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# Investigating the Maximum Instantaneous Fault Current in Power Systems with High Penetration of Type-4 Wind

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**Abstract**—The increased attention towards Renewable Energy Sources (RESs), such as wind generation, has become a priority for systems operators and policymakers worldwide. Type-4 wind generators are considered one of the most common types of wind for large-scale integration of RESs. Type-4 wind generators employ converters for their interface to the AC grid. In such generators, the power exchange with the grid is fully controlled by the converter interface that utilizes power electronic switches of limited current-carrying capability during normal and faulty conditions. Hence, type-4 wind generators have different and limited fault current contributions compared to the traditional conventional generation units based on Synchronous Generators (SGs). In future scenarios where such RESs are extensively integrated, and the SGs are also decommissioned, the SC current behavior of the systems would be affected significantly, and a fault level reduction would be witnessed too. The maximum instantaneous SC current is one of the key SC current components that should be monitored in such scenarios due to its importance for several applications such as faults detection, proper settings of the protection settings, and the design of circuit breakers ...etc. This paper is aimed at investigating the effect of the increased penetration of type-4 wind generation on the maximum instantaneous fault current in power grids with the increased penetration of type-4 wind RESs. The results and findings of this research are tested on the IEEE 9-Bus test system modeled in Matlab.

**Keywords**—*instantaneous fault current, artificial neural network, type-4 wind generation, renewable energy.*

## I. INTRODUCTION

Over time, the usage of renewable energy sources (RESs) has expanded quickly and taken center stage in the electrical sector. Increased use of RESs, such as wind power generation, can alter the traditional dynamics and characteristics from those often seen in conventional power systems based on synchronous generators (SGs) only. One aspect of a system that could be changed due to the RESs' penetration is represented by its short circuit (SC) currents [1, 2]. This is driven by the fact that most of the RESs have different fault signature from that of traditional SGs. This is due to the fact that the majority of the RESs have different fault signature from that of traditional SGs. Such distinguished SC behavior

resulted from power electronic (PE) converters, which are employed in grid integration, that have limited current-carrying capabilities. Due to low penetration scenarios in the past, SC current contributions of such sources have typically been disregarded in the belief that they have little to no impact on the accuracy of the total fault currents in the system. Yet, in cases where RESs are abundant in power systems, the SC current contribution of RESs has started to gain attention. The grid codes, which already began to define the fault-ride-through (FRT) requirement that stipulates that RESs shall stay connected during fault occurrences and should inject reactive currents to provide dynamic voltage support under faulty conditions, are another driving force behind this consideration [3, 4].

Type-4 wind generators utilize PE converters to exchange power with the grid entirely. Hence, like other RESs that are equipped with PE converters, they have limited SC current contribution [4, 5]. Besides the limitations on their current-carrying capacity, the varied control schemes and the varying FRT requirements are other reasons lead to produce highly variable SC characteristics too [1, 6]. Therefore, as these converter interfaces are constrained in their ability to allow fault currents to flow, the fault current available when integrating a high percentage of type-4 wind and decommissioning SGs, would be limited. This limited SC current would lead to reduced fault current that might be required for several aspects to ensure stable and safe operation of the power systems [7]. The maximum instantaneous SC current is a crucial component of the fault currents that should be monitored and adequately estimated for several purposes, such as proper protection settings and the design of circuit breakers ...etc. [1, 8, 9]. Hence, it is essential to understand the impact of the increased penetration of RESs, such as type-4 wind, on the level of the maximum instantaneous current available during faulty conditions.

A lot of literature has studied the SC current contribution of RESs, more specifically, those which employ fully-rated converters in their interfaces such as type-4 wind [1, 5, 10]. Moreover, few works have analyzed the SC characteristics with the increased RESs' penetration. For instance,

researchers in [1] have conducted sensitivity analysis on the transient SC current response to the penetration level of non-synchronous generation. The research has shown that the SC current components, which includes the initial symmetrical current, the symmetrical breaking current, and the maximum peak SC current have been pointedly influenced and altered due to the increased RESs' penetration. In addition, some other works have investigated fault calculations with the presence of RESs. These works have provided a good insight into the SC current signature of RESs and tackled the challenge of modeling and analyzing the SC calculation in RESs-rich power systems. However, the focus has been mainly on the initial symmetrical SC current, while the maximum instantaneous SC current has not been appropriately investigated. Moreover, these estimation/calculation methods have required detailed modeling or time-consuming simulations based on time-domain.

