Detecting and Locating Faulty Nodes in Smart Grids Based on High Frequency Signal Injection

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Abstract—An on-line method for detecting and locating a faulty node in the utility grid is proposed for smart grids. The method is based on injection of high frequency (A-Band) current signal into the grid that would impose voltages (less than 1V according to EN50065-1 standard) on the nodes to determine changes in the impedance characteristics. This detection is accomplished online without interrupting the power flow in the network. The developed algorithm has been implemented within an electrical power system model. This low voltage network model has been tested with different fault scenarios. The proposed procedure is able to detect the faulty nodes with high accuracy.

Index Terms—Faulty node detection, illegal electricity usage, smart grid services, signal injection to grid.

I. INTRODUCTION

FAULT in the power grids is an unpredictable situation which could lead to an unbalance in the overall system operation. A Faulty node (FN) could appear in between the segments of the distribution network due to a variety of reasons. Illegal connection for electricity pilferage is one unwanted way of establishing a FN. This type of connection leads to an unpredictable technical as well as economical problems in the utility industry. From an economic point of view, this issue has a dramatic impact on the supplier’s budget because of unaccounted electricity usage [1]. Early restoration of the fault improves the reliability and safety of the distribution network [2] [3].

A new method for the detection of illegal usage based on automatic meter reading has been suggested in [4]. The method is based on traditional automatic meter readers (AMR). The host controller can detect the existence of the FN in each feeder by comparing the sum of all the energy meters within the system with the host energy meter. The disadvantage of this method is its inability to localize the FN. This method also requires high quality calibrated energy meters. In [5], a FN locating method for a high voltage long range simple distribution network is presented. The fault is detected based on the difference between the injected and reflected signals. This method is not applicable for a short range or multilayer distribution network.

In [6], a method to locate the position of the FN in the low voltage simple distribution network has been introduced. The method is based on determination of the power line characteristics by injecting the current signal into the grid to be measured by smart meters. The main disadvantage of this method is the requirement of powering down the system during the test, which is not acceptable in residential networks.

In this study, a novel approach for detecting a FN, and the procedure for localizing the position of the FN in a three phase low voltage complex distribution network is presented. The approach is based on the information provided by the smart meters to the central station, and capturing the network parameters after the injection of the test signal into the network. The proposed method can be applied to a multilayer complex distribution network as opposed to other methods mentioned earlier. The localization of the FN can be accomplished quite accurately compared to most of the available technologies. Section I provides the introduction to the well-known procedures to detect and localize the FN; Section II provides an introduction to the smart grid structure and the description of the hardware needed for the new method; Section III describes the power network models at high frequency based on low frequency measurements and high frequency test signal injection; Section IV presents the proposed method for detection and localization of the FN. The test results for the example network topologies are presented in Section V; Section VI gives the summary of the research.

II. SMART GRID STRUCTURE

In modern times, smart grid infrastructure can contribute towards power network automation which would improve the capabilities of existing power networks significantly. The primary focus is the improvements in the distribution network through communication and penetration of renewable energy systems [7] [8]. This modern power grid will integrate advanced information techniques, communication techniques, computer science and pre-existing physical grids [9]. In the smart grid infrastructure, it is possible to show when, where and how the energy is used through the on line bidirectional connectivity between users and utilities. It is also possible to manage the loads in smart grid networks to increase the energy delivery efficiency [10]. The block diagram of a smart grid network in the low voltage side (LV) is shown in Fig. 1 where each individual smart meter communicates with the central unit.

Fig. 1. LV side smart grid topology.

Two important elements in the smart grid network are the smart meter and the central unit. A smart meter is the data
impedance estimation is needed to set the current value which is determined based on statistical data or on-line impedance measurements. The block diagram of the current injection unit is shown in Fig. 3.

![Fig. 3. Test signal injection Unit.](image)

### III. POWER NETWORK MODEL

The steps for locating the FN are based on the capability of the hardware as well as on a developed model of the power network.

The method relies on the load flow analysis of the power system at PLC frequency which requires the high frequency impedance of the loads. The high frequency load impedances are either directly measured at PLC frequency or first measured at power transmission frequency and then transformed into PLC frequency by smart meters using load models. If the second method is chosen for the implementation, the model of individual loads helps to predict the high frequency impedance using the low frequency impedance can be programmed into the individual smart meters. After determining the load impedances, the smart meters transmit the information to the central unit periodically to be used in the high frequency load flow analysis. Since each measurement period can be fixed, it is assumed that the load impedances are constant during these intervals. For better accuracy, the measurement periods can be shortened by the smart meters. Other information needed for this method is the network response characteristics to the injected signal. These steps are explained in detail in the following subsections.

