INFLUENCE OF AN INVERTER BASED DG ON A DOUBLE-ENDED FAULT LOCATION SCHEME

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Abstract

This paper describes the influence of Distributed Generation (DG) on a double ended fault location based on measuring the high frequency fault transients. The additional non-fundamental frequency current components from DG will influence the accuracy of an impedance based fault location technique based on non-fundamental frequencies. A double-ended impedance based fault location technique that utilizes the high frequency content (up to 5 kHz) is studied. The study showed that double-ended method is still able to locate a fault with a maximum error of 4% compared to the case without DG which showed a percentage error up to 2%.

1 Introduction

Increased attention has been directed to the installation of distributed generators in distribution systems due to economical, technical and environmental factors [1]. Economically the DGs leads to reduced losses by reducing the magnitude of the transmitted or distributed power. During the main system faults, the DGs will supply the local loads with continuous power which in turn enhances the system survivability [2]. DGs that use renewable energy technique such as photovoltaic and wind power generation help in reducing CO_2 emissions.

The addition of DGs to the distribution system represent a challenge to the traditional fault location techniques because of their contribution to the fault current which can be bidirectional as well as changing system configuration. If the rating of the DG is large, it will influence the accuracy of fault locating methods. The traditional locating method would disconnect the DGs during the fault condition to accomplish correct operation. If the DG rating is large enough it will create a problem with the operation of the system [3]. Hence, there is a requirement for a fault locating technique that considers the operation of the DGs especially for an Integrated Power System (IPS) or a MicroGrid (MG).

Recent research has been conducted to investigate fault location in distributing systems considering the influence of the DGs. Das and Santoso investigated the effect of the DG on the single-ended impedance based method [4]. The upstream and downstream faults from the DG were studied. The accuracy of the locating algorithm is compromised when faults occurs downstream from DGs. The percent error depends on factors such as the magnitude of the DG and the distance of the fault to the DGs [4]. Moreover, in [5] and [6] the effect of the inverter-based DG and the synchronised DG generator respectively are studied. In [5], it is shown that neglecting the DG current contribution or utilizing an inaccurate electrical model will significantly impact the locator accuracy [5]. While in [6] it is proposed to modify the method to include the influence of the DG for a fundamental frequency fault location method. Menchafou, et al, proposed a new fault locating technique based on Voltage-sag and current measurements at a substation to estimate the fault distance with the presence of DG [7]. The study of the effect of a synchronous generator DG on the traditional impedance base method is presented in [8]. They checked the influence of DG using a 3-phase fault and they concluded there was a significant influence of the DG. Another study investigated a fault location algorithm with the effect of the DG using positive sequence impedance at fundamental frequency [9]. The method described in [10] used the single-ended method to locate a fault in a system containing a DG. They used the superimposed circuit to calculate the infeed current from the DG terminal in order to calculate the exact fault current. If the angle of the fault current and the fault voltage at the fault point are equal, this is the fault location. Moreover, in [11] the measurement from the main source and the DG is used to estimate the fault distance. However, it needs first to detect the type of the fault as well as the location of the DG upstream or downstream in order to utilise the correct estimating equation. Another study by Jia, et al [12] studied the effect double-fed induction generator (DFIG) on a single ended impedance-base fault location method. They utilised the fault transient high frequency domain (up to 3 kHz) with short window segment in order to avoid the effect of DG on the single-ended method.

The majority of the work mentioned investigated the influence of the DGs on the single-ended impedance based fault location technique at fundamental frequency. They showed that the DG had an adverse effect on the traditional single-ended algorithms due to neglecting the DG supplied current. Though [12] studied the influence of the DG on the higher frequencies impedance-based method, it did not investigate the influence of the DGs on the double-ended method. In this work, the investigation of the influence of the invertor based DGs on double-ended impedance based fault location technique will be considered due to the lack of research in this field.

2 Double-ended algorithm review

The impedance estimation fault location method in an IPS based on double end measurement will be introduced and demonstrated. A single-phase circuit with a short circuit fault on the distribution line as in figure 1 will be used to introduce the basis of this method. The supply impedance represented by Z_s, while Z_{Load} is the equivalent load impedance. The impedance between the fault and the sending end is Z_x and the remaining impedance Z_{l-x} represents the impedance to the received end [13].