This paper tries to overcome the abovementioned shortages in the methods proposed by comprehensively investigating the maximum instantaneous SC current behavior with the increased penetration of type-4 wind generation. The rest of the paper is structured as follows: Section II presents an overview of type-4 wind technology and the SC contribution compared to SGs. Section III discusses the modeling and calculation of the SC current of type-4 according to the updated IEC 60909 standards. Section IV analyzes the effect of the increased type-4 wind penetration on the maximum SC current in power systems. Section V concludes the results.

## II. TYPE-IV WIND GENERATION

### A. Principle of operation

In type-4 wind generators, a combination of an AC/DC and DC/AC converters arrangement is used to exchange the power with the grid as shown in Fig.1 [2]. This converter can support the wind turbine's maximum capacity. It completely separates the generator from the wind turbine from the grid, enabling the generator's frequency to be adjusted as necessary. This allows for the use of various types of generators, such as induction, wound rotor synchronous, and permanent magnet synchronous generators [11].

These turbines have a wider range of speed fluctuation than other types like DFIG wind turbines. The converter is used to both guarantee that the wind turbine is connected correctly and to supply the necessary reactive power support [12]. These wind turbines' current ratings and grid-side converter voltage define their reactive power capacity. These ratings were made to comply with grid code specifications for offering a specific level of reactive power assistance under various system voltage and frequency situations. Similar to

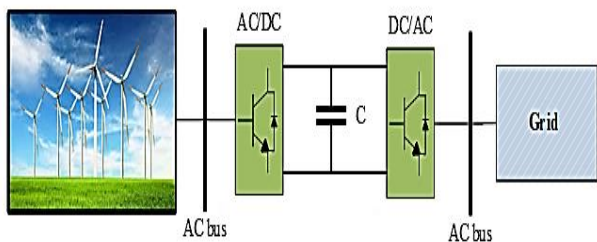


Fig.3. AC/DC and DC/AC converters arrangement in type-4 wind generators

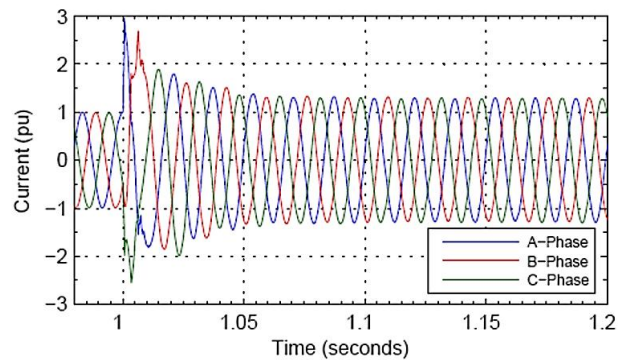


Fig.2. Typical fault current contribution of a type-4 wind generators

DFIG wind turbines, they can offer more reactive support during absorption than at production. If the converter voltage is selected to circumvent the converter voltage limitation, type-4 wind turbines can also provide the same levels of reactive assistance during both absorption and production [13].

### B. Fault contribution of type-4 wind generators

Being equipped with fully-interfaced converters, type-4 wind generators entirely separate the generator from the system. In this instance, the grid-side converter controls the SC current generated [5, 14]. Based on that, the grid-side converter interface used for grid connection ultimately controls and regulates the fault current contribution. More particularly, the control method used in the converter interface, which may differ significantly depending on the manufacturers, essentially determines the fault response of type-IV wind turbines. In general, regardless of the fault situation, the majority of type-IV wind generators only inject symmetrical fault current contributions (either balanced or unbalanced faults) [15]. In other words, unlike synchronous generators that supply negative and zero components during unbalanced faults, the negative and zero components are only sometimes considered.

