Sakarya University Journal of Science
ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University | http://www.saujs.sakarya.edu.tr/

Title: Traveling Wave and Wavelet Based Fault Location Detection in Microgrids

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Recieved: 2018-07-19 00:00:00

Accepted: 2018-12-27 00:00:00

Article Type: Research Article
Volume: 23
Issue: 3
Month: June
Year: 2019
Pages: 413-424

How to cite
Ahmet Küçüker, Muhammed Oğuz Korkmaz; (2019), Traveling Wave and Wavelet Based Fault Location Detection in Microgrids. Sakarya University Journal of Science, 23(3), 413-424, DOI: 10.16984/saufenbilder.445761
Access link
http://www.saujs.sakarya.edu.tr/issue/41686/445761

Sakarya University Journal of Science 23(3), 413-424, 2019

Traveling Wave and Wavelet Based Fault Location Detection in Microgrids

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Abstract

Demand for renewable energy sources is increasing day by day. With the increase in demand for renewable energy sources, the use of microgrids also increases. Microgrids, compared to traditional grids, have a more complex structure and need more complex protection functions. In this study, a traveling wave-based fault location detection system for microgrids with loop distribution systems (looped microgrids) was developed. In traveling wave-based fault location, measurements taken from one or both ends of a line are used. However, in looped grids, lines do not have a beginning or an end. In order to allow the use of traveling wave-based protection in loop distribution systems, the system is separated into three zones. For each three separate zone a type D fault locator method was applied, and by ensuring that, these algorithms worked in accordance, fault location detection was carried out in a looped microgrid.

Keywords: microgrid, fault location, traveling wave, wavelet

1. INTRODUCTION

As a consequence of the increase in the efficiency of renewable power generators and the decrease in these generators' costs, there has been a growth in the demand for renewable energy. Especially, it is preferred by the consumers due to the accessibility provided by the price advantage. Many power sources that are close in terms of distance (e.g., the roof or the garden of a house, etc.) but have low energy generating capacity have been wired up to electrical grids by consumers. [1,2].

These sources are called distributed generation sources (DG) due to their ability to be wired into the grid from different locations. [3]. In the one-way structure of a traditional grid, it is rather difficult to coordinate the DGs and to keep the grid in the ideal operating range [4]. To manage this situation smart grid approaches are essential.

Microgrids, are smart grids which aim to turn the disadvantages DGs create for the grid into advantages. They coordinate the DGs and the consumers and thereby establish a second grid in themselves. Energy needs of the consumers are met via the energy generated by DGs. Thus, in case of a possible power outage the main power grid, by switching to island mode, this prevents the consumers to remain without power [5].

If the DGs on the microgrid generate more energy than consumers' energy demand, this accessional

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energy is utilized by being transmitted to the main grid. As for the case where consumers demand more energy than that is generated, the microgrid provides the required energy by drawing it from the main grid. However, if there is no connection between the microgrid and the main grid (island mode), the microgrid deactivates load as much as the energy deficit and thus prevents the entire network from being disabled.

Microgrids work more efficiently compared to traditional grids. Most of the loss which occurs in traditional grid occurs during the transmission and the distribution of the energy [6]. Microgrids, keep the distance between DGs and the consumers at a minimum and therefore decrease the transmission and distribution loss at a significant rate. Moreover, it is essential to increase the voltage before sending the energy to the transmission line and to decrease the voltage before it is distributed to the consumers. Generally using lower voltage in microgrids prevents transformer loss.

Most of the DGs that are used in microgrids are inverter-based. Inverters are generally unable to produce vast amounts of fault current when a fault occurs in the grid. For this reason, it becomes more difficult for relays that provide protection depending on the fault current, to detect the fault and to isolate the grid from the fault. [7].

There have been studies that were carried out to enable protection in microgrids independently of the amount of fault current.
In case of a fault in microgrids, traveling waves that begin from the location of the fault and spread through the whole grid occur. As well as traveling waves can be caused by faults in the grid, they can also occur while generators and loads are being connected to or disconnected of the grid and therefore, can cause false functioning on the relays. In order to prevent this, busbar voltage was used in this study, so that it could be detected whether there was a fault in the grid. When a fault was detected to exist in the grid, its location was detected via the use of traveling waves [5].

In a study carried out Memorial University in Canada, wavelet-based protection was tested in a microgrid established at a laboratory. Daubechies 4 wavelet (db4) function was used for fault location. As a result of the conducted experiments, it was seen that db4 function was able to detect the errors correctly and reliably [1].

In a study carried out on digital relay protection in microgrids, it was aimed to have digital multi-relay protection systems communicate among themselves and thereby provide protection in the grid [4].