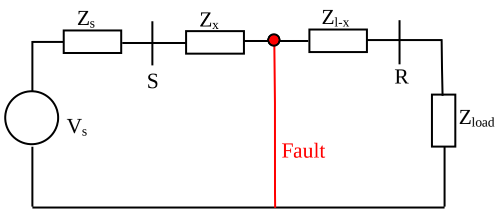


Fig. 1 Single phase circuit with a phase to ground fault

The fault can be considered to be a voltage transient source which creates voltage and current fault transients and contains information over a wide frequency range. The Thévenin equivalent impedance of the supply source at the non-fundamental frequencies is a short circuited as shown in figure 2 while the fault is represented as a transient source [13, 14].

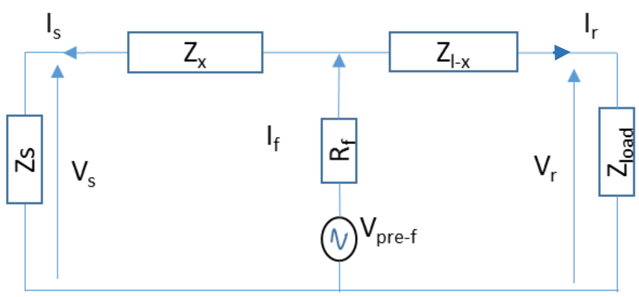


Fig. 2 System at non-fundamental frequency during fault situation

The fault provides transient voltage V_f at non-fundamental frequency and R_f is the fault resistance. The POM1 is the point of measurement at the source end while POM2 is the measurement point at the load end. Circuit theory to the measured voltage and current at both ends during fault is used to calculate the impedance between POM1 and the fault point. Kirchhoff's voltage law was applied to figure 2 giving [13, 14]:

$$V_s + I_s Z_x + I_f R_f = V_r + I_r Z_{l-x} + I_f R_f \quad (1)$$

where V_s, I_s and V_r, I_r are the measured voltage and current at both ends, I_f *and* R_f are the fault current and fault resistance. Z_x is the line impedance between POM1 and the fault, Z_{l-x} is the remaining line impedance such that the total line impedance is $Z_l = Z_x + Z_{l-x}$, hence

$$Z_x = (V_r - V_s + I_r Z_l) / (I_s + I_r) \quad (2)$$

The impedance between the fault point and source end is estimated using equation (2). The fault location can be founded by dividing the estimated impedance by the per-unit length impedance of the line. As it is clear from equation (2), the fault resistance information is not required by the double-ended method and neither is knowledge of the load and the supply impedances needed.

2.1 – Influence of DG on the Double-ended algorithm

An inverter based DG was used to investigate its influence on the double-ended impedance based fault location scheme. The DG was connected to the line through a coupling impedance as shown in figure 3.

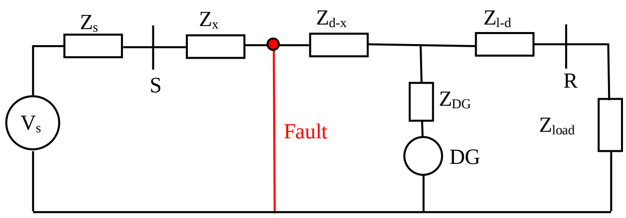


Fig. 3 The circuit with DG connected between the fault and the received end

The analysis at non-fundamental frequency showed that the DG is also considered an additional source of non-fundamental components as shown in figure 4.

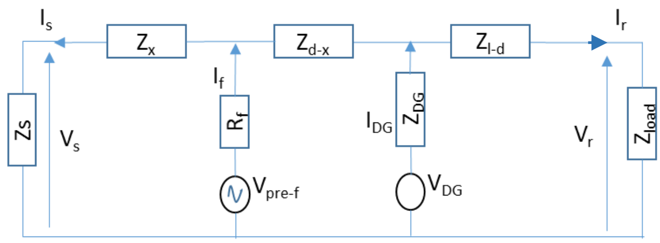


Fig. 4 The circuit with DG at non-fundamental frequencies

The derived impedance estimation equation that considers the influence of the added DG is given in equation (3).

$$Z_x = (V_r - V_s + I_r\ Z_l - (I_{DG}\ Z_d)) / (I_s + I_r - I_{DG}) \qquad (3)$$

Where:

I_{DG}: the supplied DG current and

Z_d: the impedance between POM1 and point where the DG is connected to the line.