A transient (very fast) that is followed by a fixed steady-state current component in the fault contribution are typical representations of the fault response of type-IV wind generators, as shown in Fig. 2 [16]. It is noticeable that an overshoot immediately follows the fault's inception. It only lasts for a short period (the first cycle); depending on the manufacturer, it could go as high as (3 p.u.). This transient current contains high-frequency components and may last for two cycles. This transient current may remain for two cycles and has high-frequency components. The operating conditions before the fault, the voltage dip experienced during the fault, and the rate of injection of reactive current are some factors influencing the level at which this transient can be noticed [1, 17]. However, after this transient has entirely dissipated, the fault current is capped to a certain amount, which may change depending on the fault's severity, overrating capability, and proportional gain (k-factor) specified by the FRT control. However, this steady-state regulated current can only be as much as 1.1 to 1.6 p.u. of the converter interface's rated current [16]. This may only be limited to 1.1 p.u in another study in [18], meaning that type-IV wind generators are only manufactured with an overloading capability of 10% above their rated current.

### III. FAULT CALCULATIONS ACCORDING TO IEC 60909

IEC 60909 standards provide a simple and less detailed modelling requirement method for calculating the fault currents in power systems [19]. The IEC 60909 standards have been used previously to mainly calculate the initial symmetrical SC currents during the faults,  $I_k''$ . The other components, as shown in Fig.3, such as the DC component, instantaneous peak, and symmetrical breaking currents are then calculated based on the initial symmetrical SC currents. The topology of the network and network reduction are used in this calculation, which utilizes the Thevenin equivalent.

To determine the initial symmetrical fault current  $I_k''$ , the pre-fault nominal voltage  $V_n$ , and the Thevenin equivalent impedance at the faulty point  $Z_k$  are required as expressed in (1).

$$I_k'' = \frac{V_n}{|Z_k|} \quad (1)$$

Previously, where the penetration of converter-interfaced generators (e.g., type-4 wind) was not much, this IEC 60909 standard did not take into consideration the contribution from the system's RESs. However, in scenarios of high penetration of RESs, models have been suggested to account for the SC contributions of such sources.

For instance, as far as type-4 wind generators are concerned, the IEC standard means modelling such sources as a current source with an infinite impedance for fault calculations, as shown in Fig.4 [20]. According to the manufacturer, this current source would have a limited value and is capped to a small value around the rated current that the converter can carry during faulty conditions.

The SC current contribution from different type-4 generators in the system would be calculated based on the current source modeling by accounting for the transfer impedance between the bus at which type-4 wind generators

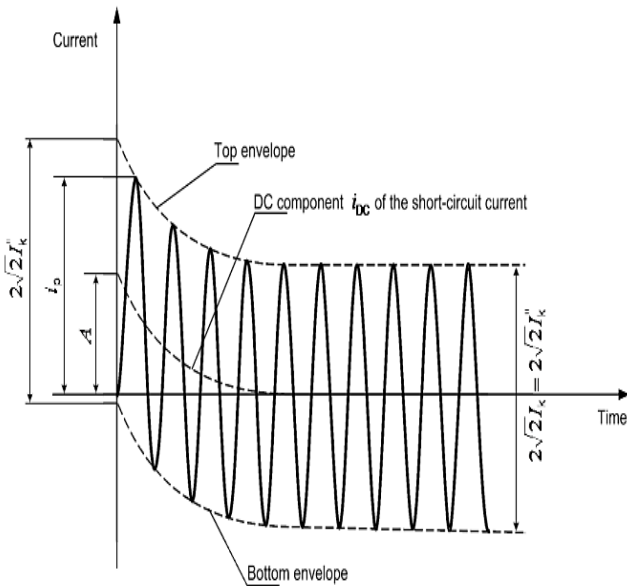


Fig.3. Components of the Short Circuit Current defined by IEC 60909 Standards [18].

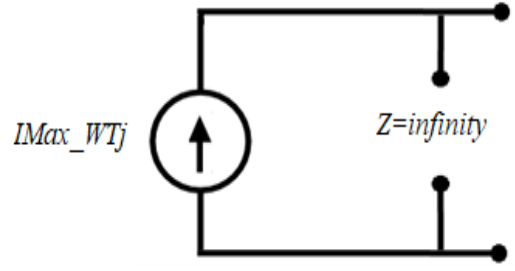


Fig.4. The model of type-4 wind generator for SC calculations according to IEC 60909

are located and the bus at which the fault is calculated (i.e., faulty bus) as shown in (2).

$$I_{k\_wind}'' = \frac{1}{|Z_k|} \sum_{j=1}^{j=M} |Z_{ij}| I_{Max\_WTj} \quad (2)$$

Where,

M: Number of the installed type-4 wind generators.