#### A. Network Impedance Model at Low Frequency

One of the most important data needed for detecting and locating the place of the FN is the power line network impedance model which consists of the node’s load impedance model and each feeder segment’s impedance model.

Reactive as well as active power measured at each node determine the basic version of the node load impedance model at low frequency. The real and imaginary parts of the impedance are determined separately. The characteristics of

![Fig. 2. EN50065-1 Standard for power line carrier communication.](image)
these two elements are determined based on the apparent power as well as active power which are measured by the smart meters.

The smart grid impedance model in the LV side is shown in Fig. 4. There are $n$ number of nodes in the network. Here $Z_{Fi}$ is the feeder impedance in section $i$, $Z_{Ci}$ is the cable impedance which connects feeder to the $i^{th}$ customer, $f_L$ is the grid frequency and $Z_{Li}$ is the $i^{th}$ load impedance which has resistive ($R_{Li}$) and inductive ($L_{Li}$) components. The parameters $R_{Li}$ and $L_{Li}$ are obtained from the energy consumption information as shown in (2) and (3).

$$Z_{Li} = R_{Li} + j2\pi f_L L_{Li}$$

$$R_{Li} = \frac{P_i}{I_{rms}^2}$$

$$L_{Li} = \frac{\sqrt{S_i^2 - P_i^2}}{2\pi f_i I_{rms}^2}.$$  \hspace{1cm} (3)

$Z_{Fi}$ and $Z_{Ci}$ are the feeder segments, $P_i$, $S_i$ and $I_{rms}$ are $i^{th}$ load real power, apparent power and RMS current.

B. Network Impedance Model at High Frequency

Smart meters in smart grids measure the apparent power as well as active power at the line frequency. The impedance measured of the power line frequency is converted to the current injection level at high frequency. It is possible to construct the high frequency impedance parameters based on the measured low frequency impedance. The polynomial mapped transfer function could be used for conversion. The transfer function varies for each load and changes with the operating frequency. The high frequency model definition is given as follows:

$$Z_{LH}(f) = H(f)Z_L$$ \hspace{1cm} (4)

where $Z_{LH}(f)$ is the complex impedance at the operating frequency $f$, $Z_L$ is the low frequency impedance and $H(f)$ is the polynomial mapped complex transfer function that converts complex low frequency impedance ($Z_L$) to $Z_{LH}(f)$. The general form for the $H(f)$ is shown in (5)

$$H(f) = (a_d + j b_d) f^d + (a_{d-1} + j b_{d-1}) f^{d-1} + \ldots + (a_0 + j b_0)$$ \hspace{1cm} (5)

where $a_n$ and $b_n$ are the coefficients of the $d^{th}$ degree polynomial to represent $H(f)$. Polynomial coefficients are defined based on the impedance magnitude and phase variations of typical loads at home. As an example, the impedance magnitude and phase variation of the residential heater are presented in Figs. 5 and 6, respectively.

**Fig. 5.** Heater impedance magnitude.

**Fig. 6.** Heater impedance phase.

Although it is possible to determine the conversion ratio for the load, it is more precise to measure the high frequency impedance directly. The current and voltage transducers should have wide bandwidth to measure the high frequency portion of the current and the voltage signals. Based on the high frequency voltage and current measurements the individual load impedances would be determined. The measured or estimated individual high frequency load impedances are communicated to the central unit by the individual smart meters. The central unit has predetermined network information which is basically the number of nodes and impedance between the individual nodes. The impedance between the nodes is based on the high frequency impedance of the power cable among the nodes. Table I shows the typical power line impedance characteristics at 90 KHz. The central unit constructs new admittance matrix every time it gathers high frequency load impedances from the smart meter. In the network architecture, there are $(2n + 2)$ number of nodes including the ground and central unit nodes. The ground is considered as node number 0. The loads are treated as an impedance between the meter location and the ground. The admittance between two nodes (node i and k) can be found as:

$$y_{ik} = \frac{1}{A_{ik} + jB_{ik}}$$ \hspace{1cm} (6)

where $A_{ik}$ and $B_{ik}$ are the real and imaginary parts of the impedance between the nodes. The admittance matrix in the network can be constructed as:

$$[I_1, I_2, \ldots, I_{2n+1}] = \begin{bmatrix} Y_{11} & Y_{12} & \ldots & Y_{1(2n+1)} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \ldots & Y_{n(2n+1)(2n+1)} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_{2n+1} \end{bmatrix}$$ \hspace{1cm} (7)