The difference between equations (2) and (3) is the effect of the DG current and the impedance between the point where the DG is connected and the sending end measuring point.

3 DG modelling

A grid forming PWM converter was simulated to represent a DG as shown in figure 5. A PI current controller working in the dq reference frame is used to control the output power of the DG and to limit its output to the rated power during the fault time. The basic structure of the grid forming power convertor is shown in figure 5 [15]. The parameters used for this model is given in table I. The operation of the DG is tested during normal and abnormal conditions. The controller response in both conditions are shown in figure 6 while a sample of the grid connected converter output is presented in figure 7. It is clear from figures 6 and 7 that the convertor works as required during normal and abnormal conditions despite a very small distortion in the signal which can be further reduced by designing a proper filter to replace the coupling impedance. The simulated converter behaviour is then typical of DG performance

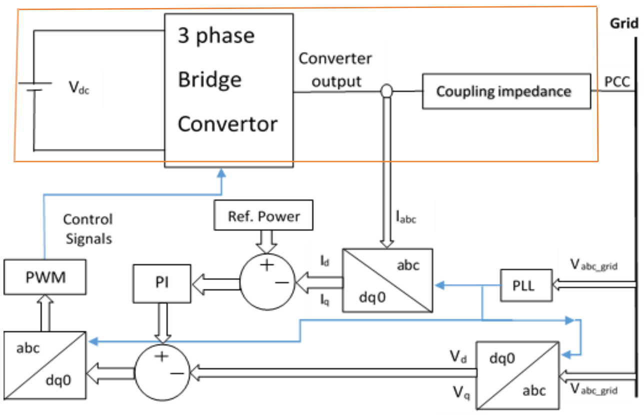
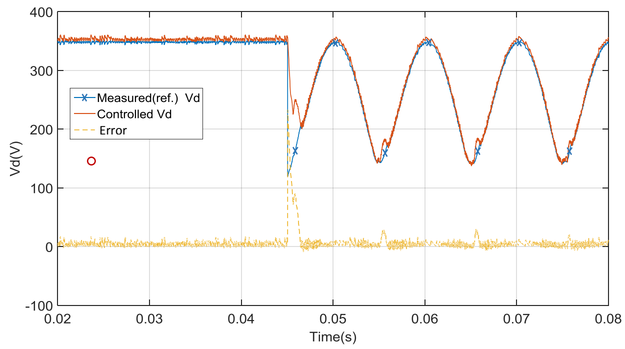


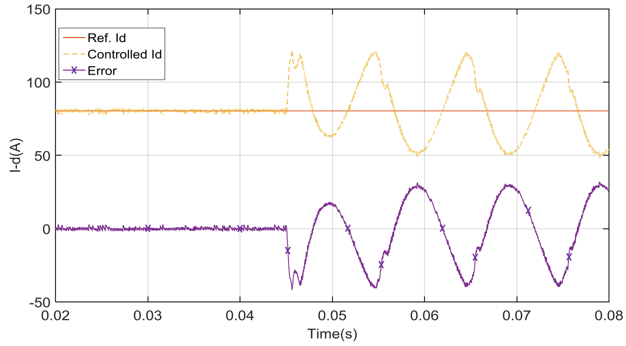
Fig. 5 Basic structure of grid connected power convertor

Parameter	Value
V_{dc}	$1.2 \times V_{L\text{-}L(grid)}$
Coupling impedance	0.001+0.910i
Proportional gain	2.663
Integration gain	395
Carrier frequency	10 kHz

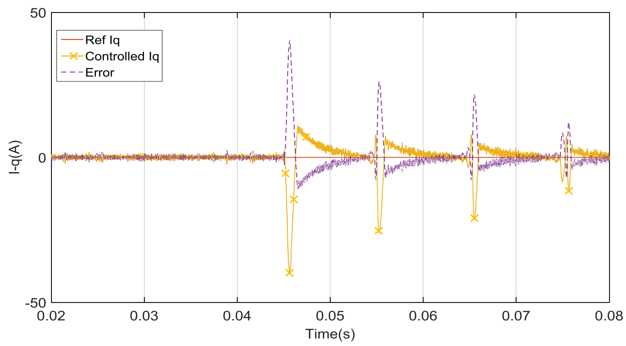
Table I DG parameter



(a)



(b)



(c)

Fig. 6 Controller parameters (a) d-axis current (b) q-axis current (c) d-axis Voltage

