Influence of DGs on the Single-Ended Impedance Based Fault Location Technique

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Abstract— **The penetration of Distributed Generation (DG) into electricity distribution systems or the integrated power system such as ship or aircraft power systems present a challenge to fault location techniques. This paper investigates the influence of inverter based DG on a single-ended fault location scheme which uses impedance measurement made from the high frequency content of fault transient. The additional non-fundamental frequency current components contributed from the DG will influence the accuracy of this type of impedance based fault location technique. A single-ended impedance based fault location technique that utilizes the high frequency content (up to 3 kHz) is studied. The study shows that the single-ended method is still able to locate faults with maximum error of 4% compared to the case without DG (which showed a percentage error up to 1%). The study also showed that the DG location has a small influence on the accuracy of the scheme.**

Keywords— DG, single-ended, Fault location, Microgrid.

I. Introduction

Technical factors as well as environmental, economic and political factors have promoted the increasing use of DGs to the distribution system and the development of MicroGrids (MG) [1]. Economically, DGs can lead to reduced losses by reducing the magnitude of the centrally transmitted or distributed power. The reliability and survivability of the distribution system could be enhanced during main system faults because the DGs will supply the local loads with their demanded power [2], but this may place challenges on protection systems.

The traditional fault location methods used for low voltage distribution systems assume that the power flow is unidirectional. However, this characteristic could be changed with the addition of the DGs to the system and the current flow becomes bidirectional. This characteristic as well as the contribution of the DG to the fault current represents a challenge to traditional fault location techniques. The influence depends on the DG supplied power. Traditional location methods would disconnect the DGs during the fault condition to accomplish correct operation [3]. Hence, there is a requirement for a technique that considers the operation of the DGs especially for Integrated Power System (IPS) and MG and how they behave during the fault.

The investigation of single-ended fault location techniques in distribution systems has been conducted for decades. The technique based on measuring the pre-fault and post fault data was developed by Takagi [4, 5]. Then Das, Florez, Salim, and Nouri have modified and extended the impedance based methods. The real and imaginary separation are used to eliminate the unknown fault resistance [6]. Another issue in these method was the unknown load current. The load current is estimated using pre-fault measurement [7, 8] or is neglected in some cases [9, 10]. Although most of the suggested methods are straight forward and more attractive for industry applications, these methods do not considered the influence of DG.

Recently, research has been conducted to investigate the effect of DGs on traditional fault location techniques in distributing systems or MGs. The researcher in [11] investigated the effect of the DG on the single-ended impedance based method. The upstream and downstream faults from the DG studied. The accuracy of the locating algorithm is affected when faults occurs downstream from the DGs. The percent error depends on a number of factors such as the magnitude of the DG and the distance of the fault to the DG [11]. Moreover, in [12] the effect of the inverter-based DG is studied. It is shown that neglecting the DG current contribution or using an inaccurate electrical model will significantly influence the accuracy of the fault locator at fundamental frequency. In [13], the influence of synchronous DG is studied. It is proposed to modify the algorithm to include the effect of the DG at fundamental frequency [13]. A new fault locating technique was proposed based on voltage-sag and current measurement at the substation to estimate the fault distance with the presence of the DG [14]. The study of the synchronous generator DG on the traditional impedance based method is presented in [15]. They investigated the effect of DG using a 3 phase fault and they concluded there was a big influence from the DG. Another study investigated a fault location algorithm with the effect of the DG using positive sequence impedance at fundamental frequency [16].

This paper [17] studied the impact of synchronous DG on impedance based methods. More recent research [18] studied the effect of a double-fed induction generator (DFIG) on the single ended impedance-base fault location method at non-fundamental frequencies. A measurement from the DG was incorporated in the proposed scheme.

Most of the works mentioned investigated the influence of the DGs on traditional single-ended impedance based fault location methods at fundamental frequency. They showed that the DG had potential adverse influence on the single-ended algorithms due to neglecting current supplied by the DG. A few studies suggested new methods to incorporate the influence of tye DG; however, synchronous

DG was mostly studied in these studies. In this work, the investigation of the influence of the invertor based DGs on a single-ended impedance based fault location technique at non-fundamental frequencies will be considered due to the lack of research in this field.

II. SINGLE-ENDED TECHNIQUE

The single-ended impedance based fault location method based on higher frequency content with and without DG effect will be introduced in this section.

