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Optimizing voltage references in a 3-leg power VSC under single-phase-to-ground faults

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Abstract. Distribution grid deals with several challenges such as the integration of the electrical vehicle, connection of renewable energy resources, management of storage systems, etc. These new factors can often produce some non-desirable effects in the grid such as electrical faults, which can damage the electricity supply quality. In order to improve the supply quality during electrical faults, power converters with specific control algorithms can be connected that modify the voltage on the loads connected to the grid during the duration of the fault. An optimal control can be ensured if a proper estimation of the voltage in the load is carried on. This paper calculates the voltage drop between the output of the power converter and the fault point so as to optimize voltage references in the power converter during single-phase-to-ground faults in islanded mode. Simulation results guarantee the successful performance of the proposal.

Key words. Smart grids, power converters, electrical faults, islanded mode, distributed generation.

1. Introduction

In the recent years, smart grids and renewable power generation have been widely developed towards cleaner and more sustainable electrical power systems. However, during emergency or abnormal situations electrical service is not guaranteed. These situations can cause single-phase-to-ground faults, the most common faults in distribution lines [1], which can isolate some parts of the grid from the mains. In this context, a grid that can run both connected and isolated from the main grid is called Microgrid.

Microgrids are local distribution systems including a set of microsources such as fuel cells, solar PV plants, wind turbines or storage systems (Fig. 1). Operation modes in AC microgrids can be classified into Grid-Following (GFL), Grid-Forming (GFM) and Grid-Supporting (GS) [2]. Neutral Point Clamped (NPC) 3-leg inverters are normally used in high power applications, which can be connected in GFL and GFM mode [3].

When single-phase-to-ground faults occur, the electrical system works under unbalanced conditions. Consequently, symmetrical components are involved in the fault analysis.

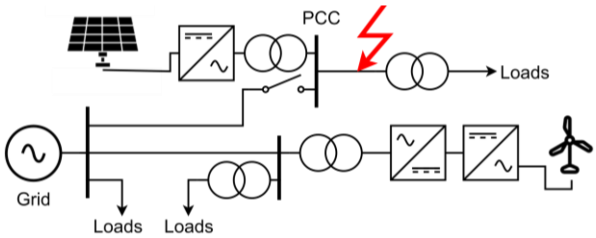

Fig. 1: Microgrid scheme.

Additionally, Petersen coils in resonant grounded systems [4] or flexible arc suppression devices [5] have traditionally mitigated single-phase-to-ground faults' effects. Recently, so as to improve electricity supply during those situations, the emerging power electronics technology in Distributed Generation (DG) systems makes possible to control converters independently for each phase on a three-phase system [6], [7]. This last option offers several advantages among the previous systems such as flexibility and the possibility of implementing additional functionalities.

In this sense, by properly regulating the three phases independently from each other, it is possible to maintain phase-to-phase voltages balanced under unbalanced situations, as demonstrated with YNyn transformers [8].

When the DG system is connected to the main grid and single-phase-to-ground faults occur, fault currents depend on the short-circuit power of the grid. However, in GFM the grid is disconnected, and grid's short-circuit power does not affect current values under fault conditions.

For that last case and considering the previously mentioned independent control for each phase, it is necessary to calculate non-affected voltages' phase-to-neutral values needed in the control of the power converter. These references are based on the balanced condition's phase-to-phase voltages and the unbalanced condition's phase-to-neutral voltages in the fault point and not in the output of the power converter. When this calculation is performed, the control on the power converter can be optimized to improve the electrical supply to the load.