One of the most commonly used measuring methods in grids is the Fourier algorithm. It enables us to carry out measurements by converting the signals that are measured in the time-domain to frequency-domain. With full-wave Fourier algorithm, DC components and integer harmonics in the measurements can be analyzed. However, full-wave Fourier algorithms are insufficient for fault location. Also, with Fourier algorithms, it is not possible to detect variable-frequency signals or non-integer harmonics. In a study which was conducted to solve this problem, the use of wavelet-based protection algorithm was suggested. With an algorithm that was developed using Chaari Wavelet algorithm, magnitude and phase information of the measured signal was analyzed. It was aimed to provide protection by making use of this information [8].

In a study on differential energy-based fault protection in microgrids, S-transform was applied to the current data collected from the buses. To determine the time of fault Gaussian Window Method was used [9].

In another study, where polarity information of the traveling wave was used for fault detection, measurements were taken from a single point on the grid and were analyzed in mathematical morphology. Thus, polarity and time information of the traveling wave was obtained [10].

In a study where fault analysis and adaptive distance protection in microgrids were aimed, Complex Wavelet Transform was used for fault analysis. In order for the relay coordination to be adaptive, ant colony algorithm was used. [11].

As for a method, where decision tree algorithm was used, firstly Wavelet transforms were used to detect the energy, entropy and standard deviation values of the fault. Then, the gathered data were processed in decision tree algorithm and so relay coordination was provided [12].

In a study where discrete-time wavelet transfer function was used, current and voltage values measured from the microgrid were processed via cubic spline interpolation method and thus the magnitude of transient fault signals was increased. Afterward, by using these signals in Karrenbauer transformation and 4th level db10 wavelet transform, fault characteristics were identified [13].

A hybrid algorithm has been developed to detect the fault location in looped microgrids. By processing the voltage measurements from DGs with wavelet transfer function and optimized multiclass support vector machine, whether there is a fault or not is detected [14].

In a study in which Particle Swarm Optimization was used, it was aimed to find out which Wavelet transform technique would reveal more distinct characteristics when applied to measurements taken from the grid. Four different techniques were tried, and their performances were compared statistically. These techniques were: Support Vector Machine, Naive Bayes, K-Nearest Neighbor, and Decision Tree Method [15].

In a study which was carried out to be able to perform high impedance fault detection in microgrids, Maximal Overlapping Discrete Wavelet Transform and Decision Tree methods were used [16].

2. PROTECTION PROBLEMS IN MICROGRIDS

Microgrids are compact grids with low capacities, which consist of energy generation, transmission, and distribution in their structures. Since they contain the whole energy process they need more complex protection functions compared to traditional grids.

2.1. Failure to Produce Sufficient Fault Current

In the event of a short circuit failure in electrical grids, it is essential to isolate the faulty area without losing any time, because in such a case, fault currents of several tens of nominal current circulate from the faulty area. Usually, to quickly respond to this type of failures, overcurrent protection relays are used. Overcurrent protection relays operate by using the severe fault current which occurs during a short circuit failure.

In case of a short circuit failure in microgrids that connected to the main grid, since the necessary fault current would be provided from the grid and the DGs the overcurrent protection would be activated, and it would isolate the faulty area. However, usually, DGs in microgrids which work in island mode cannot generate high amounts of fault current. Particularly, since inverters cannot momentarily respond to the high current demands the high amount of fault current which is necessary for the overcurrent protection to become activated may not develop. In such a case, overcurrent protection does not become activated [14].

2.2. Energy Quality in Microgrids

DGs require power electronic circuits when they are being connected to microgrids. The direct current generated by DGs such as solar panels, fuel cells, or wind turbines that operate with direct current, is converted to alternating current by the inverters before it is transmitted to the grid. As for DGs which generates alternative power, such as hydroelectric power plants, internal combustion generators, gas turbines, since the frequency is not fixed, a converter is necessary while being connected to a grid. During these conversions, a vast amount of power electronic circuits is used [3].

These circuits cause great amounts of harmonics in the grids. It is particularly difficult to detect the non-integer harmonics which are generated by the inverters [8].

Harmonics cause RMS current to increase and therefore has an effect that causes the temperature of the transistors to rise. Because of the RMS currents, motors, transformers, and parts as such get overheated and broken. RMS current causes electronic cards and measurement devices to mis operate and therefore makes it more difficult to provide protection in microgrids.

2.3. Bidirectional Grids

Power current in traditional grids happens in one direction, from the power plants towards the load group. In microgrids, there are also energy generators in the load group. Therefore, the power current is bidirectional. The fact that the energy current is bidirectional may cause protection devices that do measurements to be misled and therefore to have false activations or to have no activations when they are indeed necessary [7].