A. *Single-Ended Technique without DG*

A single-phase circuit with a short circuit fault on the distribution line, as shown in Fig. 1, will be used to introduce and demonstrate the basis of the single-ended impedance based fault location in an IPS. The supply and the load impedances are represented by Z_s and Z_L respectively. The impedance from the measuring end to the fault position is Z_x and the remaining impedance Z_{l-x} represents the impedance from the fault position to the receiving end of the line [19, 20].

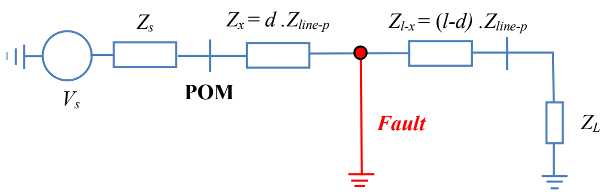


Fig. 1. Single phase circuit with a short circuit fault

The created voltage transient due to the fault is considered as a voltage source that creates a current transient. These transients contain information over a wide frequency range. The supply source is short circuited at the non-fundamental frequencies as shown in the equivalent circuit of Fig. 2, while the fault is represented as a transient source which creates an equal and opposite voltage to the instantaneous pre-fault voltage (V_{pre-f}) at the fault location [19, 20].

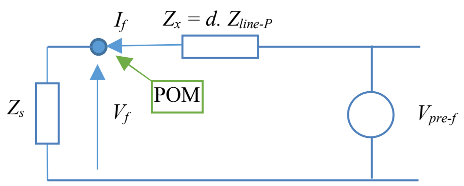


Fig. 2. System at non-fundamental frequency during fault situation

The voltage drop from the Point of Measurement (POM) to the fault location, as in Fig. 2, is calculated using Kirchhoff's voltage law as in (1) [20]:

$$V_f - I_f{*}Z_x - V_{pre-f} = 0 \tag{1}$$

Where V_f and I_f are the measured voltage and current at POM, while V_{pre-f} is the assumed voltage at the fault location. Equation (1) is rearranged in order to estimate the impedance between POM and the fault location, Z_x, yields (2):

$$Z_x = (V_f / I_f) - (V_{pre-f} / I_f) \tag{2}$$

The fault distance is estimated by dividing the estimated Z_x by the line's per meter impedance, as given by (3). The imaginary part of the estimated impedance is utilized because the fault resistance has no effect on the estimated reactance as well as at higher frequencies the reactance dominates the overall impedance more than the resistance [20].

$$d = imag\ (Z_x / Z_{line-p}) \tag{3}$$

The V_{pre-f} in (2) is a created step voltage with value equal to the measured pre-fault voltage at the POM, assuming that the voltage drops between the POM and the fault location is negligible. Based on this assumption, an initial error in the fault distance estimation is presented. To estimate the correct $V_{pre-f,}$ the initial estimated distance form (3) is used to calculate new V_{pre-f} using (4) [20]:

$$V_{pre-f(new)} = V_{pre-f(POM)} - I_{pre-f}{*}d{*}Z_{line-p} \tag{4}$$

Therefore, an iterative method is applied using (3) and (4) to reduce the error presented due to the assumption made. Firstly, an initial fault distance is estimated using (3) and this estimated distance is used to calculate new V_{pre-f} at fault location using (4). Then, equation (3) is used to re-estimate the fault location and V_{pre-f} is updated using this new distance. This iteration stops when two successive fault location estimates converge to within an acceptable tolerance of each other, for example, $d_{n+1} - d_n < 0.5$m. . Further details and flow chart is presented in [19]. The fault could be located 2 cycles after the fault is detected.

B. *Single-Ended Method with DG*

The system of Fig.1 and Fig.2 are modified to include a DG source between the measuring end the fault location as shown in Fig. 3 at the the fundamental frequency while Fig. 4 is at non-fundamental frequencies. The derived estimating equation 2 is also updated to include the effect of the DG as following:

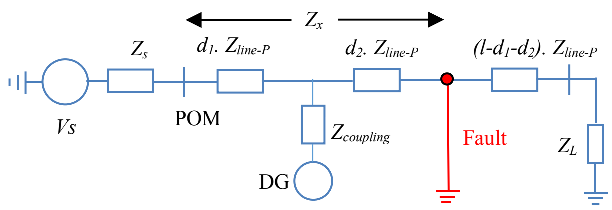


Fig. 3. Single phase circuit with DG

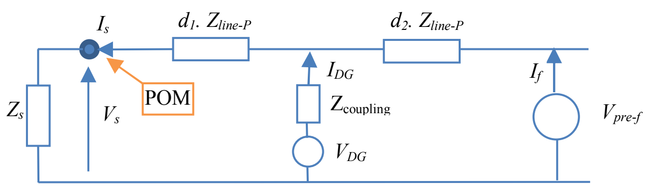


Fig. 4. System at non-fundamental frequency during fault with DG

$$V_s - I_s{*}d_1{*}Z_{line-p} + I_f{*}d_2{*}Z_{line-p} = V_{pre-p} \tag{5}$$

But, $I_f = I_s - I_{DG}$, $Z_s = V_s / I_s$ and $Z_x = (d_1 + d_2)^* Z_{line\text{-}p}$