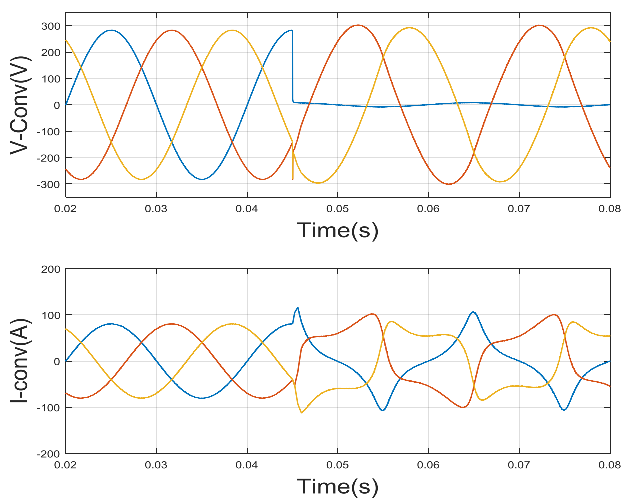


Fig.7 Grid connected inverter output voltage and current

4 Simulation and results

A simulation of a circuit composed of a main ideal source connected to source impedance, and a 100 meter transmission line connected to a pure resistive load are shown in figure 8 while the circuit element values were presented in table II. The transmission line is divided to 10 equal sections. The required data was measured from the sending and receiving ends of the transmission line of the system shown in Figure 8.

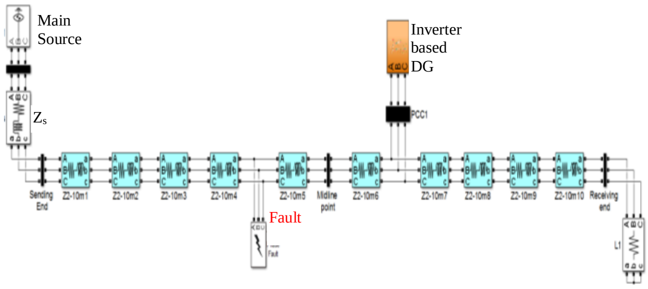


Fig. 8 The simulated circuit.

Parameter	Value
Source voltage (ph-ph)	380 (V)
Source impedance	0.1 + 0.0005i
Load resistance (L1)	1.84 Ω
Per meter line resistance	0.8 mΩ
Per meter line reactance	0.28 µH
DG power	15 kW-50kW
Sampling Frequency	50 kHz

Table II Circuit parameters

Different fault types with different DG scenarios were proposed to validate the influence of the DG on the higher harmonic double-ended impedance based fault location scheme. The first scenario was to locate a 15 kW DG at middle of the line (50m away from both ends). A single line-to-ground (SLG) was applied to six locations 20m apart. Starting from the sending end (0.0m) and finishing with received end as shown in figure 9.

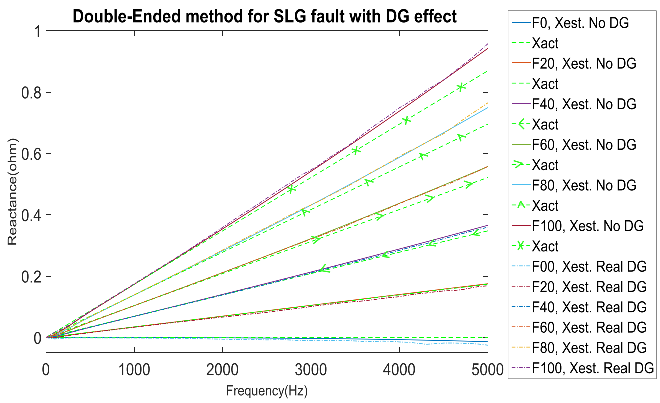


Fig. 9 estimated Reactance using the double-ended method with the effect of the DG at 50m

The estimated reactance in presence of DG (dash dotted lines) are as shown in figure 9 using (2) and are compared to the original case without the DG (continuous lines). It is apparent from the estimated reactance that the DG has small adverse effect on the reactance estimation. The influence is due to the injected non-fundamental current components that have been neglected in the estimation equation (2) used in this work. The estimated distance for all the assumed fault locations as well as the percentage error were calculated and are presented in table III and compared to the case without the DG present. The distance was calculated using the average distance through the 5 kHz frequency range considered. Then the percentage error was calculated using equation (4).