$I_{Max\_WTj}$ : The maximum contribution of SC current from type-4 wind installed at the j-th bus.

$I_{k\_wind}''$ : The total contribution of SC current of all installed type-4 wind generators.

$Z_{ij}$ : The transfer impedance between the faulty bus i-th and the bus-j.

$Z_k$ : The equivalent Thevenin impedance at the faulty bus.

Then SC current contribution from different type-4 generators would be added to the other contributions obtained using the Thevenin equivalent model for the other SGs. The superposition principle is applied, and the final resultant summation of all current components would represent the total fault current available at the faulty point. After that, a factor of  $\sqrt{2}$ , would be multiplied by the resulted current to find the maximum instantaneous SC current associated with the same fault.

### IV. RESULTS AND DISCUSSIONS

To achieve the target of this paper aiming to track the behavior of the maximum instantaneous SC current with high penetration of type-4 wind generators, the Y and Z matrices of the adjusted IEEE 9 bus system would be built in Matlab [21]. Then, the SC current would be calculated using a code considering the original system without any installed wind generators following the IEC 60909 standards. Then the RESs represented by type-4 wind generators would be installed in the system in several steps to increase the penetration level from 0% to 100%. At each step of penetration increment, the SC current contribution would be recalculated from the system without considering the installed type-4 wind generators. This would be accompanied by calculating the other component of the SC current contributed from the installed type-4 wind generators. Finally, the superposition would be applied to find the total SC current available at the faulty point at each penetration step of type-4 wind. It is worth pointing out that the total generation installed capacity remains constant in all scenarios. In other words, the installed capacity from type-4 wind generators would be accompanied by decommissioned SGs with the same capacity. The metric

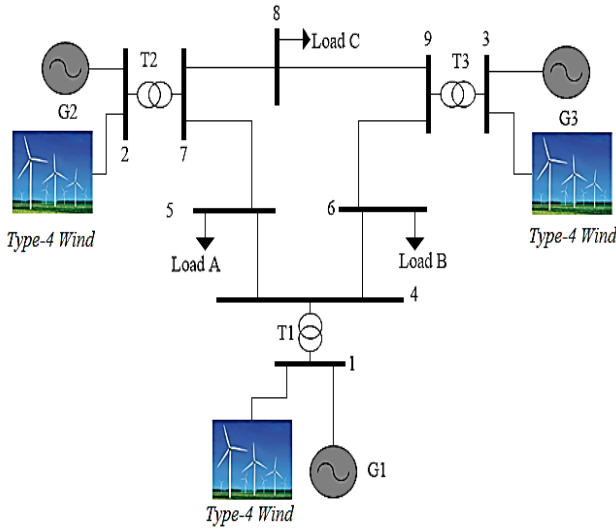


Fig.5. The adjusted IEEE 9-bus test system with type-4 wind generators.

used to represent the penetration level  $p$ , of type-4 wind generation to the total generation capacity in the system can be expressed as shown in (3).

$$p = \frac{\text{Type\_4 wind}}{\text{SGs} + \text{Type\_4 wind}} \times 100\% \quad (3)$$

The maximum instantaneous SC current,  $I_p$ , at two selected buses (Bus 5 and Bus 8) are monitored and obtained at each penetration level of type-4 wind generation. Note that the penetration level,  $p$ , is increased through 20 steps from 0% till reaching the maximum penetration level (i.e., 100%). Hence, 20 different values have been obtained for each penetration scenario.

The test system (i.e., IEEE 9-bus system) is modeled in Matlab to execute the SC currents calculations for collecting the maximum instantaneous SC currents. The developed code allows calculating the SC current contribution of each SG, RES and the resulting total SC current at the nominated buses.