$[V_1, V_2, \ldots, V_{2n+1}]$ array has the individual nodes voltages and $[I_1, I_2, \ldots, I_{2n+1}]$ array represents the source currents into the
individual nodes. The diagonal element of each node, known 
as the self-admittance, is the sum of all the admittances 
connected to it as given by:

\[ Y_{ii} = \sum_{k=0}^{2n+1} y_{ik} \text{ where } i \neq k \]  (8)

The off-diagonal element, known as the mutual admittance 
is equal to the negative of the admittance between the nodes. 
This element is given by:

\[ Y_{ik} = -y_{ki} \]  (9)

For a given high frequency injected current, load flow 
analysis has been carried out with the constructed impedance 
matrix using the Newton Raphson method [23] to find the 
voltage of the individual nodes. In the high frequency domain, 
the only source that injects the signal is the programmable 
current source; therefore, all the node currents \( I_i \) are zero 
except the first node current \( I_1 \). The individual node voltages 
are recorded in the \( V_{bus} \) array for the fault diagnosis presented 
in Section IV.

<table>
<thead>
<tr>
<th>TABLE I POWER LINE CHARACTERISTICS AT 90 KHZ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium / Steel</td>
</tr>
<tr>
<td>25.0</td>
</tr>
<tr>
<td>35.0</td>
</tr>
<tr>
<td>50.0</td>
</tr>
</tbody>
</table>

C. Response of the Network to High Frequency Test Signal

A high frequency test signal can be injected to the starting 
point of the feeder to determine the real power line network 
characteristics. The FN is also considered since the test is 
conducted on the real network. The test signal is considered as 
a programmable current source. With respect to the EN50065- 
1 standard, the amount of current is limited due to the injected 
signal peak-to-peak voltage limitation at high frequency. Two 
different methods for adjusting the current magnitude are 
proposed. The statistical data showing the average of the total 
network impedance from the base station side for a reasonable 
time period could be used for setting the current. An alternative 
approach is the adaptive current adjustment. In this approach, 
the high frequency voltage is monitored continuously. The 
amplitude of the injected current is controlled based on 
measured voltages of the individual nodes. In the second 
method, although the control is more optimum than the first 
one, the controller requires more processing time. The high 
frequency signal measurement unit is used to determine the 
characteristics of the received signal. The unit consists of the 
high voltage coupler, band pass filter and the high frequency 
RMS voltmeter. The high voltage coupler is used to separate 
the high frequency test signal from the high voltage power 
line. The structure of the coupler is based on LC band stop 
filter which has a high impedance within the range of the test 
signal. To mitigate the noise effects on the received signal a 
sharp band pass filter is used to pass only the test signal which 
has the frequency within the range of the EN50065-1 standard. 
The communication between devices can be based on power 
line carrier or wireless communication. Power and information 
flow diagram based on power line carrier communication 
method is shown in Fig. 7, where \( SM_i \)s represent the smart 
meters at the specified nodes.

IV. FAULT DIAGNOSIS

The array of the node voltages based on simulation of a 
predefined model with respect to test signal injection is \( V_{bus} \). 
The array of the measured high frequency received signal 
voltage at the nodes due to the injection of the test signal in 
the real world is \( V_{meas} \). The detection unit runs the specific 
procedure at each iteration based on the two input matrices to 
detect the existence of the FN on the network. The difference 
between the measured and estimated voltage arrays is given as:

\[ V_{diff} = V_{meas} - V_{bus} \]  (10)

In the absence of a FN, \( V_{diff} \) will be null. \( V_{diff} \) is used to 
show the changes in the predefined network impedance model. 
Each element in the array is compared with the threshold 
value. This procedure can be summarized as:

\[ \forall x \in [V_{diff}] : \text{if } x \geq V_T, \Rightarrow x \in FNA \]  (11)

where \( x \) is the set of elements in vector \( V_{diff} \), and \( V_T \) is the 
threshold voltage.

