Monitoring of fault level in future grid scenarios with high penetration of power electronics-based renewable generation

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Abstract

This paper proposes a novel method for quantifying fault level in future grid scenarios with various penetrations of power electronics-connected renewable energy sources. As it is known, the information regarding the fault level is critically important for designing protection schemes, different control loops, understanding voltage profile in the grid, etc. This method is focused on the steady-state fault level calculation and it can be used to analyse future grid scenarios including uniform and non-uniform penetration of power electronics-based generation displacing all, or just specific conventional synchronous generation in the grid. Due to different possibilities for type, size, and location of power electronics-based RES generation in future grid, it is required to analyse the unprecedented scale of scenarios. The proposed method for FLC enables us to assess the system fault level for large numbers of FG scenarios without a need for detailed system modelling and/or time-domain simulations. The simulation results demonstrated the suitability of our proposed FLC method for various penetration levels of PE-based RESs in the 2-area and the IEEE 39-bus test systems. The obtained results are compared with time-domain simulations and the IEC 60909 standards performed in DIgSILENT PowerFactory, where the efficacy of the proposed methodology is demonstrated.

1 INTRODUCTION

Fault level is used as an indicator reflecting the system strength at a faulty point. System strength is referred to the system impedance seen at that point. Thus, higher fault level, i.e. the lower impedance, implies that the power system is stronger at that point and vice versa [1, 2]. In practice, the fault level plays a key role in system protection design and relays co-ordination [3]. In conventional power systems, the system fault level had relatively high values due to high fault level contribution from synchronous generators (SGs). Hence, the fault level could be simply distinguished from the normal load currents, as it has much higher values. However, with the increasing penetration of power electronics (PE)-based generation (also called non-synchronous generation) in power systems, the fault level may fall to lower levels [4–6]. This may result in challenges for protection system as protective devices might not be distinguish faulty from the normal state and consequently to be unable to respond according to strictly defined protection security, reliability, and selectivity requirements. In particular,
integration of renewable energy sources (RESs) mainly utilizing fully-rated converters (FRCs), has already changed the system fault level in some power systems. Moreover, fault level calculation/estimation has become more challenging due to the increased penetration of FRC-based generation [7]. The contribution of RES utilizing FRC (from here it is referred as PE-based generators) to the system fault level is dependent on the converter interfaces size, the controllers and the fault ride through requirements stated by the grid code [8–12]. In particular, PE-based generators mainly have low contribution to short circuit (SC) current due to the limited overloading capability of PE switches that should be protected immediately after exceeding certain predefined values [13, 14].

Generally, characteristics of SC currents originating from SGs, as well as their models used for the FLC are well known (see e.g. [15]). The response of SGs to a fault has been divided into three different time periods (i.e. sub-transient, transient and steady-state) and modelled through voltage source behind a series reactance associated with each of those periods. This methodology has been used in the IEEE and the IEC standards for FLC in the conventional power systems [16, 17]. Recent works studied the fault contribution of PE-based generation and their impacts on the fault level of power systems [18–32]. Those studies can be categorized into two main classes:

(i) Those focused on investigating different characteristics of SC currents supplied from PE-based generation considering different control and FRT strategies [18–28]. Although such studies provided a valuable insight, they were mostly restricted to analysing the faults at the point of common coupling (PCC) using computationally demanding time-domain simulations.

(ii) Those studied focused on the influences of PE-based generation on the fault level in the distribution systems and the resulting protection challenges [29–32]. In such studies, where the fault level in distribution system is the main concern, the adequacy of the traditional protection schemes has been investigated with some solutions for better coordination of relays settings.

Traditionally, the fault contribution from the PE-based generation has been neglected in steady-state fault calculations such as IEC 60909 standards. On the other hand, the recent version of this standards (i.e. IEC 60909:2016) [17], has considered the fault contribution from PE-based generation and suggested a current source model for modelling those FRC-based RESs in fault calculations. It is assumed that these sources contribute to a limited fault current according to the maximum overrating capability during the fault. An alternative but more accurate method for fault calculation is the complete method [7]. This method is based on the superposition to account for the operation conditions prior the fault to provide more accurate estimates for the fault current. The complete method intends to account for the fault contribution from PE-based sources by using equivalent current source model. This method is already implemented to consider the dynamic voltage support according to the up-to-date IEC 60909 steady-state fault calculations in DIGSILENT PowerFactory, where the accuracy of our methodology is validated.

Recently, some methods have been proposed for FLC with PE-based generation [34–36]. In [34], an IEC60909-based iterative method is proposed to consider the dynamic voltage support and the fault current from RESs. According to [35], an adaptive fault calculation algorithm has been suggested to consider the fault contribution of the inverter-based distributed generation using the Newton–Raphson iterative technique. However, both [34] and [35], have not provided adequate validation for the proposed methods on a system scale studies. The study in [36] has suggested an equivalent circuit to represent the transient and the steady-state fault contribution of VSC-based RESs. However, the suggested method requires measured short-circuit current waveforms to extract a full current expression and equivalent circuit. Moreover, a relative error of 10%, might be expected when using that method on a system scale studies. To the best of authors’ knowledge, no studies have attempted to formulate the correlation between the fault levels in power systems and the penetration level of PE-based generation. More specifically, we intended to calculate the fault level in transmission systems with high penetration of large scale PE-based generation resulting in decommissioning of SGs. Such FLC method might also provide an efficient guidance regarding margins for the maximum allowable penetration level of PE-based generation for system operators.