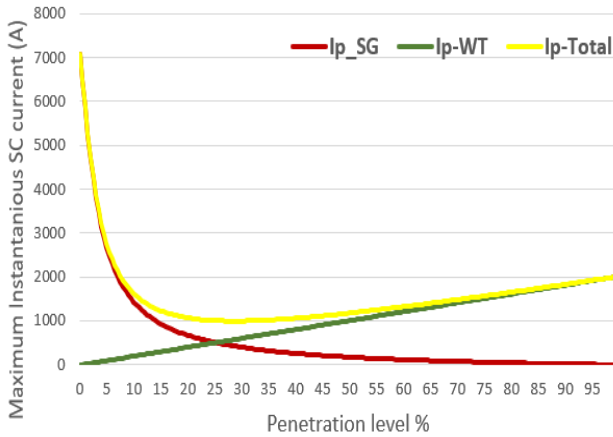


Fig.6. The maximum instantaneous SC current at Bus 5 with the increased penetration of type-4 WT

#### A. Maximum instantaneous SC current at Bus 5

The results obtained at bus 5 show that the maximum instantaneous SC current would significantly decline with the increased penetration level of type-4 wind generators. As depicted in Fig. 6, it can be observed that decommissioning the SGs, even with small levels (e.g., 10-15%) the SC current,  $I_p\text{-SG}$ , contributed from those generators would be significantly reduced from its initial value of 7063 A, down to around (1429 A- 933 A). This represents a (20%-13%) reduction compared to the initial value. It can also be noticed that while the maximum instantaneous SC current contributed from the installed type-4 wind generators,  $I_p\text{-WT}$ , keeps increasing with the increased penetration, this added SC current contribution is still minimal compared to the significant reduction of the  $I_p\text{-SG}$ . This, in its turn, leads to shifting the curve up and its impact can be clearly noticed after exceeding the 25% of penetration where both curves of  $I_p\text{-SG}$ , and  $I_p\text{-WT}$  would intersect. At that point of intersection, the total maximum instantaneous current  $I_p\text{-Total}$ , starts to increase steadily at a lower rate till reaching its maximum at 100% type-4 wind penetration. Observe that at 100% penetration scenario, the  $I_p\text{-SG}$ , contributed from SGs, would become zero as type-4 wind generators completely displace all SGs. In contrast, the maximum instantaneous SC current contributed from the installed type-4 wind generators,  $I_p\text{-WT}$ , would reaches its maximum to coincides with the total maximum instantaneous current  $I_p\text{-Total}$ . Regardless of such increment contributed by the installed type-4 wind generators, the total maximum SC current would still be considered minimal compared with the initial SC current. For instance, the current  $I_p\text{-Total}$  observed at bus 5, is around 2005 A which represents a percent of 28.38 only.

#### B. Maximum instantaneous SC current at Bus 8

The results obtained at bus 8 show an almost similar trend of variations for the maximum instantaneous SC current at bus 5. However, the reduction in the value of the SC current is slightly higher in the case of bus 8. They show that the maximum instantaneous SC current would significantly decline with the increased penetration level of type-4 wind generators. As depicted in Fig. 7, it can be observed that decommissioning the SGs even with small levels (e.g., 10-15%), the SC current,  $I_p\text{-SG}$ , contributed from those generators would be significantly reduced from its initial value of 8122 A, down to around (1424 A- 867 A). This represents a (17.5%-10.6%) reduction compared to the initial

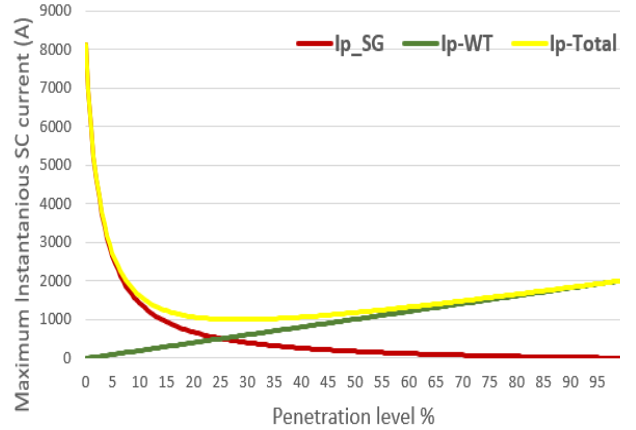


Fig.7. The maximum instantaneous SC current at Bus 8 with the increased penetration of type-4 WT