2.4. Frequency Fluctuation

Power of the microgrids that work on island mode is less than traditional grids'. For this reason, big load changes in the grid may cause frequency fluctuations [8].

2.5. High Impedance Faults

In microgrids used in industrial areas, the use of long lines may often lead to high impedance faults. Increasing the line length also increases the impedance of the line, thus reducing the severity of the traveling waves and making it difficult to detect the fault. In addition, the late arrival of the fault signal increases the response time of the protection function [7].

3. TRAVELING WAVE-BASED PROTECTION

The traveling wave-based protection method was first developed in the 1950s in order to detect the location of faults in energy transmission lines. In the following years, it has been automatized on account of the ability to transmit traveling data to remote terminals.

Digital protection relays are used for fault location detection in grids. Digital protection relays usually operate with the current, voltage and line impedance data they get from the local terminal. The location of the fault is determined by calculating the current, voltage and line impedance data in fault locating algorithms [17].

3.1. Traveling Wave-Based Fault Location Detection Methods

There are 5 different methods of detecting fault location by making use of traveling waves. Today, methods A, D, and E from these methods are used [6].

3.1.1. Type A Detection Method

In Type A detection methods, only one side of the line is used for measurement. When a fault occurs on the line, first the traveling wave that is caused by the fault, and after that the reflected traveling wave reaches to the fault location detection device. Fault location is detected by using the time difference between these two waves.

x; Distance of fault to the measurement point

t_1; Reaching time of the first traveling wave to reach the fault location

t_2; Reaching time of the reflected traveling wave to the measurement point

v; The velocity of the traveling wave

$$x = \frac{t_2 - t_1}{2} \, x \, v \quad (1)$$

3.1.2. Type D Detection Method

In Type D Detection Method, fault location detection is performed by taking measurements from both sides of the line. In case of a fault occurrence on the line, traveling waves move towards measurement points on both ends of the line. The times at which the traveling waves reach the measurement points are determined and used in the equation 2.

x; Location of fault on the line

L; Total line length

t_1; Reaching time of the traveling wave to the first measurement point

t_2; Reaching time of the traveling wave to the second measurement point

v; The velocity of the traveling wave

$$x = \frac{L + (t_2 - t_1) * v}{2} \quad (2)$$

3.1.3. Type E Detection Method

The measurement is taken from only one side of the line like it is done in Type A method. Unlike type A, it uses waves generated by closing the circuit breaker in the transmission line, instead of using the traveling waves generated by faults. The duration of the traveling wave generated by closing the circuit breaker and the duration of the reflected traveling wave from the point of failure are determined and used in the equation 3 to estimate the fault location.

x; Distance of fault to the measurement point
t_1; Reaching time of the traveling wave generated by closing the circuit breaker to the measurement point
t_2; Reaching time of the traveling wave reflected from the fault location to the measurement point
v; The velocity of the traveling wave

$$x = \frac{t_2 - t_1}{2} * v \quad (3)$$

3.2. Velocity of the Traveling Waves

Traveling waves move in both directions of the line starting from where the fault is. The motion velocity of a traveling wave is usually close to the speed of light and dependent on the parameters of the inductance and capacitance of the line. The velocity formula of a traveling wave on a line is as equation 4.

$$v = \frac{1}{\sqrt{L\ x\ C}} \quad (4)$$

In the given equation 4, L is the impedance per kilometer of the line, and C is the capacitance per kilometer of the line.

3.3. Detection of the Traveling Waves

To detect the traveling waves that occur during a fault, the waves must first reach the measuring points. The signals that reach the measuring points must be measured and recorded with time labels. The recorded measurements are put into wavelet transform as data packets and whether there is a fault or not is analyzed. If there is a fault, the data gathered from measurement points are processed in fault location detection functions and the location of the fault is detected.

3.3.1. Traveling Waves' Reaching Measurement Points

In the event of a fault occurrence in the grid, traveling waves that start from the fault location and spread through the grid occur [13]. The greater the distance between the location of the fault and the measuring points, the greater the time required for the traveling waves to reach the measuring points. Wave reach time (WRT) can be calculated with equation 5.

$$WRT = \frac{\text{Distance to the fault}}{\text{The velocity of the wave}} \quad (5)$$

3.3.2. Measurement of Voltage on Measurement Buses

The fact that the traveling waves move very quickly and the difference in the times that take them to reach the measuring points is very small, requires measurement at high speed. Current and voltage measurements taken from the grid must be at least 1 MHz [17].

3.3.3. Providing Time Synchronization of Measuring Devices

Fault location detection devices operate by using the reaching times of the traveling waves. Therefore, the data measured at the measurement points must have high time accuracy. For instance, an error of 1 microsecond in time synchronization causes the detected fault to be about 150 meters in error. GPS receivers are used to prevent synchronization errors between measuring devices [18].

