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Re-thinking Short-Circuit Current Contribution from Type IV Wind Turbines: A Perspective into How Standardization Can Be Improved

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***Abstract*—Discussions on short-circuit current (SCC) contributions from type IV wind turbines and other inverter-based resources (IBRs) are becoming more relevant and common as power systems are more and more penetrated by renewable energy sources. Several works have brought attention to the fact that IBRs do not behave entirely as a fixed current source during faults as some standards have proposed so far. In contrast, they behave as voltage- and grid-code-dependent current sources in the fault steady-state and can be highly non-linear during the fault transient stage, which increases the complexity of estimating SCC contributions. This paper presents a new perspective on how the improvement of standards and guidelines can help establish effective and intellectual property-independent approaches to estimate SCC contributions from type IV generators. To base the discussion, results from field-validated EMT models of a large-scale offshore grid-following wind turbine are shown in simulations that demonstrate the need for standardized procedures.**

***Index Terms*—Short-Circuit Current, Type IV Wind Turbine, IBR, EMT Simulation, Standards**

I. Introduction

Accurately determining the contribution of short-circuit currents (SCC) from various power sources is important in preventing blackouts, relay malfunctions, and equipment damage. To avoid such issues, short-circuit studies are necessary in the context of equipment design and protection coordination [1, 2]. Furthermore, understanding the levels of SCC and equilibrium points during faults is becoming increasingly crucial for defining stability and control strategies in modern power systems, particularly when highly penetrated by converters.

Regarding SCC, the industry is backed up by an extensive number of working groups and standards. Originally, different standards proposed the provision of sub-transient, transient, and synchronous impedances for synchronous machines. In addition, they have developed simplified methods taking into account that, during a fault, a synchronous generator behaves as a stiff voltage source behind an impedance that changes in three stages. Therefore, standards nowadays mostly provide calculation methods that account for such behaviors [2]. In current practice, the contribution from type IV wind turbine generators (WTGs) and some other inverter-based resources (IBRs) is often overlooked or oversimplified. For example, during the steady-state phase of a fault, IEC 60909-0 Ed. 2 models the contributions as fixed current sources, typically ranging from 1.1 to 1.5 per unit (p.u.), depending on the converter's capabilities supplied by the manufacturer [2].

However, as the behavior of type IV WTGs during a short circuit is more intricate, the standards generally fail to account for the multitude of influencing factors [3]. Recent works [4, 5] based on phasor models have addressed the SCC steady-state contribution of type IV WTGs as a voltage-dependent current source with algorithms that can achieve similar results as EMT simulations. In [6], a novel framework for the estimation of both transient and steady-state stages of the fault is presented based on a hybrid analytical and black-box approach.

Despite recent works, there is still no common definition of Type IV's SCC contribution. This paper addresses the main aspects regarding the SCC contribution by using a field-validated PSCAD model of an offshore type IV grid-following wind turbine as an example and then expanding the definitions to other IBRs. Section II briefly reviews current standards. Section III provides definitions of common fault ride-through control strategies and presents the simulation model used in this study. Section IV presents considerations for both the steady-state and transient stages of the fault. Section V proposes a three-step approach to improve different standardization according to the needs. Section VI concludes the work.

II. Review of Standards

Typically, short-circuit studies are performed in commercial software such as DIgSILENT Power Factory, ETAP, etc. These tools adhere to standards such as IEC 60909-0 Ed. 2 and ANSI/IEEE C37, among others that are widely accepted by

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the industry. In that sense, it is important to give an overview of some of the most important standards utilized in these tools, which are shown in Table I and in the summary below:

- IEC 60909-0 Ed2 (2016) - Short-circuit currents in three-phase a.c. systems - Part 0: Calculation of currents
- IEEE 551 (2006) - Recommended Practice for Calculating AC Short-Circuit Currents in Industrial and Commercial Power Systems.
- IEC 61363-1 (1998) - Electrical Installations of Ship and Mobile and Fixed Offshore Units, Part 1: Procedure for Calculating Short-Circuit Currents in Three-Phase A.C.
- IEEE 141 - IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book).
- C37.010-2016 - IEEE Application Guide for AC High-Voltage Circuit Breakers $>$ 1000 Vac Rated on a Symmetrical Current Basis.