$$\text{Percentage error} = ((\text{Estimated dist.} - x.) / l) \times 100\ \% \tag{4}$$

Fault distance	Estimated distance		Percentage Error	
	DG = 0kW	DG = 50kW	DG = 0kW	DG = 50kW
00	-0.65	-2.19	-0.65	-2.19
20	19.65	18.56	-.35	-1.44
40	40.011	39.46	0.011	-0.53
60	60.425	60.57	0.425	0.57
80	80.9	81.9	0.9	1.9
100	101.44	104.21	1.44	4.21

Table III Estimated reactance and percentage error

The results presented in table III confirm that the double-ended method at non-fundamental frequencies can work with high accuracy even when a DG is subsequently connected to the system and not been considered in the protection design process. It is noticeable that the max percentage error increased only by 2% when a DG with supplied power of 50 kW is added to the system 50m from the sending end. This result is explained by the fact that the DG current have small non-fundamental components that can be neglected in the estimation equation (2). A comparison of the frequency contents of the utilized DG with ideal one is shown in figure 10. It is clear that the neglected non-fundamental frequencies injected by the DG is the source of the small increased error.

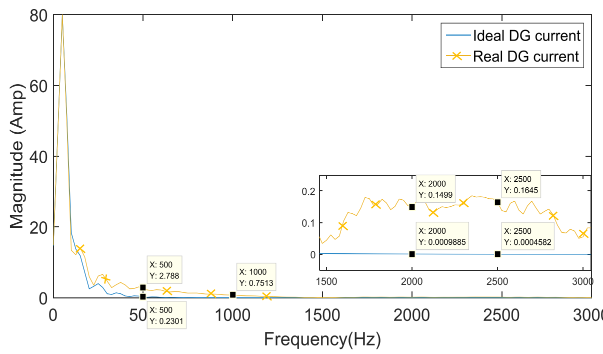


Fig. 10 frequency content of the utilized DG during fault transient

The second scenario investigates the effect of the magnitude of the supplied power by the DG. For this, three supplied power values were utilized, they are 15kW, 30kW and 50kW which represent up to 50 percent of the power required by the system load. A summarized percent error calculation is presented in table IV for simplicity while figure 11 shows three fault reactance estimates with the applied DG powers.

It can be seen from the calculation provided in table IV which also clear from figure 11, that the maximum percentage error increased by 1% when the supplied power increased from 15kW to 50kW for fault in any location throughout the total line length. Further analysis is shown in figure 12 when a comparison analysis of the frequency domain for the three cases is achieved. The figure shows as the supplied power increased, the non-fundamental DG current contained does not changed too much, where the biggest effect at the lower frequencies up to around 500 Hz.

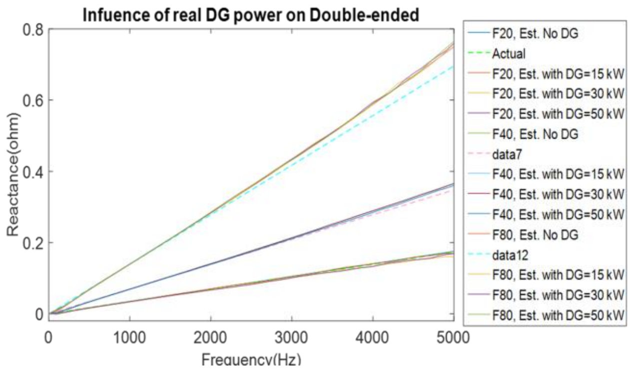


Fig. 11 Reactance estimation for three fault locations and DG

Fault location	Percentage error			
	DG = 0	DG = 15 kW	DG = 30 kW	DG = 50 kW
20	-0.35	-0.6	-1.06	-1.44
40	0.01	-0.06	-0.09	-0.5
60	0.75	0.609	0.528	0.575
80	0.89	1.34	1.79	1.9
100	1.44	3.52	3.95	4.21