In this paper, we aim to propose a new FLC method that formulates the fault level in FG scenarios including high penetration of RES utilizing FRC (i.e. PE-based generators). Our FLC method represents the impact of PE-based generation in the FLC process as a function of their penetration level at the generation side. In the proposed method, the fault level is defined as a function of SC current contribution from compound generation units in the grid (i.e. both SGs and PE-based generation) in response to a three-phase symmetrical fault in the grid. Note that due to different possibilities for size and location of PE-based generation, we need to consider different FG scenarios with various levels of PE-based generation.

Our methodology enables simple and effective assessing of the system fault level in large numbers of FG scenarios with minimum computational burden. Simulation results include FLC using the proposed method for various penetration levels of PE-based generation in the 2-area and the IEEE 39-bus test systems. The results are compared with the time-domain simulations and the up-to-date IEC 60909 steady-state fault calculations performed in DIGSILENT PowerFactory, where the accuracy of our methodology is validated.

The rest of the paper is structured as follows: Section II introduces the concept of fault level and compares the SC current contribution from PE-based generation and SGs. Section III presents the new FLC method used to quantify the fault level.
at different locations in power systems as a function of PE-based generation penetration. Section 4 discusses the simulation results and validates the accuracy of the proposed FLC method, and finally, Section 5 concludes the paper.

2 | FAULT LEVEL IN POWER SYSTEMS

Fault level is a quantity describing the MVA associated with the maximum current that could possibly flow at a certain location when a SC fault occurs at that location in a power system [15, 17]. In (1), the fault level defines the value for the symmetrical conditions, i.e. the symmetrical three-phase bolted fault, based on the maximum SC currents associated with such faults.

$$MV A_{sc} = \sqrt{3}V_N k_{sc}$$ (1)

Note that the fault level depends on the location at which the fault occurs considering various system voltage levels. In conventional power systems, SGs are considered as the main source providing SC currents. In such systems, the highest value of the SC current occurs immediately at the instant of the fault initiation as illustrated in Figure 1(a). Then the SC current shows a decaying characteristic before reaching its steady-state value, [15, 17, 37].

On the other hand, PE-based generation (RES utilizing FRC technology), which is the main focus of this paper, shows a very different response, compared to SGs with possibly a very limited fault level contribution, depending on the grid-side converter [37, 38], as shown in Figure 1(b). The controlled SC current response of PE-based generation is dependent on several factors including voltage drop seen during the fault, overloading capability of the PE interface, the FRT capability and the grid code requirements (e.g. threshold voltage, and proportional factor) [19–21]. So far, different values are suggested for the fault level contribution of PE-based generation. For instance, the fault level contribution of such technology are suggested as 1.1 and 1.5 p.u. in [19] and [20], respectively. In [21], 2 p.u. is assumed for the initial symmetrical transient SC current of PE-based generator. In our study, where type-4 wind turbine (i.e. IEC 61400-27-1 generic model [39]) available in DlgsILENT PowerFactory 2017 [33] is used); it is assumed that the controller of the PE-based generators provide dynamic voltage support by injecting reactive current in response to a voltage drop (i.e. it includes a FRT). Further, the maximum SC current from PE-based generation is set to be equal to the converter MVA rating. Note that this value has no impacts in our methodology and different values can be used as needed, as detailed in Section 3.

3 | FAULT LEVEL CALCULATION INCLUDING THE IMPACT OF PE-BASED GENERATION

3.1 | Fault level contribution from a SG and its MVA representation

The fault contribution from any connected SG in the grid can be determined using an equivalent circuit shown in Figure 2 (a,b). Using the SG voltage source, $V_g$, behind the equivalent impedance observed from the faulty point, $Z_{eq}$, the SC current can be calculated as follows:

$$I_{sc}^g = \frac{V_g}{\sqrt{3} Z_{eq}}$$ (2)

The equivalent impedance, $Z_{eq}$, includes the internal sub-transient reactance of the SG, $X''$, in series with the total equivalent series impedance of the elements connecting the generator terminal to the faulty point, $Z_g$, as shown in Figure 2(b). The
fault level associated with SG can be calculated by substituting Equation (2) in Equation (1), as given in Equation (3):

$$MV_{A_{g}}^{SC} = \sqrt{3}V_{g}\sqrt{\frac{V_{g}^{2}}{Z_{g}^{eq}}} = \frac{V_{g}^{2}}{Z_{g}^{eq}} = \frac{V_{g}^{2}}{X_{n_{g}^{eq}} + Z_{g}}$$  \hspace{1cm} (3)

