Modeling of steady state fault current contribution of inverter-connected generation in PSS/e

Lukas Sigrist, Javier Renedo, Francisco Miguel Echavarren, Francisco Pérez Thoden, Luis Rouco
Instituto de Investigación Tecnológica, ICAI
Universidad Pontificia Comillas
Madrid, Spain
lukas.sigrist@iit.comillas.edu

***Abstract*—This paper presents a method to model steady state fault current contribution of inverter-connected generation such as type 4 wind and PV generators or battery energy storage systems (BESS) in commercially available software packages like PSS/e during three-phase short-circuits. Inverter-connected generation is typically modelled as a negative load or as a generator in these packages. Both representation fail to reflect the current limiting functionality of inverters. The proposed method is based on the Norton equivalent of the generators. The method consists in adding a resonant admittance to cancel out the impact of the equivalent admittance for fault current computation. This way, iterative computations are avoided and no readjustments are needed for different fault locations. The main advantage is that the proposed method is extremely simple to implement. It has been successfully applied to a simple test system, a PV plant, and one of the isolated power systems of the Canary Islands.**

***Index Terms*—Fault current, inverter-connected generation, non-synchronous generation, short circuit**

I. Introduction

Short circuit studies are particularly important during selection and design of system equipment and relaying and protection systems [1]. Steady state fault current contribution of synchronous machines depends on whether subtransient, transient or steady state synchronous impedance is considered. By contrast, inverter-connected generation behaves as a controllable current source. Fault current contributions of inverters are limited by the converter rating and depend on the control strategy ([2], [3]). Fault current contribution of type 4 wind generators mainly depends on the residual voltage and the control strategy including the fault ride through (FRT) operation mode. Maximum current typically lies around 1.1 to 1.5 *pu* ([4], [5]).

In steady-state, inverter-connected generation is typically represented by either a negative load or a generator. The constant admittance load representation used for steady state fault current calculations makes the load current voltage dependent and fails therefore to represent current limiting functionality of inverters. Generator representation makes use of Norton equivalents of generators during faults, which is a reasonable representation for synchronous generators but also fails to reflect the current limiting functionality. Unlike other commercial software packages [6], PSS/e does currently not include the current limiting functionality for steady state short circuit analysis of inverter-connected generation. Steady state fault current contribution could be iteratively computed if current limitations of inverter-connected generation are considered ([4], [10]-[13]). In [7], a method is proposed that iteratively adjusts generator's stator impedance such that the generator's stator current is equal to the reference currents under fault. Typically, type 4 wind generators quickly reach the maximum current during short-circuits (around 50ms depending on the speed of the current control loop). Whereas reference [7] focused on type 4 full-converter wind generators, an iterative method not only for type 3 and 4 but also for type 1 and 2 generators has been presented in [8]. An equivalent Thévenin model for type 3 wind generators has been proposed in [9] to compute the magnitude of the short-circuit current generated by wind farms. In [10], an iterative procedure somewhat similar to [7] has been presented to compute the fault current contribution of ENERCON full-converter wind generators by adjusting the internal reactance. PV plants or BESS behave like type 4 wind generators.

This paper presents a new method to model and implement steady state fault current contribution of inverter-connected generation in PSS/e without using iterative approaches. The proposed method is based on the representation of generators by the Norton equivalent, used in PSS/e for switching studies (such as faults). Whereas the equivalent current source of the Norton equivalent is supposed to be a constant current source, the paralleled equivalent admittance draws current as a function of the voltage. Software packages such as PSS/e do not allow omitting the equivalent admittance of the Norton equivalent. The method adds therefore a resonant admittance to cancel out the impact of this paralleled equivalent admittance for fault current computation. Iterative computations can thus be avoided and the implementation is as simple as adding a shunt impedance for short circuit computations. The proposed method can be extended to include low-voltage quadrature current injections (reactive power) [6].

The paper is organized as follows: section 2 presents the method for computing fault current contribution of inverter-connected generators. Section 3 illustrates the effectiveness of the proposed method for three different power systems. Section 4 concludes the paper.