value. These lower levels are due to the sensitivity of these currents to the location of the fault with respect to the generation centers. More specifically, the different path of the fault and the impedance level between the faulty bus and the generation centers. It can also be noticed that while the maximum instantaneous SC current contributed from the installed type-4 wind generators,  $I_{p-WT}$ , keeps increasing with the increased penetration, and this added SC current contribution is still minimal compared to the significant reduction of the  $I_{p-SG}$ . However, this would also lead to shifting up the curve of the total SC current and its impact can be clearly noticed after exceeding the 25% of penetration where both curves of  $I_{p-SG}$ , and  $I_{p-WT}$  would intersect. At that point of intersection, the total maximum instantaneous current  $I_{p-Total}$ , starts to increase steadily at a lower rate till reaching its maximum at 100% type-4 wind penetration. Observe that at 100% penetration scenario, the  $I_{p-SG}$ , contributed from SGs would decline down to zero as all SGs are completely displaced by type-4 wind generators. Conversely, the maximum instantaneous SC current contributed from the installed type-4 wind generators,  $I_{p-WT}$ , would reach its maximum to coincide with the total maximum instantaneous current  $I_{p-Total}$ . Regardless of such increment contributed by the installed type-4 wind generators, the total maximum SC current would be still considered minimal compared with the initial SC current. For instance, the current  $I_{p-Total}$  observed at bus 8, is around 2005 A which represents a percent of 28.38 only.

## V. RESULTS AND DISCUSSIONS

The effects of increased penetration of type-4 wind generation on the maximum instantaneous fault current in power networks are investigated in this paper. The configuration and the characteristics of the short circuit (SC) currents contribution from type-4 wind generators are presented. Then, the SC current calculation in accordance with the up-to-date version of the IEC 60909 standard has been discussed, accounting for the modeling of the converter-interfaced RESs, more specifically, type-4 wind generators. The paper has studied different scenarios of increased penetration of type-4 wind generation and decommissioning sizeable central generation units based on synchronous generators (SGs) to track the changes that might be observed for the maximum instantaneous SC current in such scenarios. The results of this research are tested on the IEEE 9-Bus test system that modeled in Matlab.

The maximum instantaneous SC current,  $I_p$ , at two selected buses (Bus 5 and Bus 8) is monitored and obtained at each penetration level of type-4 wind generation. Note that the

penetration level,  $p$ , has adjusted through 20 steps from 0% till reaching the maximum penetration level (i.e., 100%). Hence, 20 different values have been obtained for each penetration scenario. The findings of the paper can be summarized as follows:

- The SC contributions from the converter-interfaced RESs, such as type-4 wind generators, are significantly different and limited compared to those from synchronous generators (SGs).
- The maximum instantaneous SC current contributed from SGs,  $I_{p-SG}$ , would be drastically affected by the increased penetration of type-4 wind generators.
- The total maximum instantaneous SC current  $I_{p-Total}$  is mainly sensitive to the penetration of the level of type-4 wind generators in scenarios of less than 25%. In such scenarios, this current sharply declines before reaching the minimum values of around 18% to 20% of its initial level at zero penetration of type-4 wind.
- The penetration level of 25% is a level of interest as both the declined contribution of the SGs and the increased contribution of the wind generators would intersect, forming the minimum level of SC current available at the faulty bus.
- Although the maximum instantaneous SC current contributed from the installed type-4 wind generators,  $I_{p-WT}$ , keeps increasing with the increased penetration, this added SC current contribution is still minimal compared to the significant reduction of the  $I_{p-SG}$ .
- At 100% type-4 penetration scenarios, the available maximum instantaneous SC current  $I_{p-Total}$ , is limited to less than 20% of the one available at the same system before the installation of wind generation and decommissioning of SGs.
- The trend at which the total maximum instantaneous SC current  $I_{p-Total}$ , is changing has shown marginal sensitivity to the location of the faulty bus. In other words, although the values of the faults might vary based on the location of the fault, this variation can be captured and generalized for all buses if it is observed for one of them. However, the initial level of the current, and the fault at the maximum penetration level (i.e., 100%) might be slightly different.

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