By re-arranging Equation (3), the fault level contribution of SG can be represented as follows:

$$MV_{A_{g}}^{SC} = \frac{1}{\left(V_{g}^{2}/X_{n_{g}^{eq}}\right)} + \frac{1}{\left(V_{g}^{2}/Z_{g}\right)}$$  \hspace{1cm} (4)

Two MVA components associated with the fault level contribution of a SG can be derived from Equation (4), as follows:

- \(\left(V_{g}^{2}/X_{n_{g}^{eq}}\right)\): Fault contribution associated with the SG subtransient reactance that represents its maximum fault capability in response to a symmetrical three-phase SC fault at its terminal, referred as \(MV_{A_{g}}^{SC} \times (*)\).
- \(\left(V_{g}^{2}/Z_{g}\right)\): Fault contribution associated with the impedance of the connecting elements between the generator terminal to the faulty point including the impedance of the step-up transformer and connecting lines, referred as \(MV_{A_{g}}^{SC} \times (*)\).

The Equation (4) can be re-written using \(MV_{A_{g}}^{SC} \times (*)\) and \(MV_{A_{g}}^{SC} \times (*)\), terms as:

$$MV_{A_{g}}^{SC} = \frac{1}{MV_{A_{g}}^{SC} \times (*)} + \frac{1}{MV_{A_{g}}^{SC} \times (*)} = \frac{MV_{A_{g}}^{SC} \times (*)}{MV_{A_{g}}^{SC} \times (*) + MV_{A_{g}}^{SC} \times (*)}$$  \hspace{1cm} (5)

Based on Equation (5), the fault level contribution associated with SG, \(MV_{A_{g}}^{SC} \times (*)\), can be defined using combinations of \(MV_{A_{g}}^{SC} \times (*)\) and \(MV_{A_{g}}^{SC} \times (*)\), as shown in Figure 2(c). Note that the second term, \(MV_{A_{g}}^{SC} \times (*)\), can be practically calculated in simple one-machine radial system (as shown in Figure 3) by using \(\left(V_{g}^{2}/Z_{g}\right)\), where the impedance \(Z_{g}\) is the summation of the series impedances connected between the generator terminal and the faulty point. However, this might not be possible in real power systems where such impedance would include a complex combination of many elements depending on the topology of the network. Therefore, in our proposed FLC method, we simplified the calculations of \(MV_{A_{g}}^{SC} \times (*)\), using \(MV_{A_{g}}^{SC} \times (*)\) and \(MV_{A_{g}}^{SC} \times (*)\) terms (without relying on \(Z_{g}\) which are initially known from the base scenario accordingly, as explained in Step 1, in the next section in more details.

### 3.2 Augmenting FLC method including the impact of PE-based generation

Penetration level metric: The penetration level, \(P\), is defined to represent the portion of power supplied from a PE generation, \(MV_{A_{PE}}\), out of the total generation capacity of the generation unit, \(MV_{A_{T}}\). In Equation (6), the penetration of PE generation can be given as follows:

$$P = \frac{MV_{A_{PE}}}{MV_{A_{T}}} = \frac{MV_{A_{PE}}}{MV_{A_{T}} + MV_{A_{PE}}}$$  \hspace{1cm} (6)

Our methodology integrates the impact of PE-based generation in Equation (5) by augmenting \(MV_{A_{g}}^{SC} \times (*)\) term as a function of penetration level of such generation at the SG terminal, i.e. \(MV_{A_{g}}^{SC} \times (*)\). Note that the star notation (*) is used for the compound generation unit including SG and PE-based generation. The representation of the fault level in Equation (5) is generalized to include the impact of newly added PE-based generation alongside de-rated SG unit, as shown in Figure 3. Our FLC method allows to study FG scenarios with various penetration of PE-based generation at all-specific SG locations, as explained below in more details. It is worth mentioning that the scope of previous related studies was limited to particular networks and/or scenarios due to use of time-consuming methodologies such as time-domain simulations. On the other hand, our FLC method can be used as a fast scanning tool for analysing large numbers of FG scenarios. Note that we augmented Equation (5) benefiting from unchanged \(MV_{A_{g}}^{SC} \times (*)\) (i.e. the fault level contribution associated with the connecting elements up to the faulty point does not change), as given in Equation (7).

$$MV_{A_{g}}^{SC} \times (*) = \frac{MV_{A_{g}}^{SC} \times (*)}{MV_{A_{g}}^{SC} \times (*) + MV_{A_{g}}^{SC} \times (*)}$$  \hspace{1cm} (7)

Note that if PE-based generation is connected to a new bus that previously included no SGs, then apart from \(MV_{A_{g}}^{SC} \times (*)\), the term \(MV_{A_{g}}^{SC} \times (*)\) also requires to be updated. Updating the \(MV_{A_{g}}^{SC} \times (*)\) in such scenarios depends on careful selection of the total equivalent series impedance of the path connecting the generator terminal to the faulty point \(Z_{g}\). This paper has made the first step towards a new FLC method representing the impact of PE-based generation in as a function of their penetration level at the generation side assuming displacement scenarios in which PE-based generation is connected to the SGs bus.
Considering displacement scenarios where PE-based generation is connected to a new bus that previously included no SGs will not impact our methodology explained here, and is part of our ongoing research. This may necessitate the need for clustering approaches.