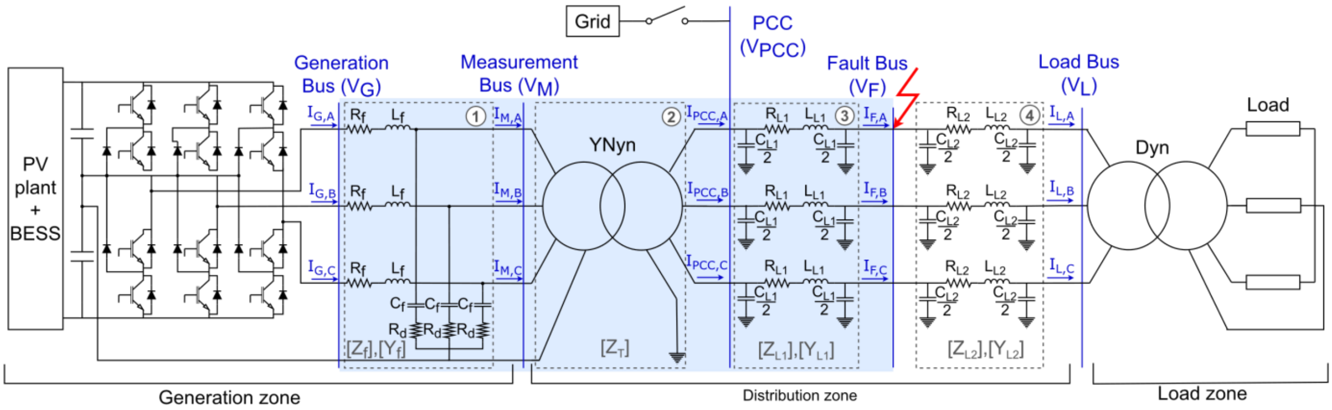

Fig. 2: Considered electrical scheme.

In this proposal, voltage drops between the output of the power converter and the fault point are defined in order to improve converter's control reference consigns. The main objective is to develop and validate through simulation the mentioned calculation process obtaining several advantages:

- Control signal improvement for power converters.
- Voltage drop quantification of electrical elements between the power converter and fault point.
- Power supply guarantee even under fault conditions.

Applying the procedure presented in this article, a solution that guarantee supply continuity in GFM electrical systems, even under fault conditions, are substantially improved regarding the power quality on the loads. Disturbances' negative effects on the load connected to the system have been considerably mitigated by means of the proposed methodology as the simulation results state.

2. Theoretical Background

When the electric scheme of a GFM is analysed usually 3 parts are considered (Fig. 2):

- **Generation zone:** a DG generation plant coupled with a VSC converter, such as a PV plant with a Battery Energy Storage System (BESS).
- **Distribution zone:** transmission line between generation and consumption, linked by step-up and step-down transformers to reduce losses.
- **Load zone:** step-down transformer reduces the voltage level to supply loads at LV. Thanks to the Dyn connection, the power quality can be improved in the load during single-phase-to-ground faults.

In order to develop the theoretical formulation of voltage drops throughout the electrical system, power, voltage and impedance bases need to be defined for each zone. Furthermore, even if each zone has its own base, a generic power base must be defined so as to allow the unification of the calculation process.

The electrical models for each grid element involved in the voltage drop calculation are those between the fault location and the generation system (Fig. 2). Hence, based on their characteristics, the theoretical basis to calculate the voltage drop through each element is specified below.

A. Electric Line

In distribution systems, long power lines up to 100 km are represented with PI models. A PI model consists of a series impedance that involves the resistance and inductance of the line, and two shunt susceptances that take into consideration the capacitive effect of the power line (Fig. 2, ③ and ④, and Eq. (1) and (2)).

$$\begin{bmatrix}\underline{I}_F\\ \underline{I}_L\end{bmatrix}=\begin{bmatrix}\frac{1}{[Z_{L2}]}+\frac{[Y_{L2}]}{2} & -\frac{1}{[Z_{L2}]}\\ \frac{1}{[Z_{L2}]} & \frac{[Y_{L2}]}{2}-\frac{1}{[Z_{L2}]}\end{bmatrix}\cdot\begin{bmatrix}\underline{V}_F\\ \underline{V}_L\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}\underline{I}_{PCC}\\ \underline{I}_F\end{bmatrix}=\begin{bmatrix}\frac{1}{[Z_{L1}]}+\frac{[Y_{L1}]}{2} & -\frac{1}{[Z_{L1}]}\\ \frac{1}{[Z_{L1}]} & \frac{[Y_{L1}]}{2}-\frac{1}{[Z_{L1}]}\end{bmatrix}\cdot\begin{bmatrix}\underline{V}_{PCC}\\ \underline{V}_F\end{bmatrix} \quad (2)$$

Impedance matrix is defined from total impedances and admittances determined per unit in the symmetrical components reference frame. Afterwards, they need to be referenced into the system's base and transferred into three-phase (abc) reference frame, by defining self and mutual impedances and admittances (Eq. (3) and (4)).