3.3.4. Data Retention

For the detection of traveling waves, wavelet functions are usually used. In order to be able to analyze the wavelet functions, the data must be collected beforehand and analyzed collectively. Memory units were used for data collection. The amount of data to be collected is determined by the 2^n formula. In this formula, n refers to the level of the Wavelet function.

3.3.5. Data Processing

Electrical grids are subject to voltage fluctuations since they have a continuously changeable structure. It is important that these voltage fluctuations and the traveling waves generated by the faults can be separated from each other so that the fault can be correctly detected. Traveling waves created by faults overlap with Wavelet db4 wavelet model to a large extent. For this reason, it is usually tried to determine the existence of traveling waves by applying the db4 Wavelet function to the data received from the memory unit.

4. PROPOSED METHOD

In order to test the protection algorithm, we developed, a microgrid was established in a Matlab Simulink setting. This established grid was designed by making changes on the IEEE 9 bus system. System parameters are as in Table 1.

Table 1. System parameters

Line Parameters	Value	Unit
Self-Impedance of the Line	$0{,}9337\ x\ 10^{-3}$	H / Km
Self-Capacitance of the Line	$12{,}74\ x\ 10^{-9}$	F / Km
The Velocity of the Traveling Wave	289942,318	Km / Second
Sampling Rate	$100 \text{ x } 10^6$	Sample / Second
Total Power of DGs	3 x 3 = 9	kVA
Amount of Load	7 x 1 = 7	kW
Total Line Length of the First Zone	4	km
Total Line Length of the Second Zone	4	km
Total Line Length of the Third Zone	4	km
Error Impedance of the Fault	20	Ohm
Earth Impedance of the Fault	5	Ohm

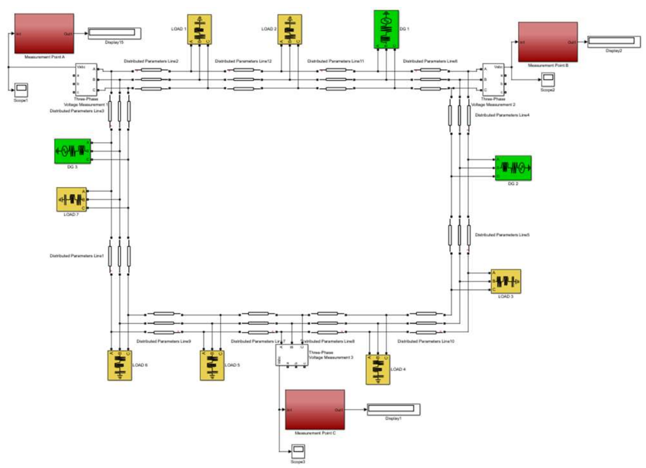

Figure 1. Microgrid Matlab simulation

The flowchart of the proposed method is given as Figure 2. The abbreviation “FDT” shown in the flowchart means is fault detection time.