As explained above, this is the first step made towards formulating the effect of displacement of the SG by PE-based generation on the system fault level. Our methodology for FLC including the impacts of PE-based generation is summarized in the following steps:

Step 1 Calculating $MV_A^{SC_{gi},t}$ for each displaced SG from the base case:\footnote{Note that the base case is referred to the existing power systems before analyzing FG scenarios including further uptake of PE-based generation.}

Step 2 Calculating of the updated terminal fault level $MV_A^{SC_{gi},t}(P)$ as a function of the PE-based generation penetration: The maximum available fault level, at the terminal of the generation unit at any penetration level of PE-based generation, is equal to sum of the fault level supplied from both de-rated SG, $MV_A^{SC_{gi},t}(P)$, and PE-based generation, $MV_A^{PE_{gi},t}(P)$, as given in Equation (9).

$$MV_A^{SC_{gi},t}(P) = MV_A^{SC_{gi},t}(P) + MV_A^{SC_{PE_{gi},t}}(P)$$ (9)

Where, the terms $MV_A^{SC_{gi},t}(P)$ and $MV_A^{SC_{PE_{gi},t}}(P)$ can be calculated as follows:

$$MV_A^{SC_{gi},t}(P) = rac{MV_A^{SC_{gi},t} \times MV_A^{SC_{gi},t}}{MV_A^{SC_{gi},t} - MV_A^{SC_{gi},t}}$$ (8)

In the proposed FLC method, once calculated, $MV_A^{SC_{gi},t}$ is assumed to be fixed regardless of changes that might occur at the generation side, as explained above.

Step 2.1 Updated fault contribution from SG at its terminal, $MV_A^{SC_{gi},t}(P)$: The maximum fault level of a SG at its terminal can be determined using its rating voltage and internal sub-transient reactance, as given in Equation (10):

$$MV_A^{SC_{gi},t} = \frac{MV_A^{SC_{gi},t}}{x''_{gi}}$$ (10)

where, $x''_{gi}$ is the sub-transient reactance in per unit.

In displacement scenarios, which are the focus of most FG scenario studies, it is assumed that the SG rating is reduced to $(1-P_i)$ due to the increased penetration of PE-based generation to $(P_i$). In such a case, the terminal fault level in Equation (10) also will be decreased by the same factor, as follows:

$$MV_A^{SC_{gi},t} (P_i) = \frac{(1-P_i) \times MV_A^{SC_{gi},t}}{x''_{gi}}$$ (11)

Step 2.2 Fault contribution from PE-based generator at its terminal, $MV_A^{PE_{gi},t}(P)$: It is assumed that the PE-based generator comply with the grid code requirement by injecting reactive current in proportional to a voltage dip resulting from the fault. Hence, a proportional gain ($k$-factor) of two is chosen according to several grid codes such as the German grid code [41]. Also, the maximum contribution of the PE-based generator to a SC at its terminal depends on the overloading capability represented by $(\alpha_{PE})$ in Equation (12).

$$MV_A^{SC_{gi},t} = \alpha_{PE} \times MV_A^{PE_{gi},t}$$ (12)

Using Equation (6), the rating of PE-based generation, $MV_A^{PE_{gi},t}$, can be defined based on total installed generation capacity, $MV_A^{T_i}$, which is assumed to be equal to the SG rating before decommissioning (i.e. $MV_A^{T_i} = MV_A^{SC_{gi},t}$), hence $MV_A^{PE_{gi},t}$ can be represented as:

$$MV_A^{PE_{gi},t} = P_i \times MV_A^{T_i}$$ (13)

By substituting Equation (13) in Equation (12), the fault level contribution at the terminal of the PE generation can be given as follows:

$$MV_A^{SC_{gi},t} = \alpha_{PE} \times P_i \times MV_A^{T_i}$$ (14)

Considering the fault contributions from both the SG and the PE-based generator, which are given in Equations (11) and (14) respectively, the maximum fault level from the compound generation at its terminal can be written as:

$$MV_A^{SC_{gi},t} (P_i) = (1-P_i) \times MV_A^{SC_{gi},t} + \alpha_{PE} \times P_i \times MV_A^{T_i}$$ (15)
Step 3 Calculating of the updated fault level contribution $MV A_{SCg_i}^P (P_i)$ as a function of the PE-based generation: The total fault level contribution from both de-rated SG and PE-based generation, $MV A_{SCg_i}^P (P_i)$, can be obtained by substituting Equation (15) in Equation (7), as follows:

$$MV A_{SCg_i}^P (P_i) = \frac{[(1 - P_i) \times MV A_{SCg_i}^P + \alpha P_i \times MV A_{SCg_i}^P]}{[(1 - P_i) \times MV A_{SCg_i}^P + \alpha P_i \times MV A_{SCg_i}^P]} \times MV A_{SCg_i}^P$$

(16)