$$Z_m=\frac{Z_0-Z_1}{3};Z_s=\frac{2Z_1+Z_0}{3}\rightarrow[Z_i]=\begin{bmatrix}Z_{s,i} & Z_{m,i} & Z_{m,i}\\ Z_{m,i} & Z_{s,i} & Z_{m,i}\\ Z_{m,i} & Z_{m,i} & Z_{s,i}\end{bmatrix} \quad (3)$$

$$Y_m=\frac{Y_0-Y_1}{3}\ ;\ Y_s=\frac{2Y_1+Y_0}{3}\ \rightarrow\ [Y_i]=\begin{bmatrix}Y_{s,i} & Y_{m,i} & Y_{m,i}\\ Y_{m,i} & Y_{s,i} & Y_{m,i}\\ Y_{m,i} & Y_{m,i} & Y_{s,i}\end{bmatrix} \quad (4)$$

$where\ \ i = Line\ 1\ (L1),\ Line\ 2\ (L2),\ Transformer\ (T)\ and\ filter\ (f).$

B. Transformer

When analysing voltage drops in power transformers three-phase balanced load is considered, and this statement is accomplished in the current study. Transformers are represented as a series impedance (Eq. (5) and (6)), neglecting magnetization current. Once direct, inverse and homopolar impedances are defined per unit, they must be transferred into three-phase (abc) reference frame defining self and mutual impedances (Eq. (3) and (4)).

$$\underline{I}_M=\underline{I}_{PCC} \quad (5)$$

$$\underline{V}_M=[Z_T]\cdot\underline{I}_{PCC}+\underline{V}_{PCC} \quad (6)$$

C. LC Filter

An LC filter can be represented as a particularization of a PI line, considering that the left shunt susceptance is null. Therefore, the model for the LC filter consists of a series impedance that involves the wire resistance and the filter inductance and a single shunt susceptance that takes into consideration the filter capacitance (Fig. 2, ① and Eq. (7)).

$$\begin{bmatrix} \underline{I}_G \\ \underline{I}_M \end{bmatrix} = \begin{bmatrix} \frac{1}{[Z_f]} & -\frac{1}{[Z_f]} \\ \frac{1}{[Z_f]} & -[Y_f] - \frac{1}{[Z_f]} \end{bmatrix} \cdot \begin{bmatrix} \underline{V}_G \\ \underline{V}_M \end{bmatrix} \tag{7}$$

Once the equivalent PI particularized model's impedance and admittance are defined, they need to be expressed in per unit and referred into the system's base. Furthermore, parameters must be transferred from symmetrical components reference frame into three-phase (abc) reference frame. For that, self and mutual impedances and admittances must be defined (Eq. (3) and (4)).

3. Proposed System

The proposed system to be analysed (Fig. 2) consists of a DG system, connected in series to a LC filter and a YNyn connection step-up transformer that feeds a distribution line. The electric line can be supplied either by the DG system or by the main grid, and feeds at the same time a step-down transformer where the load is connected.

In order to calculate the voltage drop in each element of the system, direct, inverse and homopolar impedances and admittances are defined from their characteristic parameters. Those parameters vary depending on the element itself and on the known equipment data.

A. Electric Line Parameters

In the line characterization process, conductances are neglected since its contribution to shunt admittance is not significant compared to other parameters. Furthermore, the disposition of the conductors on the electric tower determines the calculation of the inductance and capacitance per distance unit values of the line (Fig. 2, ③ and ④). The calculation of those parameters is developed based on Carson equations [9], especially since calculating homopolar values is dependent on several complex variables [10].

In order to determine the impedance and the admittance of the power line at both parts of the fault, it is essential to define the fault location in the line. For that, several methods can be applied. Conventional fault location methods are based on travelling wave methods [11] impedance calculation methods [12], or voltage and current synchronisation measurement [13]. Furthermore, recent studies propose signal injection techniques [14], and fault location based on artificial intelligence techniques [15]. In this work the location of the fault is a given parameter.

B. Transformer's Parameters

To characterize power transformers equivalent direct, inverse and homopolar impedance need to be determined from nominal values such as rated apparent power (S_N), rated voltage (U_N), short-circuit impedance (Z_1) or short-circuit voltage (u_{cc}) and load losses (P_{cuN}). If short-circuit impedance and resistive short-circuit impedance (R_1) are not directly known, they can be calculated from other data (Eq. (8) - (11)).

$$Z_1 = \frac{u_{cc} \cdot U_N^2}{S_N \cdot 100} \tag{8}$$

$$R_1 = \frac{u_{rc} \cdot U_N^2}{S_N \cdot 100} = \frac{P_{cuN}}{3 \cdot I_N^2} \tag{9}$$

$$X_1 = \sqrt{Z_1^2 - R_1^2} \tag{10}$$

$$\underline{Z}_1 = R_1 + jX_1 \tag{11}$$

Transformers are passive elements which have same direct and inverse impedance values. Despite the possibility of calculating direct and inverse impedance values, determining homopolar value is not trivial. When homopolar values are not provided by the transformer's manufacturer, it can be determined following IEC 60076 [16] standard depending on the transformer's connection type and constructive and operational characteristics.