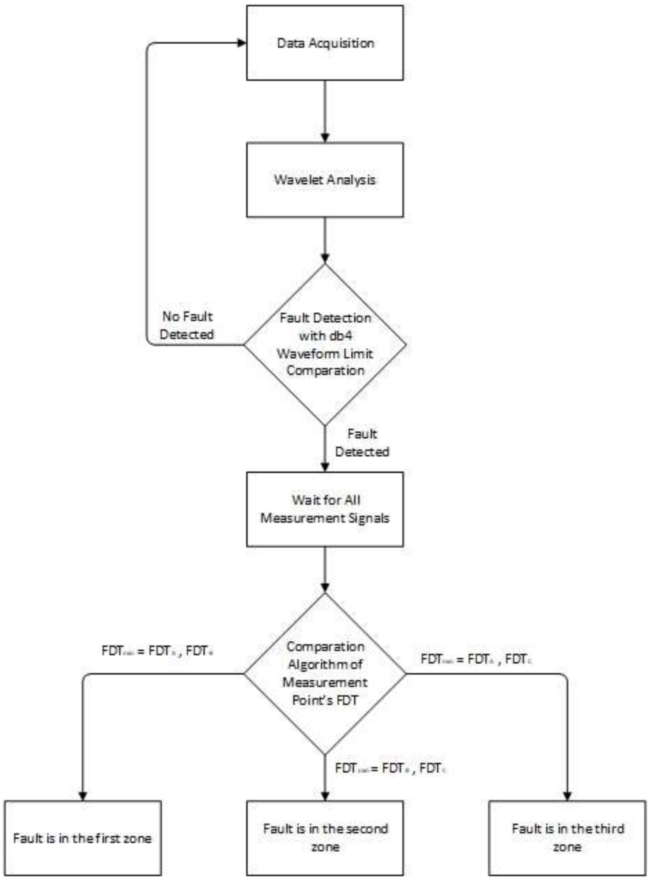

Figure 2. Flowchart of the proposed method

4.1. Analyzing the Fault Signal

In traditional grids, Fourier transform is generally used for the measurement of alternating currents. The measurement interval is fixed since the fixed window method is used for time detection in the Fourier transformation. Therefore, Fourier transforms are suitable for measuring fixed-frequency signals, but not for measuring variable-frequency signals. In the wavelet transform, since windows with different sizes are used, the signals with variable frequencies can also be measured. To calculate the db4 Wavelet function we use in the protection function; 3 vectors are needed [20].

1) The incoming signal should be divided into data groups according to which level it is going to be processed at and then transformed into a vector.
2) To obtain the average value signal (A), scale vectors (V) are required.
3) Wavelet vectors (W) are required to obtain the detail signal (D).

The scale vectors are constructed as follows.

$$\alpha_1 = \frac{1+\sqrt{3}}{4\sqrt{2}} \qquad \alpha_2 = \frac{3+\sqrt{3}}{4\sqrt{2}} \tag{6}$$

$$\alpha_3 = \frac{3-\sqrt{3}}{4\sqrt{2}} \qquad \alpha_4 = \frac{1-\sqrt{3}}{4\sqrt{2}}$$

$$V_1^1 = (\alpha_1, \alpha_2, \alpha_3, \alpha_4, 0,0,0,0,0,0,0,0, \dots, 0) \tag{7}$$

$$V_2^1 = (0,0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, 0,0,0,0,0,0, \dots, 0)$$

$$V_3^1 = (0,0,0,0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, 0,0,0,0, \dots, 0)$$

$$\dots$$

$$V_{\frac{N}{2}-1}^1 = (0,0,0,0,0,0, \dots, 0,0, \alpha_1, \alpha_2, \alpha_3, \alpha_4)$$

$$V_{\frac{N}{2}}^1 = (\alpha_3, \alpha_4, 0,0,0,0, \dots, 0,0,0,0,0, \alpha_1, \alpha_2)$$

The scale vectors can be generalized as equation 8.

$$V_m^1 = \alpha_1 V_{2m-1}^0 + \alpha_2 V_{2m}^0 + \alpha_3 V_{2m+1}^0 + \alpha_4 V_{2m+2}^0 \tag{8}$$

$$V_m^2 = \alpha_1 V_{2m-1}^1 + \alpha_2 V_{2m}^1 + \alpha_3 V_{2m+1}^1 + \alpha_4 V_{2m+2}^1$$

Wavelet vectors are as follows.

$$\beta_1 = \frac{1-\sqrt{3}}{4\sqrt{2}} \qquad \beta_2 = \frac{-3+\sqrt{3}}{4\sqrt{2}} \tag{9}$$

$$\beta_3 = \frac{3+\sqrt{3}}{4\sqrt{2}} \qquad \beta_4 = \frac{-1-\sqrt{3}}{4\sqrt{2}}$$

$$W_1^1 = (\beta_1, \beta_2, \beta_3, \beta_4, 0,0,0,0,0,0,0,0, \dots, 0) \tag{10}$$

$$W_2^1 = (0,0, \beta_1, \beta_2, \beta_3, \beta_4, 0,0,0,0,0,0, \dots, 0)$$

$$W_3^1 = (0,0,0,0, \beta_1, \beta_2, \beta_3, \beta_4, 0,0,0,0, \dots, 0)$$

$$\dots$$

$$W_{\frac{N}{2}-1}^1 = (0,0,0,0,0,0,0, \dots, 0, \beta_1, \beta_2, \beta_3, \beta_4)$$

$$W_{\frac{N}{2}}^1 = (\beta_3, \beta_4, 0,0,0,0, \dots, 0,0,0,0,0, \beta_1, \beta_2)$$

Wavelet vectors can be generalized as equation 11.

$$W_m^1 = \beta_1 V_{2m-1}^0 + \beta_2 V_{2m}^0$$

$$+\beta_3 V_{2m+1}^0 + \beta_4 V_{2m+2}^0 \quad (11)$$

$$W_m^2 = \beta_1 V_{2m-1}^1 + \beta_2 V_{2m}^1$$

$$+\beta_3 V_{2m+1}^1 + \beta_4 V_{2m+2}^1$$

After these vectors are obtained, the average value signal and the detail signal are calculated using the following equation 12 and equation 13 [20].