An anomalous increase in matrix elements shows the area 
where a FN is present. The peak value of elements inside the 
faulty node area (FNA) shows the FN which is the closest 
ode to the fault location in the network. The definition of the 
FN is given as:

\[ \forall x \in F.N.A : \text{if } x_i > x_k, k \neq i \Rightarrow x_i = FN \]  (12)

The method allows the detection of the existence of the 
FN as well as the determination of the FN location. The flow 
diagram for the detection and localization method is given in 
Fig. 9.
V. CASE STUDIES

Different case studies are conducted to verify the validity of this novel method in experimental and simulated networks. In Section A, three different scenarios are simulated in the proposed three layer network to examine the validity and the performance of the concept. In Section B, the proposed method is tested in the real network with eight nodes. The effects of inaccurate measurements are also presented in simulated and experimental networks.

A. Network Simulation

A three layer network has been selected as the example network. The studied three layer network is shown in Fig. 8. This model includes the most possible complicated topology for the low voltage power line network. All of the simulations have been performed on this model. In the first case, there is no FN in the network. In the second and third cases, one FN is located at different locations for each one of the cases. In the simulated three layer network, there are 45 nodes (1, 2, ... 45), and only 22 of them (24, 25, ... 45) have a smart meter (sm24, sm25, ... sm45). The loads are selected based on the typical home load pattern. Inductive and resistive loads are both considered in this case study. In the model, each feeder and cable segments are modelled as a shunt medium transmission line. For modelling the feeder segments, the characteristics of the cable are obtained from Table I based on the $25m^2, Al/Fe$ cable model. The feeder and cable are modelled as:

$$Z_{Fi} = R_{Fi} + j2\pi f_H L_{Fi}$$
$$Z_{Ci} = R_{Ci}$$

where $Z_{Fi}$ is the $i^{th}$ feeder segment impedance, $Z_{Ci}$ is the cable impedance which connects the feeder to the $i^{th}$ load, and $f_H$ is the frequency of the injected signal. The feeder segment resistance ($R_{Fi}$) is taken to be $100\, \text{m}\Omega$ and the feeder segment inductance ($L_{Fi}$) is taken to be $16\, \mu\text{H}$. Since the length of the cable which connects the feeder to each load is very short, it is modelled with just a resistive element ($R_{Li}$), $R_{Li}$ has a range of (3 to 10\, \Omega) and $L_{Li}$ has a range of (0 to 20\, m\text{H})

The test signal frequency is selected as 90 KHz.

Three different scenarios are considered for method validation. In the first one, the network is running in the normal mode; $V_{diff}$ is about zero where there is no illegal connection or FN in the network.

In the second situation, a FN is considered close to node 40 with a $2\, \Omega$ resistive load connection. Due to the absence of a meter at node 20, the $V_{diff}$ vector has a peak in node 40 which is the closest node to the FN.

For the third scenario, the FN is considered to be near node 16. The impedance of the FN is the same as the second scenario. As shown in Fig. 11, $V_{diff}$ has the largest value near node 34. Since node 34 is the closest smart meter near the FN, we can conclude that the algorithm accurately detects
the FN in the network. It can also be concluded that the FNA is depended on the value of the threshold voltage ($V_T$). The elements in the $V_{diff}$ vector which are greater than the $V_T$ are considered as a FNA. The $V_T$ should be selected so that the FNA could be identified with a reasonable accuracy. Selecting $V_T$ as $3 \times 10^{-3} \text{V}$ gives accurate identification of the FN in the third scenario.

Many factors have an effect on the accuracy of the FN location estimation. The dominant factors that lead to miss identification of the FN are the truncation effects due to the analog-to-digital converter resolution, the inaccurate model of the power line impedance matrix, and the non-linearity of the load estimation model. It is expected that the magnitude of the $V_{diff}$ at the FN is much larger than the $V_{diff}$ in any other node in the network. The faulty node detection ratio ($FNDR$) given in (14), is defined as the ratio of the $V_{diff}$ magnitude at FN to the next largest $V_{diff}$ value at any node in the network. The $FNDR$ is a good measurement for the quality of the FN detection.

$$FNDR = \frac{V_{diff}(FN)}{\max(V_{diff}(i))_{i \neq FN}}$$ (14)

The analysis of the effect of the analog-to-digital converter resolution on the $FNDR$ is presented in Fig. 12. $FNDR$ should be greater than 1 for the possibility of the FN detection; the quality of the detection increases as $FNDR$ increases. The high frequency network model is based on node power measurements and linear load conversion from low to high frequencies. Tolerance of power measurements causes inaccuracy in network model estimation. The tolerance is modelled by injecting a random error to the final network model before performing the power flow analysis. Relation between the tolerance percentage vs. total error is shown in Fig. 13. The total error means the number of miss identification of the FN when the location of FN is changing from the first node to the last.