TABLE I
STANDARDS AND THEIR CURRENT CONSIDERATIONS ON TYPE IV WTGS

Standard	Application for Type IV Wind Turbines
IEC 60909-0 Ed2	Fixed current sources
IEEE 551	Not mentioned
IEC 61363-1	Not mentioned
IEEE 141	Not mentioned
IEEE C37-010	Not mentioned

Additionally, there are ongoing and finalized initiatives from working groups/standards. The IEEE Power Systems Relaying Committee has issued a technical report under Working Group C24 Modification of Commercial Fault Calculation Programs for Wind Turbine Generators, which defines iterative and lookup table approaches [7]. The Short Circuit Modeling Work Group (SCMWG) under the Western Electricity Coordinating Council (WECC) is working to augment existing models that can be used for any short circuit software with input from OEM, software vendors, and especially the users [8]. Furthermore, on IEEE P2800.2 Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems, short circuit information of IBR needed for the provision of SCC limits for protection design based on prototype tests are being proposed.

III. FAULT RIDE-THROUGH CONTROL AND MODEL

This section gives simplified definitions of the utilized fault ride-through (FRT) control and EMT simulation model.

A. FRT Control for Grid Following Wind Turbines

The SCC contribution from an IBR is mainly driven by Fault Ride-Through (FRT) control that follows grid code requirements and factors such as prevailing voltage and current, k-factor, and the reference voltage used for current calculation. Therefore, although standards may present simplifications, the contribution of IBRs to short circuits cannot always be reduced to a simple inductive fixed current source.

The current industrial context relies mostly on standards such as IEC 60909-0:2016, which models type IV WTGs as fixed current sources during a fault. However, although WTGs and other IBRs behave as current sources in such scenarios, the reactive and active current magnitude (I_r and I_a) depend on the positive and negative sequence residual voltages (V_{res}^+ and V_{res}^-) at the WTG terminals, the operating point, and network conditions during the fault, as in Eq. (1). The residual voltages are defined by the terminal voltage measured during the fault. In this example, the priority is given only to the positive sequence current. K_{factor}^+ and K_{factor}^- are the converter's current control proportional gain in positive and negative sequence; V_C is a voltage quantity dependent on the grid code (GC); I_r^+ is the positive sequence reactive current that the converter injects based on V_C and V_{res}^+; $I_{r,lim}$ is the FRT limit for the reactive current injection; $I_{r,pf}^+$ is the reactive component of the pre-fault WTG current; and D_{band} is the considered deadband for the voltage difference.

$$I_r = \begin{cases} I_r^+ = K_{factor}^+ \left(|V_C| - |V_{res}^+| - D_{band}\right) + I_{r,pf}^+ \\ I_r^- = 0 \quad \text{or} \quad I_r^- = -K_{factor}^-(|V_{res}^-|) \\ I_r^+ + I_r^- \leq I_{r,lim} \\ I_{r,lim} = 1 \text{ p.u} \end{cases} \tag{1}$$

This paper addresses the following grid code examples based on experiences from European TSOs:

- GC1 - V_C is the WTG nominal voltage (1 p.u.) and neither the dead band nor pre-fault reactive current is included in the injection during a fault, as in Eq. (2);
- GC2 - V_C is the WTG positive sequence pre-fault voltage (V_{pf}) minus a dead band equal to 0.1. In addition, the reactive component of the pre-fault WTG current ($I_{r,pf}^+$) is added to the right-hand side of the I_r^+ calculation, as in Eq. (3).

$$\text{GC1}: \quad I_r^+ = K_{factor}^+ \cdot \left(1 - |V_{res}^+|\right) \tag{2}$$

$$\text{GC2}: \quad I_r^+ = K_{factor}^+ \cdot \left(|V_{pf}| - |V_{res}^+| - 0.1\right) + I_{r,pf}^+ \tag{3}$$

This study does not investigate grid codes where the active current is given priority as opposed to the reactive current. For the active current injection, the total current limitation and injected reactive current are considered along with the pre-fault active power injected to calculate the available room for active current during the fault.

B. Transition from Steady-State to FRT Control

The FRT control described previously starts to control the current as soon as the converter control detects a voltage below a settable threshold. This means that there are two periods before the fault steady state described in Fig. 1 in which, first the control still has not identified the fault and second the converter identifies and begins the transition to fully controlling the current according to the voltage at the terminals and grid code. As seen in [3], during the transient stages of the fault, the converter will likely inject more current than in the steady state as it acts as a quasi-voltage source during the very initial stages of the fault and the FRT control has not been activated yet. The currents are further limited by the hardware transient peak limit safety mechanisms in place to protect the converter.