Step 4 Calculating of the updated total fault level $MV A_{SG}^P (P_T)$ as a function of the total PE-based generation: The Equation (16), which is valid for a single compound machine considering the corresponding local penetration level at generation bus (i.e. $P_i$), can be used for each displaced SG. By doing so, the FLC can be extended to consider various displacement scenarios. This will enable representing the fault level as a function of the total system-scale penetration level (i.e. $P_T$). Note that the local penetration level at a system scale, $F_T$, and the local penetration level at a certain generation bus, $P_i$, are correlated as follows:

$$P_T = \sum_{i=1}^{N} MV A_{PEg_i}^P = \sum_{i=1}^{N} P_i \times MV A_{Ti} = \sum_{i=1}^{N} MV A_{Ti}$$

(17)

Using these metrics, the total fault level as a function of the total penetration level, $P_T$, can be represented by summing up the contributions from all the connected generation units formulated based on the local penetration level, $P_i$, as follows:

$$MV A_{SG}^P (P_T) = \sum_{i=1}^{N} MV A_{SCg_i}^P (P)$$

(18)

For better understanding, let us to consider an example where the PE penetration displaces the SG $g_1$, as shown in Figure 4. By following the proposed FLC method, the only variable here will be the fault level contribution from the displaced SG (e.g. $MV A_{SCg_1}^P$). Then, Equation (18) is re-written as follows:

$$MV A_{SG}^P (P_T) = MV A_{SCg_1}^P (P) + \sum_{i=2}^{N} MV A_{SCg_i}^P (0)$$

(19)

From Equation (19), it can be noted that the total fault level at the faulty point before decommissioning of the SG $g_1$, $MV A_{SG}$, is divided into two parts: (i) variable fault contribution from the SG $g_1$, $MV A_{SCg_1}^P$, and (ii) fixed fault contribution from the other connected generators in the grid (i.e. $P_i = 0$, for $i \neq 1$). The later can be represented by an equivalent grid, as given in Equation (20).

$$MV A_{SG}^P (P_T) = MV A_{SCg_1}^P (P) + MV A_{SG grid}$$

(20)

Then, the Equations (7)–(16) should be used for calculation of the fault level as a function of PE-based generation penetration, $MV A_{SCg_i}^P (P_i)$, as given in Equation (16). In other words, at this stage, we include the impact of PE-based generation and decommissioned SG $g_1$ in the FLC method. Finally, the calculated $MV A_{SCg_1}^P (P_i)$, given in Equation (16), should be added to the fixed fault level contribution from the rest of the grid, $MV A_{SG grid}$, as shown in Equation (21). These steps are also summarized in Figure 5, which shows a flow chart for the proposed FLC method.

$$MV A_{SG}^P (P_T) = \frac{[(1 - P_T) \times MV A_{SCg_1}^P + K_{PE1} \times P_T \times MV A_{Ti}]}{[(1 - P_T) \times MV A_{SCg_1}^P + K_{PE1} \times P_T \times MV A_{Ti}]} + MV A_{SG grid}$$

(21)

3.2.1 Special case (uniform PE penetration scenario)

In such scenarios, PE-based generation penetration is evenly increased at all generation buses (i.e. $P_1 = P_2 = \ldots = P_N$). As a result, the value of the total penetration level is equal to the local penetration level, (i.e. $P_T = P_i$). In order to apply our FLC method for such scenarios, it is assumed that the fault level $MV A_{SCg_i}^P$ is decomposed into two aggregated components: (i) fault contribution associated with the aggregated SGs at its terminal, $MV A_{SCagg}^P$, and (ii) fault level associated with the aggregated impedance $Z_{Agg}$, represented by $MV A_{SCagg}$.

These imply that the SC current is fed from one aggregated source, through aggregated impedance that is connected

\[ \text{FIGURE 4} \quad \text{Representation of the fault level at non-uniform penetration scenario (a) the original system, (b) the system with PE-based generator, (c) MVA representation} \]
FIGURE 5  Flow chart for the proposed FLC Method

in series between the generation unit and the faulty point, \( Z_{Agg} \). This is similar to the schematic diagram shown in Figure 2. Terms, \( MVA_{Agg}^{SC, t} \) and \( MVA_{Agg}^{SC, Zs} \), can be calculated using Equations (22) and (23) respectively.

\[
MVA_{Agg}^{SC, t} = \sum_{i=1}^{N} MVA_{i}^{SC, t}
\]

(22)

(23)

Using Equation (15), the value of the aggregated terminal fault level in Equation (22) can be updated, as follows:

\[
MVA_{Agg}^{SC, t} (P_t) = (1 - P_t) \times MVA_{Agg}^{SC, t} + K_{PE} \times P_t \times MVA_{t}^{T}
\]

(24)

Substituting Equations (23) and (24) in Equation (7), the fault level for uniform penetration is given by Equation (27):

\[
MVA_{SC} (P_t) = \frac{[1 - P_t] \times MVA_{Agg}^{SC, t} + K_{PE} \times P_t \times MVA_{t}^{T}] \times MVA_{Agg}^{SC, t} + MVA_{Agg}^{SC, Zs}}{[1 - P_t] \times MVA_{Agg}^{SC, t} + K_{PE} \times P_t \times MVA_{t}^{T} + MVA_{Agg}^{SC, Zs}}
\]