The transformer that links the NPC converter with the distribution is YNyn type since maintaining an unbalanced regime in the line implies transferring unbalanced phase-to-neutral voltages from the generator side of the transformer into the other side. For YNyn connection type homopolar impedance value is standardized between 80-100 % of the direct impedance [16].

C. Filter Parameters

The design of the filter depends on the quality of the output signal from the VSC converter that needs to be optimized. Despite grid connected converters usually employ LCL filters [17], when followed by a transformer a suitable filter type is LC [18] since the transformer performs as the second inductance of the LCL filter. Therefore, an LC filter is going to be considered, whose parameters will be defined after developing the VSC converter's output signal analysis for each practical case.

D. Proposed System's Voltages and Currents Resolution

Usually, solving fault problems implies neglecting prefault parameters and only taking into consideration fault's effect, since its values are significantly greater. Nonetheless, in this case the goal of the power converter is to reduce the voltage in the fault point so as to supress the electrical fault. Thus, the value of fault current is minimized, and the problem is solved considering prefault situation.

The problem to be solved consists of a system of linear equations formed by all the matrix equations corresponding to the elements in the electrical scheme (Eq. (1) and (2), and Eq. (5) - (7)).

This system has 8 linear equations that relate 10 parameters for each phase. Therefore, to achieve a unique solution, 2 input parameters for each phase need to be known, i.e. Load Bus voltage and current in the case of prefault current determination.

4. Simulation Results

After having completed the theoretical development for the calculation process, the effectiveness of the proposed solution has been demonstrated through simulation.

To validate the theoretical approach, a simulation model has been designed in Matlab-Simulink based on the proposed electrical scheme (Fig. 2). Moreover, the NPC converter has been simplified into single-phase independent voltage sources since the system operates in GFM [19].

The total voltage drop calculation under single-phase-to-ground fault to improve the converter reference has been addressed by means of several simulations.

A. Input Data

The analysis is performed in per units, and consequently bases for each zone are established (Table 1).

Table 1: Base parameters for each zone.

Zone	S_{Base_i}	U_{Base_i}	I_{Base_i}	Z_{Base_i}
Generation	2.5 MVA	700 V	2.061 kA	0.196 Ω
Distribution	2.5 MVA	15 kV	96.225 A	90 Ω
Load	2.5 MVA	400 V	3.608 kA	0.064 Ω

According to i-DE's distribution overhead line project samples [20], 47-AL1/8-ST1A (LA 56) wires have been chosen as they can conduct up to 202 A (Table 2), and the disposition of the tower is considered a simple three-phase circuit (Fig. 3).

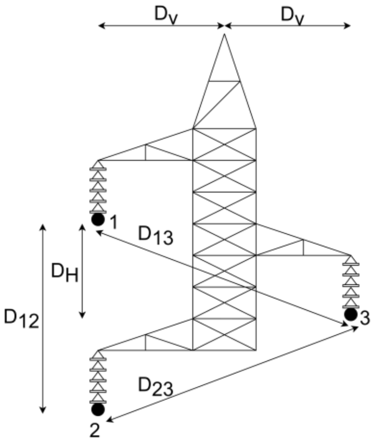

Fig. 3: Electric tower disposition.

For the transformer, as short-circuit voltage (u_{cc}) is standardized in IEC 60076 [16] and resistive short-circuit voltage (u_{rcc}) in ITC-RAT-07, values corresponding to 2.5 MVA and 20 kV have been selected (Table 2). Finally, regarding the LC filter, parameter values have been chosen following filter design procedures mentioned in section 3.C (Table 2).

Table 2: Input data.