Table IV Influence of real DG supplied power on the error

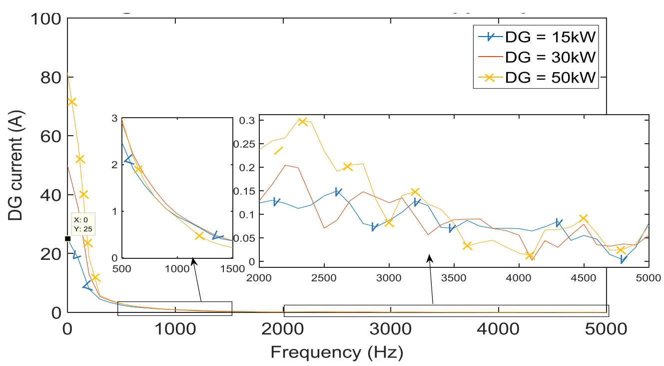


Fig. 12 frequency content of the DG current fault transient

The third scenario was to check the influence of the DG location upstream (between the sending end and the fault location) and downstream (between the fault and the receiving end). Hence, for the same fault, the DG is placed upstream and then downstream. For this, a fault is initiated 40 m away from the s-end and the DG once place at 20 m from s-end and then moved to 60 m form s-end as shown in the reactance estimation figure 13(a). The difference between the two cases was very small less than 0.5% that can be neglected. Another fault test that can confirm this finding is shown in figure 14, where the fault was initiated at 60m and the DG placed upstream at 40m and downstream at 80m. The reason is that the DG has very small non-fundamental current components at higher frequencies that been shown in figure 12 which result in small influence on the estimated reactance at these frequencies.

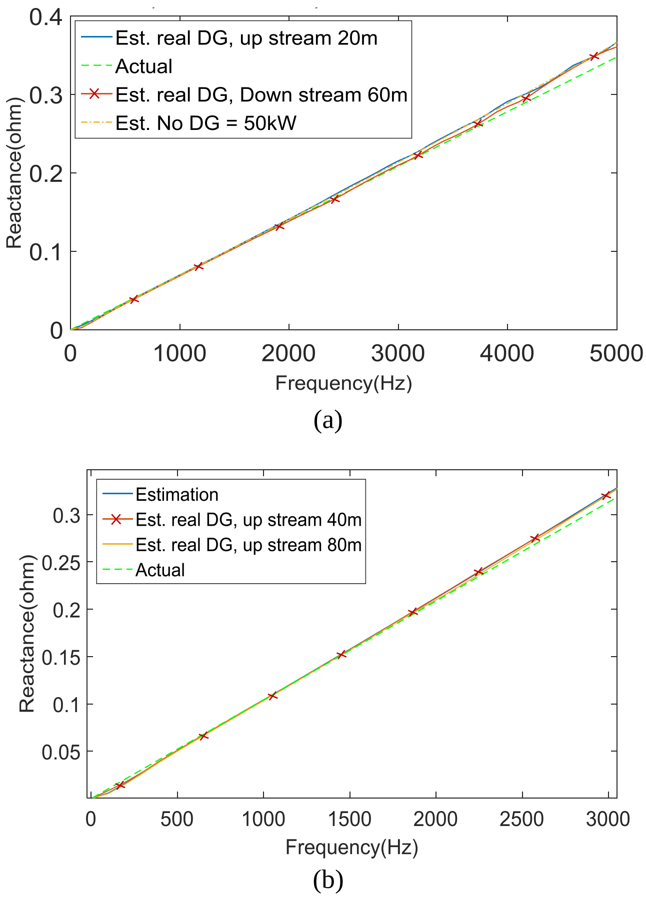


Fig. 13 Influence of DG location on the double-ended method (a) fault at 40m (b) fault at 60m

5 Conclusion

This paper investigated the influence of the inverter based grid connected DG on the higher harmonics impedance based fault location method utilizing the measurement from two ends. Three different scenarios were given to analyse the effect of the DG addition to the system on the double-ended method. The presented result showed that the DG penetration will have a small adverse effect on the fault location technique. However, the calculated percentage error showed that the maximum increases was 2% and the total error increased to 3.5% when the DG supplied 50% of the required power by the load. If the supplied power reduced to 30 kW or 15 kW, the maximum error could be reduced by 0.7%. The last scenario was to study the DG location influence on the accuracy of the fault location scheme. The analysis showed that the DG location upstream or downstream has a very small impact on the accuracy which can be considered neglected. Finally, this study shows that the accuracy of impedance based fault location method that uses the non-fundamental component of the fault transient will not be highly affected when an inverter based DG with power up to half the demand is added to the line. Currently, the experimental work is going to undertake in order to validate the simulation results.

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