(25)

FIGURE 6  Adjusted two-area test system

FIGURE 7  Fault level with different levels of \( P_2 \) (Scenario 1)

4  RESULTS AND DISCUSSION

The new method for FLC presented in Section 3, is used for fault level calculation in the 2-area and the IEEE 39-bus test systems [33, 41] with the increased penetration of PE-based generation, and the obtained results are compared with the simulations performed in DiGSIENT PowerFactory, where accuracy of our methodology is proven. The following sections discuss simulation results in more details.

4.1  Two-area system

4.1.1  Scenario 1 (displacing SG-2)

In this scenario, a wind power plant utilizing FRC technology (i.e. Type-4) has gradually displaced the SG-G2 starting from 0% up to a penetration level of 100% (i.e. \( P_2 = 1 \)) of PE-based generation as shown in Figure 6. Note that this represents a maximum total PE penetration level of 25% (i.e. \( P_T = 0.25 \)). The fault level is monitored at all the buses in the test system, but shown at Buses 6 and 7, for the illustration purpose.

The results show that the system fault level tends to decrease with the increased penetration of PE-based generation in the system as shown in Figure 7. This is due to the fact that maximum fault level of PE-based generation is limited to its MVA rating of FRC (e.g. \( \alpha_{PE} = 1.0 \) is considered here). Also,
Figure 7 compares the results obtained from our FLC method (Section 3) and the one obtained from dynamic simulation carried out in DIgSILENT.

It can be seen that the results obtained from our method are almost the same as the time-domain simulation results. For this scenario, the maximum absolute error between our FLC method and time-domain simulations is less than 3.1%. Note that the results in Figure 7 are demonstrated for two typical Buses in the system, while the same trend was observed for other buses in the grid. Further, the fault level on Buses 6 and 7 have experienced a reduction from (4375 and 3328 MVA at \( P_T = 0 \)) to (2907 and 2706 MVA at \( P_T = 1 \)), respectively. These represent 33% and 18% reduction in the fault level on Buses 6 and 7 at 100% PE penetration, respectively. Observe that the reduction on Bus 7 is less than the one observed on Bus 6 due to the sensitivity of the fault level to the location of the displaced SGs. Note that the calculation steps using the FLC method in Section 3 are detailed in Appendix A.

### 4.1.2 Scenario 2 (displacing all SG generators uniformly)

In this scenario, PE-based generation units (wind power plants) are connected to all four SG locations. The penetration level, \( P_T \), is increased gradually from 0% to 70%. The fault level is then calculated for all the buses, as depicted in Figure 8. Similarly to the observed pattern in Figure 6, a reduction in the fault level for Buses 6 and 7 is noted with the increased penetration of PE-based generation in the grid. The maximum reduction in the fault level is occurred at the highest penetration level (i.e. 70%), as expected.

The fault level on Buses 6 and 7 are reduced from (4248 and 3328 MVA at \( P_T = 0 \)) to (3093 and 2667 MVA at \( P_T = 0.7 \)), respectively.

This indicates a reduction of 18% and 20% in the fault level on Buses 6 and 7, respectively. It is worth mentioning that the error in this scenario is slightly higher than the non-uniform penetration scenario, which is due to higher numbers of PE-based generation in the grid. Nevertheless, the maximum absolute error is still less than 4%. The simulation results showed the efficiency of our FLC methodology for analysing large numbers of FG scenarios in a short period of time.

### 4.2 IEEE 39-bus test system

To demonstrate the accuracy of the proposed FLC method on a large test system, the adjusted IEEE 39-bus test system, shown in Figure 9, is used with two different scenarios as follows:

(i) scenario 1 \((P_1 = 0.5, P_3 = 1, P_6 = 0.5, P_2 = P_4 = P_5 = P_7 = P_8 = P_9 = P_{10} = 0)\).

(ii) scenario 2 \((P_1 = 0.7, P_3 = P_4 = P_6 = P_7 = 1, P_2 = P_5 = P_8 = P_9 = P_{10} = 0)\).

Note that Scenarios 1 and 2 mentioned above represent a total penetration of (36%) and (59%), respectively. The fault level at Buses 9 and 16 is calculated (see Appendix B for detailed calculations of our proposed methodology in Section 3) and compared with the steady-state fault calculations based on the up-to-date IEC 60909 standards and the complete methods. These Buses are chosen based on their location in the system as Bus 9 represents a close to generation faulty point while Bus 16 represents a faulty point at the middle of the system and far from the generation side. All these methods are then validated against the results obtained from the dynamic simulations as shown in Figures 10 and 11, respectively. It can be seen that the system fault level is falling with increasing the penetration of PE-based generation on both buses. Observe Bus 9, where the fault level has reduced from (4758 MVA) at the base scenario (i.e. \( P_T = 0% \)), down to (4481 and 4344 MVA) at a total penetration \( P_T \) of (36% and 59%), respectively. On the other hand, Figure 11 shows that the fault level at Bus 16 has reduced from (7303 MVA) at the base scenario (i.e. \( P_T = 0% \)), down to (6913 and 5891 MVA) at a total penetration \( P_T \) of (36% and 59%), respectively. Figures 10 and 11 also provide a comparison between the results obtained from our FLC method with
RMS simulations, the up-to-date IEC 60909 standards and the complete method. Observe that our proposed FLC method can accurately predict the trend of the falling fault level on both buses with a negligible error when compared with other methods (maximum absolute error of 5.1%).