	PARAMETER	**VALUE**
Load characteristics	U_L	400 V
	S_L	2.5 MW
Fault characteristics	Z_{fault}	50 Ω
Line characteristics	D_v	1.5 m
	D_h	1.5 m
	D_{12}	3 m
	D_{23}	3.354 m
	D_{31}	3.354 m
	L_{total}	20 km
	r_{L1}	0.6619 Ω/km
	r_{L2}	0.6619 Ω/km
	r_{L0}	0.9410 Ω/km
	l_{L1}	1.2656 mH/km
	l_{L2}	1.2656 mH/km
	l_{L0}	4.4990 mH/km
	c_{L1}	8.940 nF/km
	c_{L2}	8.940 nF/km
	c_{L0}	4.860 nF/km
Transformer characteristics	u_{cc}	6.25 %
	P_{CuN}	22 kW
	R_1	0.7920 Ω
	R_0	0.6336 Ω
	L_1	177 mH
	L_0	142 mH
Filter characteristics	L_f	3.53 mH
	R_f	36.25 μΩ
	C_f	20 μF
	R_d	100 mΩ

B. Influence of the Voltage Drop Consideration and Power Quality on the Load

In this first simulation case, the line length is constant (20 km), and the fault happens in the middle of the line (10 km). Voltage in the Fault Bus and power quality on the load, by means of Voltage Unbalance Factor (VUF, Eq. (12)) [21] are measured and analysed (Fig. 4 and Fig. 5).

$$VUF(\%) = \frac{V_2}{V_1} \cdot 100 = \frac{|\frac{1}{3} \cdot (V_{AB} + a^2 V_{BC} + a\, V_{CA})|}{|\frac{1}{3} \cdot (V_{AB} + a\, V_{BC} + a^2 V_{CA})|} \cdot 100 \quad (12)$$

When the generation reference only considers the voltage drop until the Measurement Bus (MB), fault conditions are imposed in the MB (Fig. 4). In this case, when a fault happens, the voltage of the affected phase in the Fault Bus is not completely annulated, and the voltage supplied to the load is smaller than the rated voltage. Moreover, the VUF parameter is 1.42 %.

However, if the generation reference is calculated following the proposed system and theoretical development, phase-to-phase voltages in healthy phases of the Load Bus can be maintained (Fig. 5) improving the electricity supply in the load.

Moreover, when fault happens, the voltage of the affected phase in the Fault Bus is almost completely annulated, and the voltage supplied to the load remains at the rated voltage. Furthermore, the VUF parameter is 0.001 %.

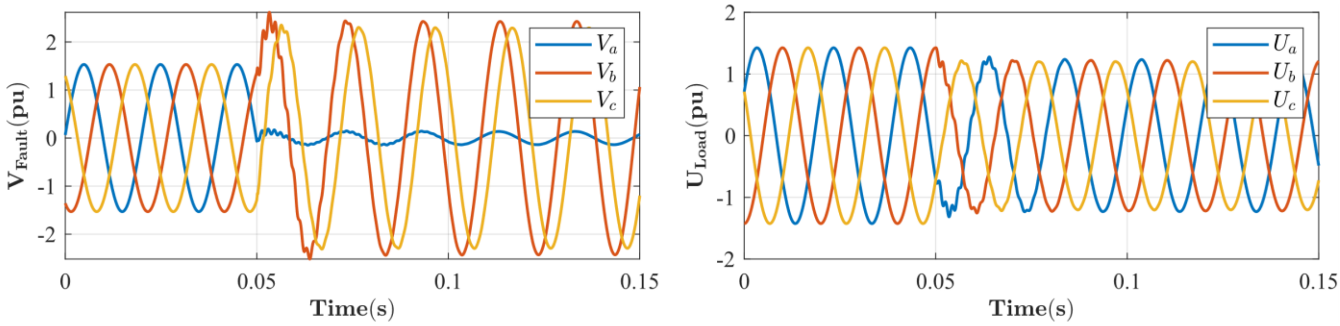

Fig. 4: Phase-to-neutral fault voltages and phase-to-phase load voltages when fault conditions imposed in the MB at t=0.05 s.

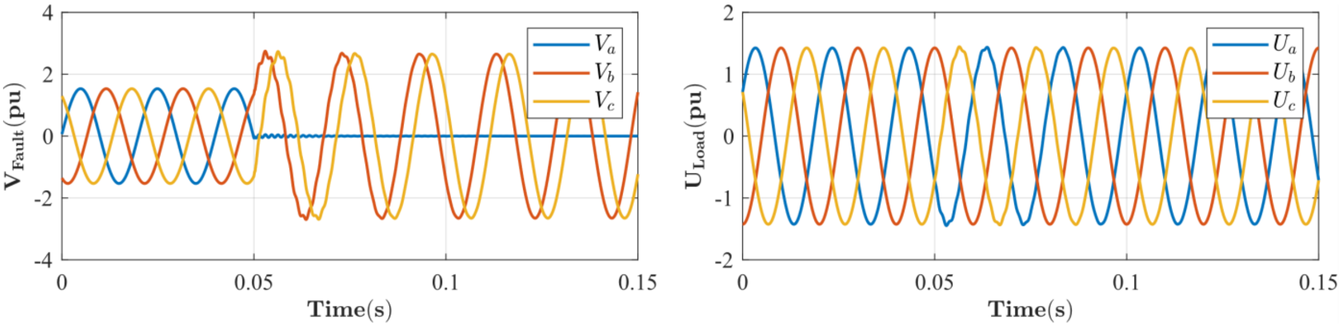

Fig. 5: Phase-to-neutral fault voltages and phase-to-phase load voltages when fault conditions imposed in the fault point at t=0.05 s.