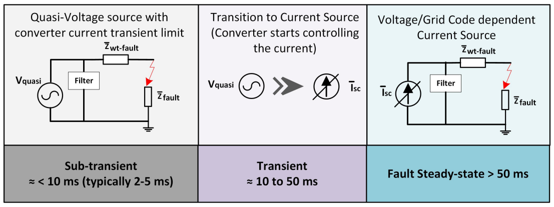

Fig. 1. Transition - operating mode of current source

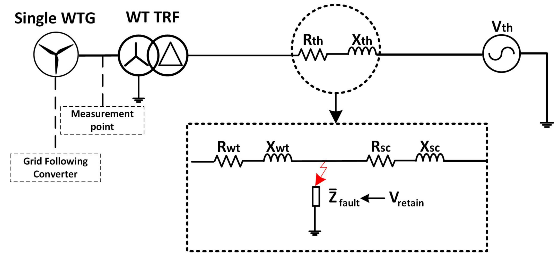

Fig. 2. Single Turbine - Infinite Bus Simulation Model

C. Simulated Model

The industrial EMT model of a Type IV WTG in this study is validated against real-site measurements for Fault Ride-Through (FRT) events. The model is developed in PSCAD™ and comprises the following components:

- **Mechanical System** includes an aerodynamic and shaft models.
- **Electrical System** encompasses a permanent magnet synchronous generator, full-converter, DC link, grid-side converter reactor, filter, WTG transformer (with saturation and harmonic model), and measurement ports.
- **Control System** comprises the WTG level controller for EMT-type simulations, and the converter controller manages the generator, grid-side converters, and the DC link. The actual converter control is implemented as a dynamic link library (*.dll*), including protection features at both turbine and converter levels.

The model was validated against real-site measurements for FRT events, adhering to relevant grid codes and standards, such as IEC 61400-21-1 [9]. Additionally, the industry is progressing in testing individual components and subsystems, incorporating real-time solutions that integrate both hardware and software [10].

A single-turbine system interfaced with a Thevenin equivalent grid model serves as the experimental model, as shown in Fig. 2. Before applying the fault in each simulation, the WTG was allowed to initialize and attain a steady-state condition. A set of EMT simulations was performed using a time-step lower than 10 μs, with a 5 kHz sampling rate for data acquisition. All sequence components were calculated using full-cycle windows (i.e. 20 ms for 50 Hz) and a sampling rate of 2 kHz. All faults were simulated for more than 150 ms so that a fault steady-state condition was achieved. Measurements of steady-state currents and voltages started 100 ms after the fault occurrence. Then, they were averaged during the rest of the fault period.

IV. Simulation Results

In light of the FRT control definitions presented before, this section discusses important considerations regarding the short-circuit current contribution of full IBRs and how those differ from current standardization practices.

A. Steady-State Stages

Fig. 3 shows balanced fault simulations of the considered single-bus system regarding different equivalent grids (given by the SCR) for the two grid codes under analysis. The images depict the steady-stage reactive currents achieved during a variety of fault scenarios. For each SCR and GC combination, 81 simulations varied the fault location from 0.1 to 0.9 by changing the percentage of R_{th} and X_{th}, and the retained voltage at the fault point from 0.1 to 0.2 p.u. Both parameters were incremented with constant steps.