Then rearranging (5) gives

$$Z_x = [(V_{pre\text{-}f} - V_s)/ I_f] + (I_{DG} / I_f) * d_2 * Z_{Line\text{-}p} \quad (6)$$

Whereas:

$$(I_{DG} / I_f) = (Z_s + d_1 . Z_{Line\text{-}p}) / Z_{coupling} \quad (7)$$

Where, Vs and Is are the voltage and current measured at the source end (POM), I_{DG} is the supplied DG current, d_1 is the impedance between the POM and the DG coupling position, while d_2 is the impedance between the coupling position and the fault. Zcoupling is the coupling impedance between the DG and the grid. Comparing (2) and (6) shows that the amount of the DG influence depends on the ratio of DG current to measuring end current at the higher frequencies content.

III. DG Modelling

The DG used and simulated in this study is a PWM converter. Fig. 5 presents the basic structure of the grid forming power converter [21]. A PI current controller in direct and quadratic reference frame is utilized to control the output power of the DG as well as to limit the output to the rated power during the fault time. Table I shows the utilized parameter for this model. The operation of the DG is tested during normal and abnormal conditions. In [22], more details on the operation and the test of the simulated DG is presented. It has been shown that the DG works as required during normal and abnormal conditions.

Table I. DG's parameter

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

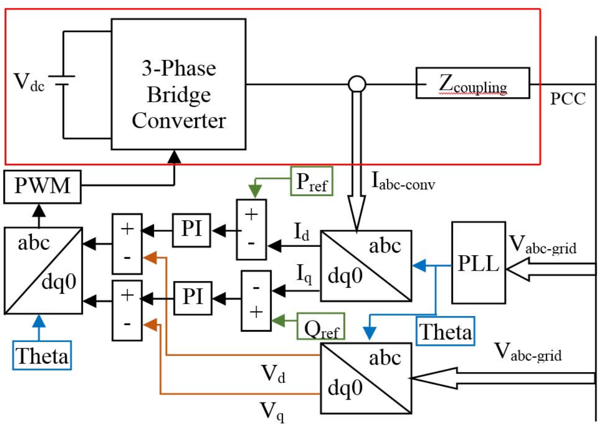


Fig. 5. Basic structure of grid connected power convertor

IV. Simulation and Results

An integrated power circuit consists of main ideal source with source impedance, a 50 metre distribution line connected to a pure resistive load is simulated as shown in Fig. 6 while the value of the circuit elements is presented in Table II. The distribution line is divided to 5 equal sections. The required data was measured from the POM1 (S-End) terminal of the distribution line of the system shown in Fig. 6. Moreover, the inverter based DG is shown in the orange block and it is connected to the distribution line.

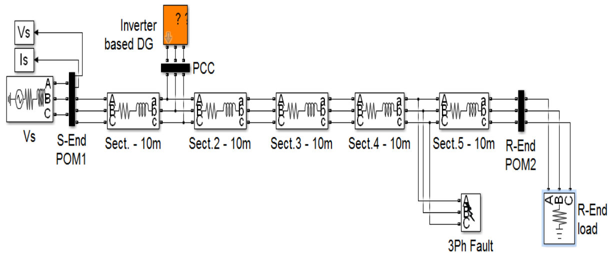


Fig. 6. The simulated circuit.