C. Influence of the Fault Distance

Despite having considered a unique location of the fault in section 4B, in this simulation the effect of the fault location variation is also studied (Fig. 6). The total length of the line continues being 20 km and voltage drop samples are measured every 100 m of the length. It should be pointed out that in order to show the voltage drop in each equipment and the total voltage drop between the MB and the Fault Bus at the same time, the corresponding data is plotted stacked (Fig. 6). The voltage drop in the transformer is almost constant, while power line's voltage drop is proportional to the distance from the fault point to the PCC (Fig. 2). In this particular case, until 9.7 km the voltage drop in the transformer is more significant than the drop in the power line (Fig. 6). However, when the fault distance is greater than 9.7 km the voltage drop in the line is increasingly relevant since it determines more than a 50% of the total drop that usually is neglected.

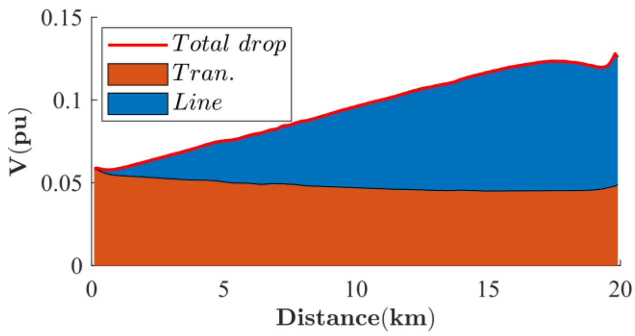

Fig. 6: Voltage drop depending on the fault distance.

D. Measurement Error Quantification

While the proposed methodology optimizes control consignments, it has several limitations due to potential errors in input parameters from measurement equipment.

The mentioned errors can be due to several sources. In this case, errors due to prefault current module measurement, prefault current angle measurement and fault distance estimation are quantified (Fig. 7). These measurement errors effects on the proposed methodology are compared to the reference case where fault conditions are imposed on the MB (Fig. 7, MB) neglecting measurement errors.

All analysed measurement errors have a linear effect on the fault voltage. It should be noted that the most significant effect is the one corresponding to the current angle measurement, even though the obtained results are more accurate than the reference case (Fig. 7).

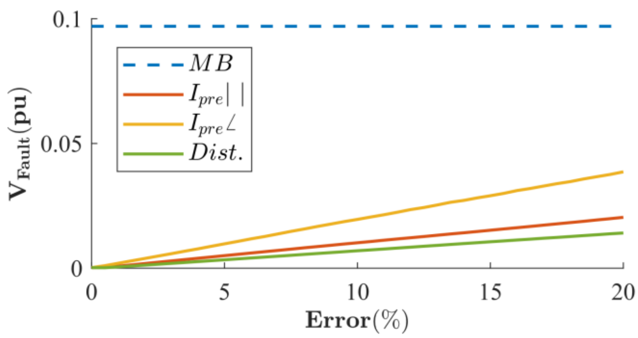

Fig. 7: Measurement errors' effect on fault voltage.

5. Conclusions

Single-phase-to-ground faults are non-desirable events that may happen in microgrids and can greatly deteriorate the power supply quality. Power converters can be used to control phase voltages in the microgrid, in order to maintain phase-to-phase voltages constant and improve the power supply during single-phase-to-ground faults.

Nevertheless, if the voltage drop generated by all the elements between the power converter and the fault point is not taken into account, the voltage on the fault point cannot be properly minimized.

This paper has proposed an accurate calculation of the total voltage drop between the power converter and the fault point, which improves and optimizes the power converter's control consign during single-phase-to-ground faults. Several simulation results have been provided in order to ensure the improvement of the power supply quality when the proposed system is considered. Moreover, a comparison among the possible errors in measurement equipment have also been analysed in this work. As future lines, the analysis of the transient regime as well as the consideration of an NPC power converter are proposed.

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