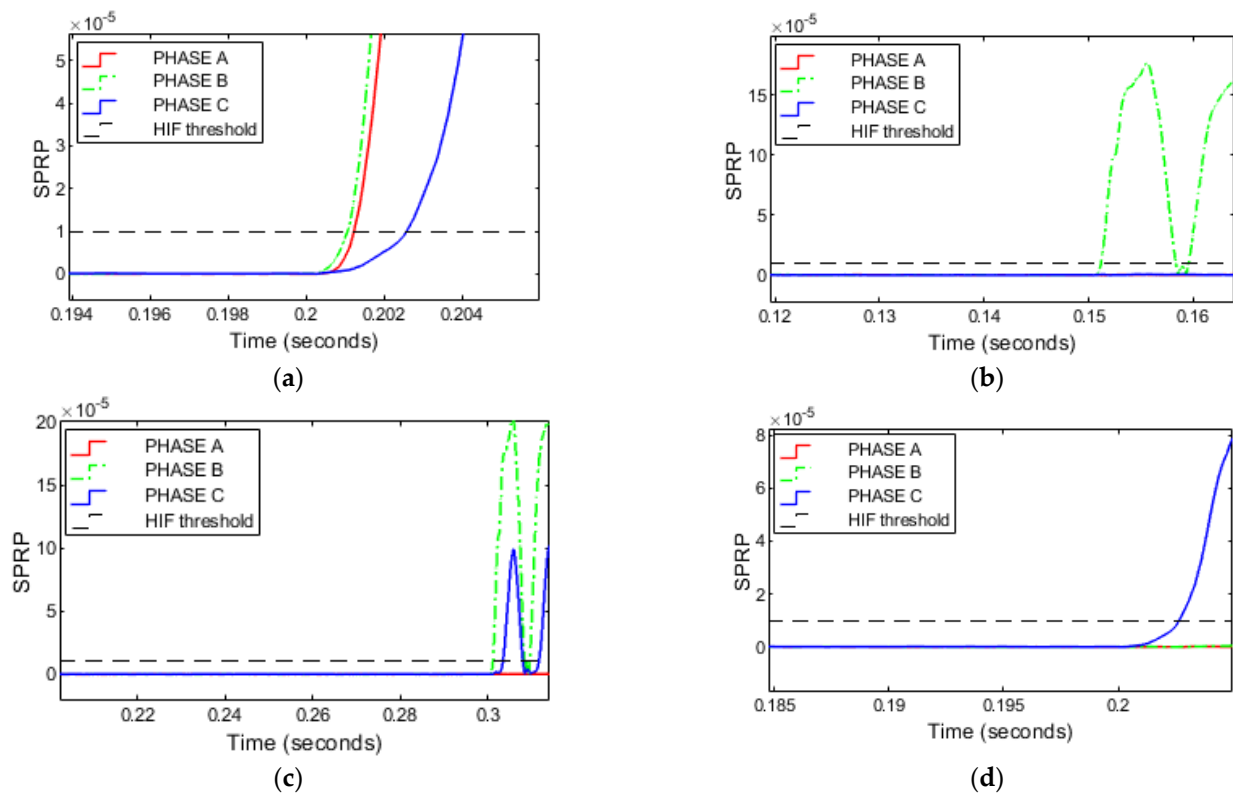


Figure 4. (a) Three-phase HIF with $R = 200$ ohm. (b) Single-phase HIF with $R = 100$ ohm. (c) Double-phase HIF with $R = 250$ ohm. (d) Single-phase HIF with $R = 150$ ohm.

6. Conclusions

In this paper, a new HI fault detection/classification strategy is proposed for REBDNs. The suggested strategy is based on the Time-Varying Kalman filter (TVKF). TVKF is applied to the voltage and current signal of each phase to extract harmonic components. Then, the TVKF-based harmonic components are utilized to calculate the single-phase reactive power (SPRP) individually. If the SPRP of any individual phase is higher than a pre-defined threshold value, the corresponding phase is considered faulty.