$$A^1 = (f.V_1^1)V_1^1 + (f.V_2^1)V_2^1 + \cdots \quad (12)$$

$$+(f.V_{\frac{N}{2}}^1)V_{\frac{N}{2}}^1$$

$$D^1 = (f.W_1^1)W_1^1 + (f.W_2^1)W_2^1 + \cdots \quad (13)$$

$$+(f.W_{\frac{N}{2}}^1)W_{\frac{N}{2}}^1$$

Having found the A^1 and D^1 values 1st level db4 Wavelet transform is completed. For the 2nd level db4 Wavelet transform V_m^2 and W_m^2 vectors are used [20].

$$A^2 = (f.V_1^2)V_1^2 + (f.V_2^2)V_2^2 + \cdots \quad (14)$$

$$+(f.V_{\frac{N}{4}}^2)V_{\frac{N}{4}}^2$$

$$D^2 = (f.W_1^2)W_1^2 + (f.W_2^2)W_2^2 + \cdots \quad (15)$$

$$+(f.W_{\frac{N}{4}}^2)W_{\frac{N}{4}}^2$$

To perform reverse transformation, the addition of the detail signal and the average signal is sufficient. After the wavelet transform is performed in the first level, the reverse transform is as equation 16 [20].

$$f = A^1 + D^1 \quad (16)$$

After the wavelet transform is performed in the second level, the reverse transform is as equation 17.

$$f = A^2 + D^2 + D^1 \quad (17)$$

Since we used the 4th level db4 Wavelet function for fault detection in the algorithm we use, 16 data must be processed at the same time [19].

The α coefficients are constant and the β values which required for the wavelet function can be obtained by using the α values. The relationship between α and β values is as equation 18.

$$\beta_k = (-1)^k \; x \; \alpha_{N-1-k} \quad (18)$$

In the simulation setting, there are measurement buses in 3 different places of the microgrid. These buses take 100 x 106 samples per second from the point they are in. The received measurements are first processed in the wavelet function and then in the fault detection algorithm.

Taken samples are converted to data packets in groups of 16 since 4th level Wavelet transform is going to be applied. Traveling wave detection is performed by applying Wavelet transform to each data packet.

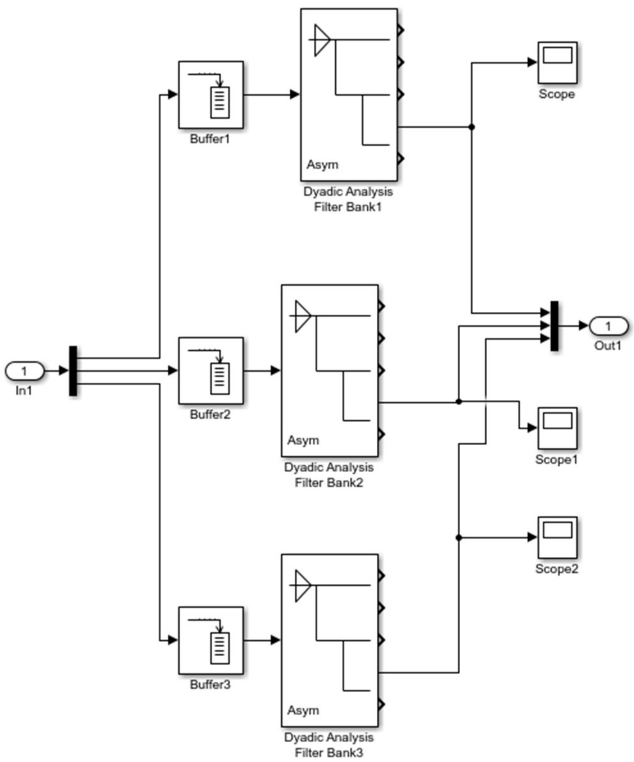

Figure 3. Wavelet block diagram

Detected traveling waves are sent to the fault detection function. This function checking the magnitude of the traveling wave, it is determined if it occurred due to a fault or due to temporary conditions that are not faults. If the traveling wave is determined to occur due to a fault, time of the fault is recorded.