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II. FAULT CURRENT CONTRIBUTION

Inverter-connected generation such as type 4 wind and PV generation or BESS behaves as a controllable current source during faults. Inverter-connected generators are usually required to increase reactive power injection as a function of voltage, limiting active power eventually (see for example [11], where reactive power current is at least 90% of the nominal current for voltages below or equal to 0.5 *pu*). If equipped with voltage controllers with proportional gains (see [12]), nominal current could be reached even for voltages around 0.8 *pu*. Typically, inverter-connected generators quickly reach the maximum current limit for close faults. This section shows that iterative methods can be avoided and that fault current contribution can be directly computed in commercially available software packages.

In software packages such as PSS/e [13], inverter-connected generation is typically represented by either a negative load or an equivalent generator. Once current limits are reached during a fault, current of inverter-connected generation is voltage independent, which makes the representation of inverter-connected generation as constant admittance loads less suitable. The inverter-connected generation is therefore represented by a generator and its Thévenin equivalent as illustrated in Figure 1 a) in steady state. However, during switching events (such as faults), generators are modeled in PSS/e by their Norton equivalent as shown in Figure 1 b).

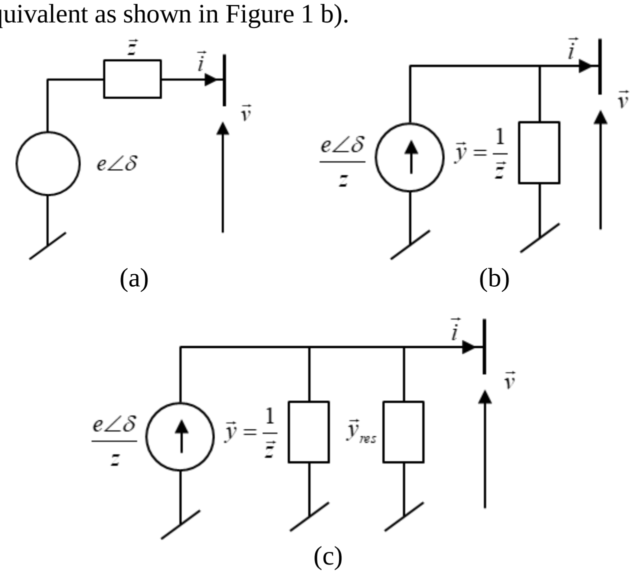

Figure 1. Generator representation in PSS/e: a) Thévenin equivalent, b) Norton equivalent, and c) proposed method.

It can be clearly seen that the Norton current source depends on the internal voltage *e*, the operating point defined by active and reactive power generation, and the stator impedance $\bar{z}$. The equivalent Norton current source $\vec{i}_{cs}$ can be written as:

$$\vec{i}_{cs} = \frac{e\angle\delta}{\bar{z}} = \frac{\vec{v}}{\bar{z}} + \left(\frac{\bar{s}}{\vec{v}}\right)^{*} \quad (1)$$

where $\bar{s}$ is the complex power. Inverter-connected generators behaving as controllable current sources are naturally represented by a Norton equivalent with zero admittance $\bar{y}$ (i.e., $\vec{i} = \vec{i}_{cs}$). However, an infinite impedance $\bar{z}$, leading to a zero admittance, would also annul the Norton current source in Figure 1 b). If voltage controllers of inverter-connected generation saturate during faults and according to the prioritization of active or reactive power in the control strategy, the equivalent Norton current source $\vec{i}_{cs}$ is at most equal to the maximum current $i_{cs,max}$. Under given pre-fault conditions, the impedance $\bar{z}$ can then be determined such that the Norton current source is equal to $\vec{i}_{cs,\max}$. From equation (1) and by acknowledging that maximum current $\vec{i}_{cs,\max}$ has both magnitude and phase according to the control strategy, the impedance can be computed as follows:

$$\bar{z} = \frac{v^2}{\vec{v}^{*} \cdot \vec{i}_{cs,\max} - \bar{s}^{*}} \quad (2)$$