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References

- Guardado, J.L.; Torres, V.; Maximov, S.; Melgoza, E. Analytical approach to modeling the interaction between power distribution systems and high impedance faults. *IET Gener. Transm. Distrib.* **2018**, *12*, 2190–2198. [[CrossRef](#)]
- Gonzalez, J.A. Study of High Impedance Fault Detection in Levante. In Proceedings of the Ninth International Conference on Harmonics and Quality of Power, Orlando, FL, USA, 1–4 October 2000; pp. 1011–1016.
- Mumtaz, F.; Imran, K.; Basit, S.; Bukhari, A.; Khalid, K. A Kalman Filter-based Protection Strategy for Microgrids. *IEEE Access* **2017**, *10*, 1–11. [[CrossRef](#)]

4. Hou, D.; Laboratories, S.E. Detection of High-Impedance Faults in Power Distribution Systems. In Proceedings of the 2007 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, Clemson, SC, USA, 13–16 March 2007; pp. 1–11.
5. Emmanuel, J.A.; Cyganski, A.; Orr, D. High impedance fault arcing on sandy soil in 15 kV distribution feeders: Contribution to the evaluation of the low-frequency spectrum. *IEEE Trans. Power Deliv.* **1990**, *5*, 673–686. [[CrossRef](#)]
6. Kwon, W.H.; Lee, G.W.; Park, Y.M.; Yoon, M.C.; Yoo, M.H. High impedance fault detection utilizing incremental variance of normalized even order harmonic power. *IEEE Trans. Power Deliv.* **1991**, *6*, 557–564. [[CrossRef](#)]
7. Macedo, J.R.; Resende, J.W.; Bissochi, C.A., Jr.; Carvalho, D.; Castro, F.C. Proposition of an inter harmonic-based methodology for high-impedance fault detection in distribution systems. *IET Gener. Transm. Distrib.* **2015**, *9*, 2593–2601. [[CrossRef](#)]
8. Kim, C.-H.; Kim, H.; Ko, Y.-H.; Byun, S.-H.; Aggarwal, R.; Johns, A. A Novel Fault-Detection Technique of High-Impedance Arcing Faults in Transmission Lines Using the Wavelet Transform. *IEEE Trans. Power Deliv.* **2002**, *17*, 921–929. [[CrossRef](#)]
9. Torres, V.; Ieee, G.; Ruiz, H.F. High Impedance Fault Detection Using Discrete Wavelet Transform. In Proceedings of the 2011 IEEE Electronics, Robotics and Automotive Mechanics Conference, Cuernavaca, Mexico, 15–18 November 2011; pp. 325–329. [[CrossRef](#)]
10. Mahari, A.; Seyedi, H. Electrical Power and Energy Systems High impedance fault protection in transmission lines using a WPT-based algorithm. *Int. J. Electr. Power Energy Syst.* **2015**, *67*, 537–545. [[CrossRef](#)]
11. Routray, P. High Impedance Fault Detection in Radial Distribution System Using S-Transform and Neural Network. In Proceedings of the 2015 IEEE Power, Communication and Information Technology Conference (PCITC), Bhubaneswar, India, 15–17 October 2015.
12. Cheng, J.; Huang, S.; Hsieh, C. Electrical Power and Energy Systems Application of Gabor—Wigner transform to inspect high-impedance fault-generated signals. *Int. J. Electr. Power Energy Syst.* **2015**, *73*, 192–199. [[CrossRef](#)]
13. Gautam, S. Detection of High Impedance Fault in Power Distribution Systems Using. *IEEE Trans. Power Syst.* **2013**, *28*, 1226–1234. [[CrossRef](#)]
14. Torres, V.; Guardado, J.L.; Ruiz, H.F.; Maximov, S. Electrical Power and Energy Systems Modeling and detection of high impedance faults. *Int. J. Electr. Power Energy Syst.* **2014**, *61*, 163–172. [[CrossRef](#)]
15. Maximov, S.; Torres, V.; Ruiz, H.F.; Guardado, J.L. Analytical Model for High Impedance Fault Analysis in Transmission Lines. *Math. Probl. Eng.* **2014**, *2014*, 837496. [[CrossRef](#)]
16. Costa, W.; Alencar, B.; Silva, N.; Brito, D.; Bezerra, F. High Impedance Faults: From Field Tests to Modeling. *J. Control Autom. Electr. Syst.* **2013**, *24*, 885–896. [[CrossRef](#)]
17. Basiri, M.H.; Azad, N.L.; Fischmeister, S. Distributed Time-varying Kalman Filter Design and Estimation over Wireless Sensor Networks Using OWA Sensor Fusion Technique. In Proceedings of the 2020 28th Mediterranean Conference on Control and Automation (MED), Saint-Raphaël, France, 15–18 September 2020; pp. 15–18.
18. Grimbale, M.J. *Robust Industrial Control: An Optimal Design Approach for Polynomial Systems*; Prentice-Hall, Inc.: Hoboken, NJ, USA, 1994.