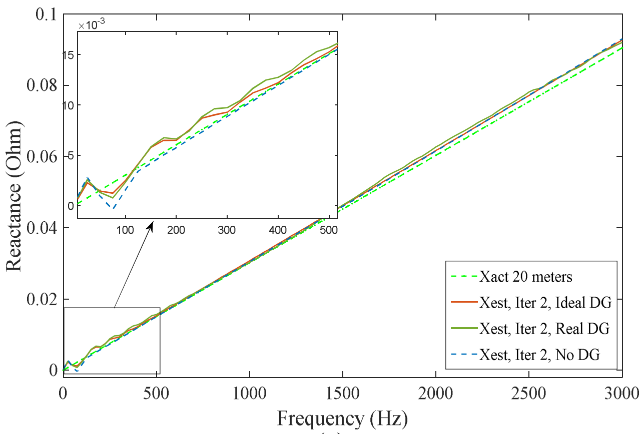
Table II. Circuit parameters

Parameter	value
Source voltage (ph-ph)	440 (V)
Source impedance	0.011 + 0.0096i
Load	100 kW
Per meter line resistance	30 µΩ
Per meter line reactance	0.24 µH
DG power	50kW
Sampling Frequency	100 kHz

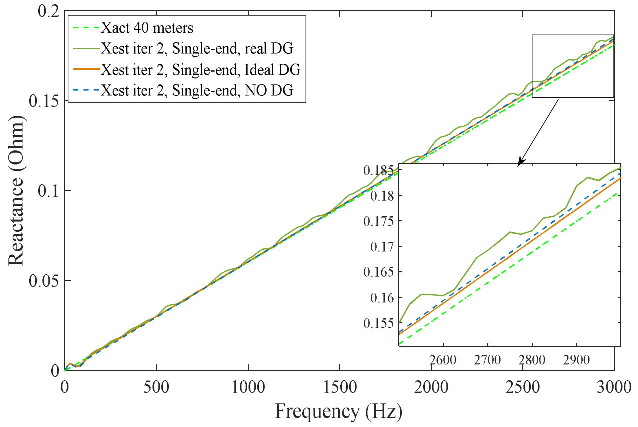
The influence of the DG on the higher harmonic single-ended impedance based fault location technique is investigated using different fault types with different DG scenarios as following:

The first scenario was to locate a 50 kW DG 10 meters away from the measuring end (POM1) as shown in Fig. 6. A short circuit Single Line-to-Ground (SLG) is applied separately to three locations downstream from the DG. The first fault test is at 20 m, then at 40 m and the final fault test at the R-End (POM2) which is 50 m away as shown in Fig. 7. The estimated reactance (Xest.) in Fig. 7a, 7b, 7c with the presence of realistic DG (dark green solid lines) is very close to actual values (Xact. in light green dashed Lines) as well as to the estimated reactance without DG penetration (blue dashed lines).

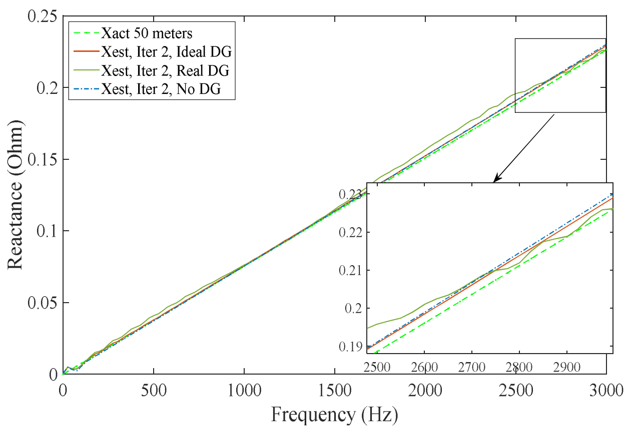
These simulations confirm the minimal influence of DG penetration for the proposed fault location method. The small influence is because of the injected non-fundamental current components that have been neglected in (2) used in this work. Note that the abbreviation (Iter. 2) in the legend means only 2 iterations is required for the method to converge to the final presented value. This consequently results in very fast processing time which leads to estimate the fault location on 3 cycles after the fault is been detected.



(a)



(b)



(c)

Fig. 7. Estimated Reactance using the single-ended method with the effect of the DG; (a) fault at 20m (b) fault at 40m and (c) fault at the received end

Moreover, the effect of the realistic DG (PWM inverter) is compared to the effect of ideal DG (Controlled Voltage Source in Red solid line) as shown in Fig. 7. Table III presents the estimated distance for all the tested fault positions as well as the calculation of the percentage error. This Table also shows comparison of the cases with DG to the case without DG penetration. The estimated reactance is divided by the line's reactance per meter at each higher frequency to find the distance to the fault. Consequently, the distance is calculated using the average distance through the total 3 kHz frequency range considered in this study. Then the percentage error is calculated using (8).

$$\text{Percentage error} = ((\text{estimated distance} - \text{actual distance}) / \text{Line length}) \times 100\% \quad (8)$$