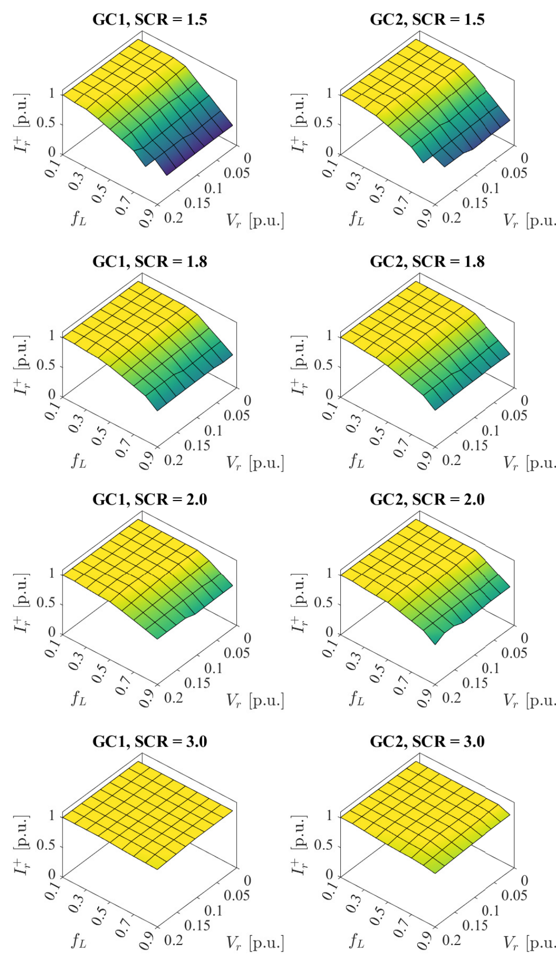

Fig. 3. GC1 and GC2 simulations of three-phase faults

Fig. 3 demonstrates that assuming a fixed current source fails to represent the actual behavior of the fault for weaker power grids (SCR < 2.0) in the steady state. The interpretation of such results comes from the fact that in weaker grids, the impedances between the IBR and the fault are larger (e.g. distant AC-connected offshore wind farms) and therefore the voltage at the terminals of the IBR can become higher for distant faults as opposed to stronger grids where the equivalent impedance is lower. In future power systems where grids get weaker, the figure shows that it becomes even more important to accurately estimate the SCC.

B. Transient Stages

Fig. 4 shows the per unit peak currents in a variety of simulation scenarios. In this plot, GC1 is used and both active power and voltage references are kept at 1 p.u., while other quantities are varied. The plot is separated per fault type (i.e. single-phase, two-phase, and three-phase faults). Four comparisons are made varying three features: fault location; SCR; and voltage at fault point, also known as retained voltage. Additionally, the residual voltage is plotted varying the three features. In the other three subfigures, the boxplots show the peak current range for one of the three features fixed, whereas the other two were varied.

For the specific IBR used in the study, the maximum peak current is 1.8 p.u. As seen in Fig. 4, this value is achieved particularly for two- and three-phase faults in front of the turbine. However, note that peak currents can vary substantially even when the turbine is injecting full-rated power. This is because of the three features (SCR, fault location, and retained voltage). The peak currents between two- and three-phase faults are relatively similar and generally hit the maximum limits, while for single-phase to ground faults they are generally lower. Fig. 4 also shows that the peak currents are not necessarily decreasing but rather have larger variations as the residual voltages become higher.

In the context of grid codes, the California Independent System Operator (CAISO) [11] has recently started requiring manufacturers to supply different tables containing current magnitudes and angles per fault type and for a range of 0 to 0.9 p.u. of positive sequence residual voltage in three different stages of the fault (i.e. 1st cycle, 3rd cycle, and 5th cycle). As seen in the figure, even at fixed power and voltage references, it can be observed that peak currents and naturally the currents at each cycle time can have a large variation even if the voltage at the terminals of the turbine is still the same.

V. Discussion and Recommendations

As previous sections have shown, there is a clear need for improving standards regarding the short-circuit current contribution of IBRs. In this context, Fig. 5 shows the set of processes for improvement of standardization and guidelines. The faults from IBRs can usually be divided into four different stages, namely sub-transient, transient, steady-state, and clearing/recovering. A three-step process is proposed:

Step I - Suggestions for Steady-State: As shown in Fig. 6, IBRs short-circuit current response to faults is dependent on the voltage reference at its terminals and in turn, this voltage is dependent on the response of this device. Therefore, standards need to revisit the calculation methods for networks with a large number of IBRs, where iterative methods need to be considered as well as the convergence issues and limitations of these methods.