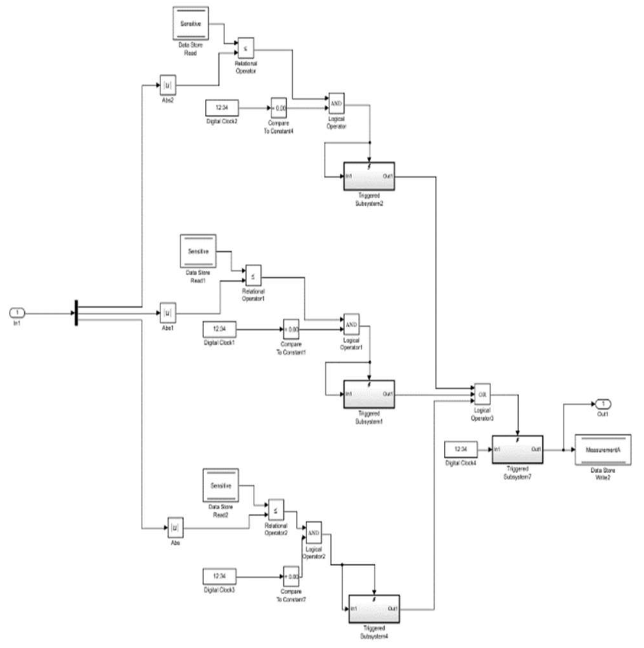

Figure 4. Fault detection block diagram

These procedures are applied at all measuring points. Since the distances of the measurement points are different from each other, the times of fault recordings held at the measurement points are also different. This time information is sent to the fault zone detection function so that it can be determined where the fault has occurred.

4.2. Fault Zone Detection

The grid is divided into 3 zones so that the fault location in the microgrid can be determined precisely. In the following zone detection algorithm, it is expected that the fault time data will come from 3 measurement points on the looped microgrid.

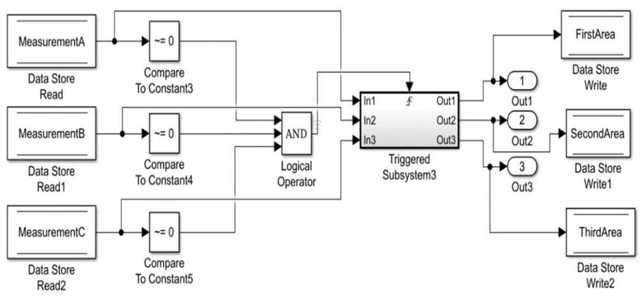

Figure 5. Analysing time data coming from all measurement points

After reaching the fault time information in the fault zone, these three data are compared in time and thus the point with the greatest fault time is determined. This point is the furthest point from the fault. Therefore, this point must be eliminated by the decision mechanism and the fault points which have the shortest fault times should be left. In this way, it is concluded that the fault is between these two points, and the fault zone is detected.

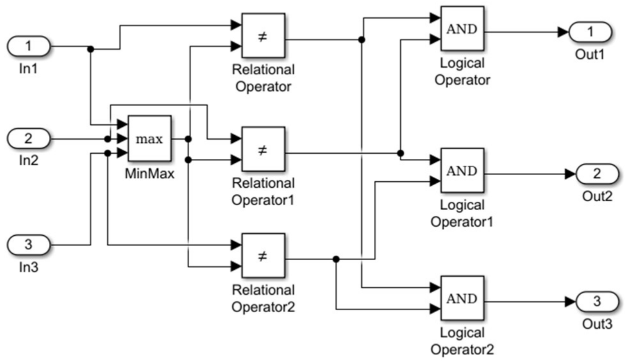

Figure 6. Zone detection block diagram

4.3. Fault Location Detection

After having detected the location of the zone where the fault has occurred, a signal that actuates fault location detection algorithm of that zone (figure 8) is produced. The triggered fault location detection algorithm uses the time information taken from the two measurement points in that zone to locate the fault.

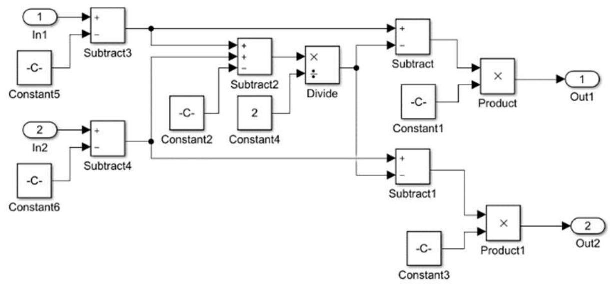

Figure 7. Function to measure the distance between fault and measurement point

4.3.1. Finding the Time of Fault Occurrence

To be able to calculate how far the fault occurred from the measurement points, it is essential to know the time when the fault occurred.

The velocity of the traveling waves that were established on the grid is calculated to be 298942,318 km/second. A traveling wave at this velocity travels one kilometer in 3,45 microseconds. Since the line length between measurement points is fixed, the time for the traveling wave to travel the line can be calculated by multiplying the line distance by 3,45 microseconds.

x; Line length between measurement points

L; Line L

$$x = L \; x \; 3{,}45 \; x \; 10^{-6} \qquad (19)$$

By subtracting the time for the traveling wave to travel the line from the total of the time length the traveling wave arrived at the measurement points at that zone, and dividing the result by two, the time of the fault occurrence can be found.