TABLE III. ESTIMATED REACTANCE AND PERCENTAGE ERROR

Fault dist.	**Average estimated distance**			**Percentage Error**		
	DG = 00	**Ideal DG**	**Real DG**	**DG = 0kW**	**Ideal DG**	**Real DG**
00	0.35	0.53	0.47	0.71	1.08	0.95
10	10.33	10.55	10.52	0.67	1.1	1.04
20	20.31	20.78	20.92	0.63	1.6	1.85
40	40.26	41.00	41.7	0.55	2.1	3.44
50	50.25	50.9	52.4	0.55	2.2	4.2

The result presented in Table III validate that the proposed single-ended technique at higher frequencies can work with high accuracy even when the DG has been added to the system and not compensated for in the protection design process. It is noticeable that the maximum increases in percentage error is only 3.5% when a DG with supplied power of 50 kW is added to the system 10m from the S-End. This minimum influence is explained by the fact that the DG current has small higher frequency components that are neglected using (2). A comparison of the frequency contents of the realistic DG at 10 m with ideal one is shown in Fig. 8. It is clear that the neglected non-fundamental frequencies injected by the DG is the source of the small increased error.

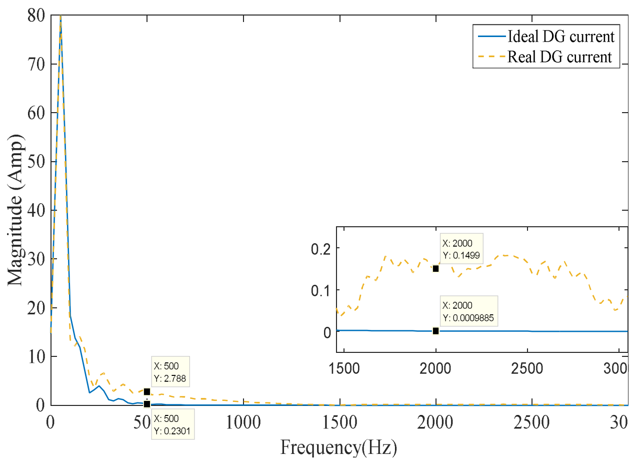


Fig. 8. Frequency content of the utilized DG during fault transient

The second scenario was to study the effect of the DG location upstream (between the sending end and the fault location) and downstream (between the fault and the receiving end). Hence, using one fault position, the DG once placed upstream and then downstream. Thus, a fault is initiated 20 m away from POM1 and the DG once place at 10 m from POM1 and then moved to 40m from POM1.

Fig. 9 shows the estimated reactance when the DG location is changed. The difference between the two cases was very small less than 0.5% which can be neglected. The reason is that the DG has very small non-fundamental current components at higher frequencies that have been shown in Fig. 8 which caused a small influence on the estimated reactance at these frequencies.

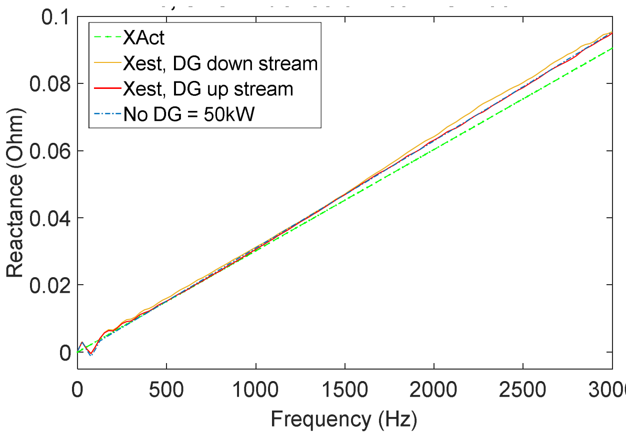


Fig. 9. Influence of DG location on the single-ended method

V. CONCLUSION

This paper investigated the influence of the inverter based grid connected DG on the single-ended impedance based fault location technique at non-fundamental frequencies. Two scenarios were suggested to analyse the effect of the DG on the fault location technique. The presented result showed that the DG penetration will have small adverse effect on the studied technique; however, the calculated percentage error showed that the maximum increases in the error was 3.5% and the total error increased to 4.2%. This result based on DG suppling 50% of the required power by the load. The second scenario was to study the effect of the DG location 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 negligible. Finally, this study shows that the accuracy of impedance based fault location method that uses the higher frequency component of the fault transient will not be highly affected when a DG with power up to half the demand is added to the transmission line.

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