### B. Experimental Network

A one-layer eight-node network has been implemented in the laboratory to analyse the performance of the proposed method in a real system. Higher load impedance compared to the low impedance characteristics of the feeder segments increases the complexity of the FN detection procedure. In the experimental network, the impedance of the nodes have been selected in the range of 40Ω to 80Ω to reflect the worst case scenarios. The implemented network is shown in Fig. 14.
to measure the injected signal effect on that node. The coupling/decoupling circuit built in the lab is shown in Fig. 15. Coupling/decoupling circuits are made of a high pass filter that blocks the 60 Hz signal. Circuits protect the low voltage current injection and voltage measurement circuitry from higher power levels in the network.

![Fig. 15. Coupler/Decoupler circuit.](image)

The EN50065-1 standard has been followed for current injection into the power network during the laboratory experiments. The amplitude of the current injected into the feeder is 142 mA. Amplitude of the injected current has been set based on maximum allowed peak-to-peak imposed voltage on each one of the nodes which is 1V [21]. The voltage and the current of each node were used to compute the high frequency load impedances. Characteristics of the feeder segments are defined based on the length of each segment. The injected signal waveform is shown in Fig. 16.

![Fig. 16. Injected test signal waveform.](image)

The test has been conducted with the FN connected to node 5. The voltage and current information for each node have been collected based on the 142mA current injection. High frequency impedances for each node along with the predetermined cable impedance are combined to form the high frequency impedance network. The high frequency load flow analysis is performed for the injected current. The measured and the estimated node voltages from the load flow analysis are compared to calculate $V_{\text{diff}}$. Table II shows the measured and estimated node voltages.

<table>
<thead>
<tr>
<th>Node</th>
<th>Without FN (Simulated)</th>
<th>With FN (Measured)</th>
<th>$V_{\text{diff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.020</td>
<td>0.992</td>
<td>0.028</td>
</tr>
<tr>
<td>2</td>
<td>0.596</td>
<td>0.596</td>
<td>0.004</td>
</tr>
<tr>
<td>3</td>
<td>0.515</td>
<td>0.388</td>
<td>0.127</td>
</tr>
<tr>
<td>4</td>
<td>0.362</td>
<td>0.232</td>
<td>0.130</td>
</tr>
<tr>
<td>5</td>
<td>0.234</td>
<td>0.170</td>
<td>0.065</td>
</tr>
<tr>
<td>6</td>
<td>0.167</td>
<td>0.132</td>
<td>0.035</td>
</tr>
<tr>
<td>7</td>
<td>0.141</td>
<td>0.097</td>
<td>0.045</td>
</tr>
<tr>
<td>8</td>
<td>0.149</td>
<td>0.096</td>
<td>0.053</td>
</tr>
</tbody>
</table>

![Fig. 17. $V_{\text{diff}}$ for each node where FN is close to node 5.](image)

The voltage matrix elements are used in the FN detection algorithm. Based on the developed method as it is shown in Fig. 17, the FN has been identified to be close to where the fault occurred. The absolute value of $V_{\text{diff}}$ peaks at node 4 which is very close to the FN (node 5).

The measurement accuracy can affect the performance of the detection procedure. Measurement error has been added to the measured data to show the sensitivity of the performance with respect to measurement accuracy. The error tolerance is in the range of 0 to 20% of the total measurement. In Fig. 18, the minimum voltage difference of FN voltage compared to those of other node voltages are presented with respect to the measurement error tolerance.

![Fig. 18. Minimum voltage deference of FN voltage to other node voltages vs. measurement error tolerance.](image)

In order to have a sufficient voltage difference for detecting the FN, the measurements and the low to high frequency conversion matrices should have a good accuracy. High error tolerance in the measurement or the conversion matrices makes inaccurate detection for FN.
VI. Conclusion

In this paper, a novel method for detecting and localizing a FN in low voltage power line networks is presented. The method can be run in a live network without any interference. The procedure is based on the power line network characteristics and the response of the network to a high frequency test signal. Simulations based on three different scenarios have been implemented to demonstrate the validity of the method. The truncation effects of analog-to-digital conversion on localizing the FN have been identified; the dependence of the method on the resolution of smart meters are simulated. The method has been validated with an experimental network developed in the laboratory. Experimental results showed that the proposed method effectively detects and localizes the FN.

REFERENCES