Equation (2) takes into account the pre-fault operating point and the actual voltage. Under classical short circuit assumptions, voltage magnitudes are equal to unity and the pre-fault operating point is neglected ($\bar{s}$ =0), implying that the impedance is equal to inverse of the maximum current. If maximum current was equal to 1 *pu*, then magnitude of the impedance $\bar{z}$ should be 1 *pu*. According to Figure 1 b), the total current is the sum of the Norton current source and the current flowing through the parallel admittance $\bar{y}$:

$$\vec{i} = \frac{\vec{v}}{\bar{z}} + \vec{i}_{cs} \quad (3)$$

To cancel the current contribution through the admittance, a resonant admittance $\bar{y}_{res}$ should be connected in parallel as shown in Figure 1 c). The resonant admittance is given by equation (4):

$$\bar{y}_{res} = -\bar{y} = -\frac{1}{\bar{z}} \quad (4)$$

If the impedance $\bar{z}$ complies with equation (2) and the resonant admittance given by equation (4) is connected, a total current $\vec{i}$ equal to the Norton current source $\vec{i}_{cs,\max}$ is obtained. The resonant admittance is necessary since otherwise the current $\vec{i}$ flowing out of the inverter-connected generator is different from $\vec{i}_{cs,\max}$, the current actually imposed by the current limiting functionality of the inverter. Note that the resonant admittance is only connected during switching events but not in steady state, which can be easily implemented and automated in PSS/e.

III. APPLICATION

The proposed method to compute the fault current contributions of inverter-connected generators is applied to three systems of different size and features and increasing complexity. The first system is a very simple test system consisting of two generators connected through a line. The second system corresponds to a PV plant. Finally, the third system corresponds to one of the isolated power systems of the Canary Islands. The impact of high penetration of inverter-connected generation is also studied for this isolated power system. All three systems are modelled in PSS/e [13].

A. Simple test system

Figure 2 shows the single line diagram of the test system. The line has been assumed lossless. Generator 1, representing the bulk grid, is the swing bus. Initially, generator 2 produces 80 MW and 0 Mvar. A three-phase short-circuit is applied at bus 1.

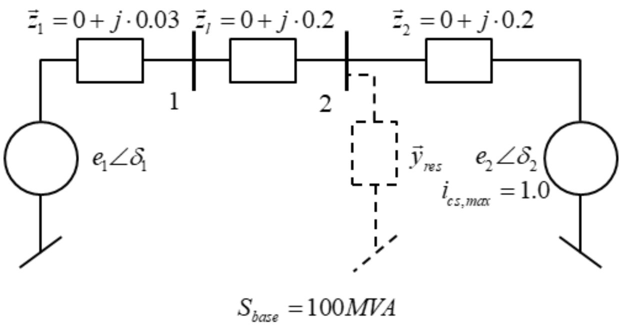

Figure 2. Single line diagram of the simple test system.

Under classical short circuit assumptions and when modeling both sources as synchronous generators with initial values of the impedance $\vec{z}$ as shown in Figure 2, fault currents provided by generator 1 and generator 2 are 33.33 and 2.5 *pu*, respectively. Now suppose generator 2 is an inverter-connected generator. By assuming nominal reactive power current injection during the fault, the impedance of generator 2 making its Norton current source equal to 1 *pu* can be calculated by using equation (2):

$$\bar{z}_2 = \frac{v^2}{v\cdot j\cdot 1 - p} = 0.78\angle -128.7^{o} \quad (5)$$

The resonant susceptance is then:

$$\bar{y}_{res} = -\frac{1}{\bar{z}_2} = 1.28\angle -51.3^{o} \quad (6)$$

By omitting initial loading as under classical short-circuit assumptions, x_2 and congruently b_{res} become 1 *pu* and -1 *pu*, respectively. Adding the resonant susceptance could be done by adding a fixed shunt of b_{res} in PSS/e as depicted in Figure 2. Now, fault contribution of generator 1 is still 33.33 *pu*, but fault contribution of generator 2 is 1 *pu*. For the given fault, the same result could have been obtained by setting x_2 to 0.8 *pu*, but this solution would only be valid for the fault at bus 1 and not for a fault at bus 2 for example. In case of a fault at bus 2 and in order to limit current to its nominal value, x_2 should be equal 1.0 *pu*.