4.3.2. Calculation of the Distance Between Fault and Measurement Points

In order to calculate the distance between the fault and the measurement points, it is necessary to find out how long it takes for the traveling wave which was caused by the fault, to arrive at the measurement point. While calculating this time period, the time of the fault occurrence is subtracted from the time measured at the measurement point.

Multiplying the calculated time period with the velocity of the traveling wave gives us the distance between the fault and the measurement point.

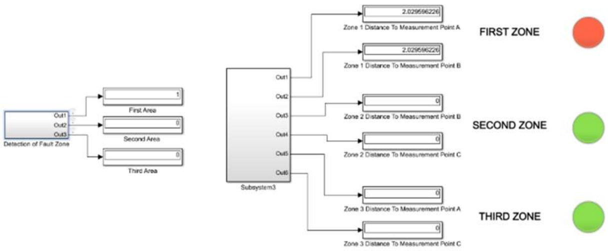

Figure 8. Fault indication

4.4. Error Rate

In the system established for the simulation, traveling wave velocity was calculated as 289942,318 km/second. Since 100 x 10^6 data were gathered per second, the time difference between two data is 10 nanoseconds. Measured data were kept in data sets of 16, therefore the protection algorithm made an evaluation every 160 nanosecond. In order to calculate the error rate, equation 20 was used.

$$\textit{Error rate} = \textit{The Velocity of the Traveling Wave} \; x \; \textit{Evaluation Time Interval} \qquad (20)$$

$$\textit{Error rate} = 289942{,}318 \frac{km}{second} \; x \; 160 \; x \; 10^{-9} \; second$$

Error rate = 46,39 x 10^{-3} km

According to this calculation, during a fault location in the system, the maximum error rate for the found results is 46,39 meters.

5. RESULTS

The suggested protection algorithm is tested in Matlab/SIMULINK. During the test, phase-phase, phase-earth, three phase, and three phase earth fault conditions were applied to the simulated microgrid from different points.

Table 2. First zone test results

FIRST ZONE	Distance of Fault Point to A (km)	Measured Distance of Fault Point to A (km)	Error Rate
A – G	1,000000	1,043792	4,3792%
B – G	1,000000	1,014798	1,4798%
C – G	1,000000	1,043792	4,3792%
A – B	1,000000	1,043792	4,3792%
A – C	2,000000	2,029596	1,4798%
B – C	2,000000	2,029596	1,4798%
A – B – G	2,000000	2,029596	1,4798%
A – C – G	3,000000	3,015400	0,5133%
B – C – G	3,000000	3,015400	0,5133%
A – B – C	3,000000	3,015400	0,5133%
A–B–C-G	3,000000	3,015400	0,5133%

In this study, traveling wave-based fault location method which is used for fault location detection was made available to be used in looped microgrids.

It is seen from the measurements done, that the maximum error rate is 43,79 meters. This value is lower than the 46,39-meter error rate we have estimated in section 4.4.

Moreover, temporary conditions such as sudden load changes that can cause fluctuations in the grid should not be perceived as faults. In the performed tests it was seen that the used protection algorithm had the selectivity to be able to distinguish faults and temporary conditions.

Table 3. Second zone test results

SECOND ZONE	Distance of Fault Point to B (km)	Measured Distance of Fault Point to B (km)	Error Rate
A – G	1,000000	1,043792	4,3792%
B – G	1,000000	1,014798	1,4798%
C – G	1,000000	1,043792	4,3792%
A – B	1,000000	1,043792	4,3792%
A – C	2,000000	2,029596	1,4798%
B – C	2,000000	2,029596	1,4798%
A – B – G	2,000000	2,029596	1,4798%
A – C – G	3,000000	3,015400	0,5133%
B – C – G	3,000000	3,015400	0,5133%
A – B – C	3,000000	3,015400	%0,5133
A–B–C-G	3,000000	3,015400	%0,5133

Table 4. Third zone test results

THIRD ZONE	Distance of Fault Point to C (km)	Measured Distance of Fault Point to C (km)	Error Rate
A – G	1,000000	1,043792	4,3792%
B – G	1,000000	1,014798	1,4798%
C – G	1,000000	1,043792	4,3792%
A – B	1,000000	1,043792	4,3792%
A – C	2,000000	2,029596	1,4798%
B – C	2,000000	2,029596	1,4798%
A – B – G	2,000000	2,029596	1,4798%
A – C – G	3,000000	3,015400	0,5133%
B – C – G	3,000000	3,015400	0,5133%
A – B – C	3,000000	3,015400	0,5133%
A–B–C-G	3,000000	3,015400	0,5133%

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