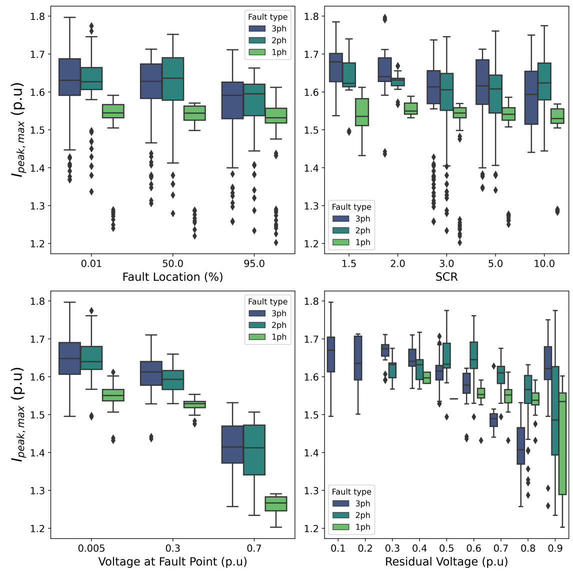

Fig. 4. Transient peak current in p.u

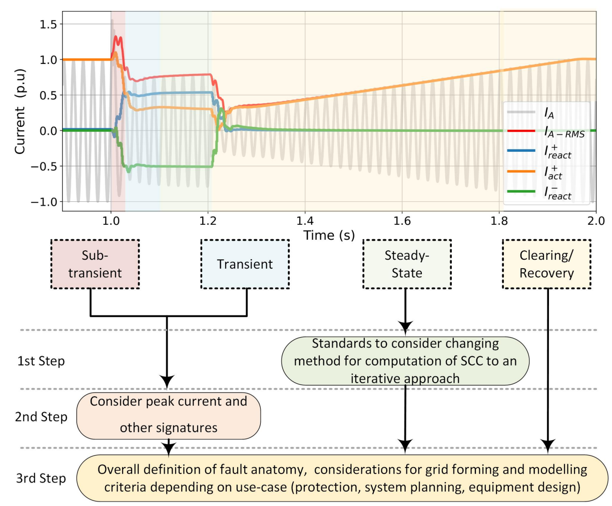

Fig. 5. Step-wise process for improvement of standardization and guidelines of SCC based on different stages of the fault

Step II - Suggestions for Transient Stages: Section IV shows results for the peak currents at the transient stage of the fault. Currently, standards do not consider peak currents to be higher than $\sqrt{2}$ times the steady-state current [2]. In parallel, some grid codes and working groups have proposed to create lookup tables for transient currents in different time frames based on fault type and some other variables [7]. This is however not accurate as seen by the plots and other works published [3]. As an initial stage, OEMs can provide the maximum current that the IBR is supposed to inject. Furthermore, although complex behaviors are present, it would be beneficial to work on a general understanding of these

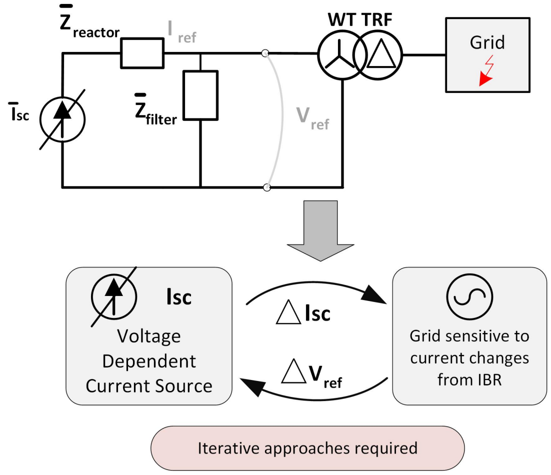

Fig. 6. Iterative Approach for SCC estimation during steady state

stages so that further standardization on how information is provided by the manufacturers is possible.

Step III - Overall Definitions of Fault Anatomy, Considerations for Grid Forming (GFM), and Modeling Criteria Depending on Use Case: As a third step, standardization can tackle the definition of overall anatomy for the fault current where the clearing/recovery stage is described. Additionally, recent definitions of GFM controls have proposed that these devices should maintain the voltage source behavior during the transient stages of any events [12] and may not necessarily follow grid codes in terms of current support during fault as grid-following converters. However, due to limitations of the power electronics hardware, the converter cannot freely inject current as a current source. Therefore, standards should also consider GFM devices and different topologies for fault current limitation during FRTs. Finally, different levels of detail are needed depending on use cases, thus in the future, it could be valuable to divide SCC modeling needs based on whether only steady-state is needed (long-term planning and some types of protection) or if transient stages are necessary (e.g. switching equipment design and fast protection algorithms).

VI. Conclusion

This paper explored the importance for the industry to seek more standardization regarding the short-circuit current contribution of Type IV wind turbines to the power system. Through the use of a field-validated PSCAD model for a Type IV wind turbine, brief results for steady-state and transient currents were shown and overall discussions on steps moving forward were presented.

During the fault steady-state, it is shown that the SCC from current IBRs is dependent on the voltage used as a reference for the control at the terminals of the device which are then affected by the current injection itself. Furthermore, results show that as grids become weaker, currents can deviate further from the general assumptions of a fixed current source presented by standards nowadays. Therefore, there is a clear need for standardization that takes into account these interdependencies.

Regarding the transient stage, this paper has demonstrated that peak currents can be relatively high during the transient of the fault and depend on several factors. It is also shown how complex it is to define look-up tables to indicate currents at different cycles by showing the large variation of peak currents during the transient stages. Therefore, initially, it is proposed that considerations regarding the maximum peak current can be incorporated into standards but further information needs to be discussed in more detail for protection-related standards.

In future work, practical and effective solutions could be developed for grid-following SCC estimation of IBRs as potential paths to enable new standards. Furthermore, analyzing and proposing ways to address grid-forming SCC estimation of IBRs is in the scope of our future research.

Legal Disclaimer

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