B. PV plant

The proposed method is now applied to a PV plant. The PV plant consists of 16 three-phase PV inverters of 400 V and 0.525 MVA each. Figure 3 shows a single line diagram of the PV plant. Each inverter is connected to the 33 kV PV plant network through a step-up transformer. The PV plant network itself is connected through a transformer to the 132 kV grid, represented by an equivalent generator.

Three-phase solid short-circuits at buses 1000 and 1001 have been consecutively simulated by using the proposed method for computing the fault contribution of the PV inverters directly. Buses 1000 and 1001 are at the beginning and at the end of the two feeders of the PV plant of Figure 3. Fault currents amount to 30.85 and 28.53 *pu* (on a 100 MVA basis). Figure 4 shows the MV-side transformer currents, whereas Figure 5 shows the bus voltage magnitude at the PV inverter terminals for the two faults. It can be easily seen that PV inverters inject nominal current (9.2 A at MV-side). Voltage profile in Figure 5 shows voltage deviations above 0.8 *pu*, for which reactive current set point will reach 1 *pu*. Despite the voltage profile, PV inverter inject rated current. The obtained results confirm the accuracy of the proposed approach.

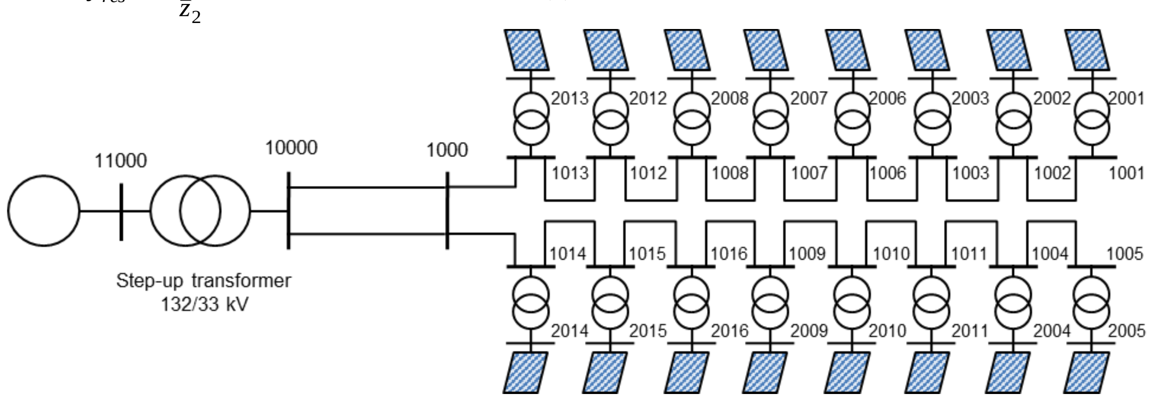

Figure 3. Single line diagram of the PV plant.

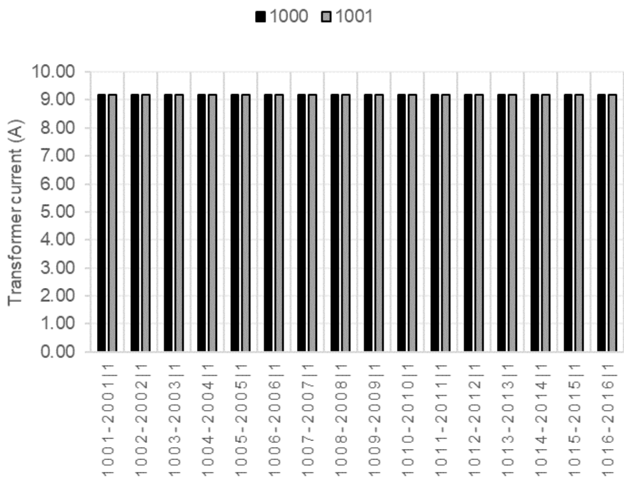

Figure 4. MV-side transformer current for faults at buses 1000 and 1001.