In contrasts, the IEC 60909-based fault calculation has provided misleading results in some cases, as it has shown an increasing fault level on Bus 9. Observe from Figures 10 and 11, the increasing error gap between the IEC standards and the simulation results. This error has registered very high values especially at scenario 2 (i.e. $P_T = 0.59$). For example, a maximum absolute error of 67.1% and 38.6% are registered at Bus 9 and Bus 16 respectively. This might be due to the fact that the IEC 60909-based method considers the maximum fault contribution from the PE-based sources regardless of the location of the fault. Hence, higher fault currents will be considered even for faults far from the sources.

On the other hand, the complete method has provided decent estimations for the fault level at both scenarios when compared with the IEC 60909-based method. Observe that the maximum errors were 9.9% and 10.1% for scenario 1 and scenario 2, respectively. This improved accuracy compared to the IEC-based method as a result of the dynamic voltage support which accounts for the reactive current injected according to the severity of the fault. However, the proposed FLC method has shown its superiority among these three methods with maximum errors of 2.9% and 5.1% for the same scenarios. This proved that the proposed FLC method not only formulated the fault level in future scenarios as a function of the penetration level of NSGs, but also it provides a new method for quantifying the changes in the variable fault level and calculate the fault level in a simplified and less computational requirement with a superior accuracy without any further need for detailed modelling or time-consuming dynamic simulations.

5 CONCLUSION

In this paper, a new method for steady-state fault level calculation (FLC) including the impact of high penetration of inverter-based RES, referred here as PE-based generation, is proposed. Our proposed method is formulated based on correlation between the fault level and the penetration of PE-based generation in the power system. Our generic modelling method can assist in estimating/predicting of the system fault level in wide range of future grid scenarios without a need for detailed system modelling or time-domain simulations. The proposed new FLC method has been tested using different test systems, whereas in this paper the results for two representative test systems, i.e. (a) 2-area test system and (b) IEEE 39-bus test system, are presented. The proposed FLC method has demonstrated adequate applicability, with small absolute errors, smaller than 5.1%, when compared to the full scale dynamic simulation results based on detailed network modelling.

Furthermore, the results obtained have shown that the proposed FLC method has a superior accuracy when compared with the complete and the IEC60909-based fault calculations. It was noted that the IEC60909 standard may result in a conservative/inaccurate outcomes in some cases. For example, in the case of the IEEE 39-bus test system, the IEC60909-based fault calculation demonstrated an increasing fault level on Bus 16 with increased PE-based penetration, which was opposite to the actual results obtained from dynamic simulation. In contrast, our proposed FLC method demonstrated accurate trend of fault level with the increased penetration of PE-based generation, as confirmed by dynamic simulations. On the other hand, the complete method has provided better results compared to the IEC60909 standard, but still not as accurate as our proposed method.

Although the simulation results showed that the transmission system fault level may decrease with the increased penetration of PE-based generation, these reductions may show different trends in different power systems, depending on the fault location and the synchronous generation (SG) displacement scenarios. For instance, it can be noted that those buses which are closer to the displaced SGs, may experience lower fault levels, compared to the remote ones. On the other hand, an approximately homogeneous fault level reduction may be experienced in the network when the SGs are uniformly replaced.
by PE-based generation. This implies the impact of PE-based generation location on the fault level reduction, and our FLC method can assist researchers and system operators to analyse large numbers of FG scenarios with different possibilities for type, size and location of PE-based RESs.

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APPENDIX A: TWO-AREA TEST SYSTEM (SCENARIO 1)

Step 1 Calculating $MVA_{g2}^{SC}$, for SG, G2, using (8)

| G2 rating [MVA] | $MVA_{g2}^{SC}$ | Calculated $MVA_{g2}^{SC}$, $Z_s$ |
|----------------|----------------------|----------------------------------|
|                | Bus 6 | Bus 7 | Bus 6 | Bus 7 |
| 900            | 3750 | 2252 | 1434 | 6100 | 2397 |

The fixed fault level contribution, $MVA_{grid}^{SC}$

| Bus 6 | Bus 7 |
|-------|-------|
| 2123  | 1980  |

Step 2 Calculating of the updated terminal fault level $MVA_{g2}^{SC,*}$ ($P_2$), using (15).

| Penetration level ($P_2$) | $MVA_{g2}^{SC,*}$ ($P_2$) |
|---------------------------|---------------------------|
| 0.1                       | 4266                      | 3369                      |
| 0.2                       | 4150                      | 3319                      |
| 0.3                       | 4027                      | 3265                      |
| 0.4                       | 3897                      | 3204                      |
| 0.5                       | 3759                      | 3137                      |
| 0.6                       | 3611                      | 3061                      |
| 0.7                       | 3453                      | 2975                      |
| 0.8                       | 3284                      | 2877                      |
| 0.9                       | 3103                      | 2765                      |
| 1                         | 2907                      | 2634                      |

note that $\alpha_{PE} = 1.0$

Step 3 Calculating of the updated fault level contribution $MVA_{g2}^{SC,*}$ ($P_2$), using (16).

| Penetration level ($P_2$) | $MVA_{g2}^{SC,*}$ ($P_2$) |
|---------------------------|---------------------------|
| 0.1                       | 2143                      | 1389                      |
| 0.2                       | 2027                      | 1339                      |
| 0.3                       | 1904                      | 1285                      |
| 0.4                       | 1774                      | 1224                      |
| 0.5                       | 1636                      | 1157                      |
| 0.6                       | 1488                      | 1081                      |
| 0.7                       | 1330                      | 995                       |
| 0.8                       | 1161                      | 897                       |
| 0.9                       | 980                       | 785                       |
| 1                         | 784                       | 654                       |

APPENDIX B: IEEE 39-BUS TEST SYSTEM

Step 1 Calculating $MVA_{g2}^{SC}$ for each displaced SG from the base case, using (8).

| $G_i$ | Rating (MVA) | $MVA_{gi}^{SC}$ | Contribution $MVA_{gi}^{SC}$, $Z_s$ |
|-------|-------------|----------------|----------------------------------|
|       | Bus 9 | Bus 16 | Bus 9 | Bus 16 |
| G1    | 10000 | 25000 | 3112  | 1331  |
| G2    | 700   | 2000  | 493   | 482   |
| G3    | 800   | 2222  | 426   | 581   |
| G4    | 800   | 2247  | 107   | 1024  |
| G5    | 600   | 2857  | 60    | 681   |
| G6    | 800   | 2500  | 108   | 958   |

| Penetration level ($P_2$) | $MVA_{g2}^{SC}$ ($P_2$) |
|---------------------------|---------------------------|
| 0.1                       | 4266                      | 3369                      |
| 0.2                       | 4150                      | 3319                      |
| 0.3                       | 4027                      | 3265                      |
| 0.4                       | 3897                      | 3204                      |
| 0.5                       | 3759                      | 3137                      |
| 0.6                       | 3611                      | 3061                      |
| 0.7                       | 3453                      | 2975                      |
| 0.8                       | 3284                      | 2877                      |
| 0.9                       | 3103                      | 2765                      |
| 1                         | 2907                      | 2634                      |

note that $\alpha_{PE} = 1.0$
### Step 2 Calculating of the updated terminal fault level contribution \( MV_{A_{SC}^{g_i}}(P_t) \), using (15)

| \( G_i \) | Rating (MVA) | \( MV_{A_{SC}^{g_i}} \) | \( \frac{MV_{A_{SC}^{g_i}}}{Z_i} \) | Bus 9 | Bus 16 | Bus 9 | Bus 16 |
|---------|--------------|-----------------|-------------------|-------|-------|-------|-------|
| G7      | 700          | 2272            | 74                | 716   | 76    | 1047  |
| G8      | 700          | 2222            | 114               | 413   | 120   | 508   |
| G9      | 1000         | 2222            | 76                | 477   | 79    | 607   |
| G10     | 1000         | 4000            | 189               | 639   | 198   | 760   |

### Step 3 Calculating of the updated fault level contribution \( MV_{A_{SC}^{g_i}}(P_t) \), using (16)

| Scenario 1 (36%) | Scenario 2 (59%) |
|------------------|------------------|
| \( G_i \)       | \( \frac{MV_{A_{SC}^{g_i}}}{P_t} \) | \( \frac{MV_{A_{SC}^{g_i}}}{P_t} \) |
|------------------|------------------|------------------|
| G1 0.5           | 18000 (0.7)      | 3039 (0.7)       |
| G2 0             | 2000             | 493             |
| G3 1             | 880              | 108             |
| G4 0             | 2247             | 2857            |
| G5 0             | 2857             | 1               |
| G6 0.5           | 1090             | 0.5             |
| G7 0             | 2222             | 349             |
| G8 0             | 2222             | 349             |
| G9 0             | 2222             | 349             |
| G10 0            | 4000             | 349             |

Note: \( \alpha_{PE} = 1.1 \)

### Step 4 Calculating of the updated total fault level, \( MV_{A_{SC}}(P_t) \), using (19)

| Scenario           | \( MV_{A_{SC}}(P_t) \) |
|--------------------|-------------------------|
| Scenario 1 (36%)   | 4609                    |
| Scenario 2 (59%)   | 4566                    |

| Scenario 1 (59%)   | 7028                    |
| Scenario 2 (59%)   | 6133                    |