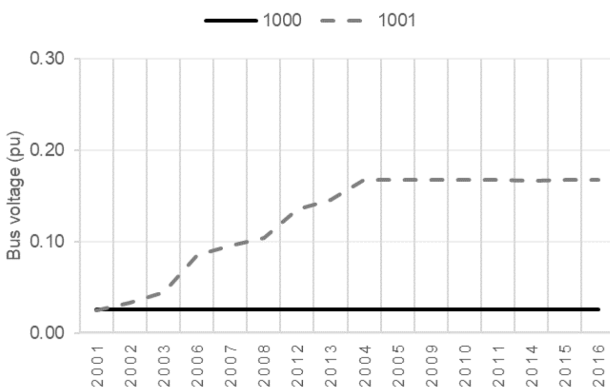

Figure 5. Voltage profile at the PV inverter terminals for faults at buses 1000 and 1001.

C. Isolated power system of the Canary Islands

The proposed method is finally applied to one of the isolated power systems of the Canary Islands. Peak demand of this power system is around 550 MW. Current installed capacity of PV and wind generation amounts to 107 MW and 35 MW, respectively [15]. It is expected that another 200 MW of wind power generation will be installed within the coming years. New substations will be built for this purpose. Figure 6 shows a simplified single line diagram of the 220 kV transmission grid of the isolated power system, indicating where the majority of the future wind power generation will be located. Conventional power plants exist at buses 29280, 29285 and 29235. A future off-peak demand (299 MW) scenario has been considered with two different RES penetration levels of 29.7% (low-RES) and 76% (high-RES) of the demand, respectively. Note that conventional power plant at buses 29235 is not dispatched in the high-RES scenario. Wind farms and PV plants have been represented by equivalent inverter-connected generators.

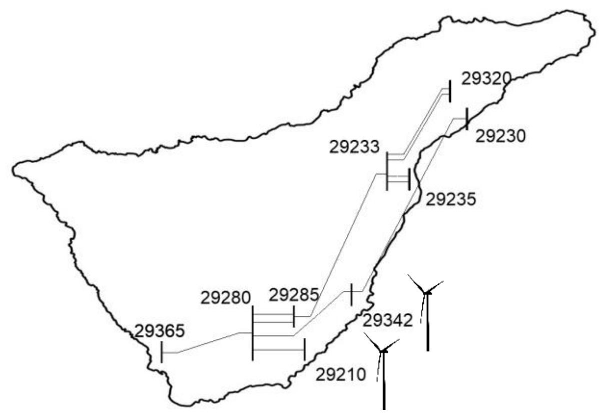

Figure 6. Simplified single line diagram of the transmission grid of the isolated power system (source: [14]).

For both RES penetration scenarios, solid three phase short circuits at each 220 kV bus have been simulated. Figure 7 shows the fault currents at the 220 kV buses in *pu* on a 100 MVA system basis. Fault currents decrease with decreasing presence of conventional generators, i.e., short circuit power decreases. However, short circuit power is still sufficiently high to detect a fault in the transmission grid. This is due to the fact that although each inverter-connected generator injects about nominal reactive current, the total inverter-connected generation produces still a large current.

Figure 8 shows the voltages at 66 kV buses of selected equivalent inverter-connected generators for both the high and low RES penetration scenario when considering faults at 220 kV buses 2965 and 29320. Voltages at 66 kV buses are below 0.4 *pu* in both scenarios, although the high RES penetration scenarios leads to lower voltages due to the lower fault currents in the grid as indicated in Figure 7. Such low voltages lead to rated current injection of the inverter-connected generation. The decreasing trend in voltages with increasing RES penetration might impede proper operation of distance relays, when these voltages become extremely low, since distance functions require a finite amount of voltage [16]. Similarly, a finite amount of currents is needed.

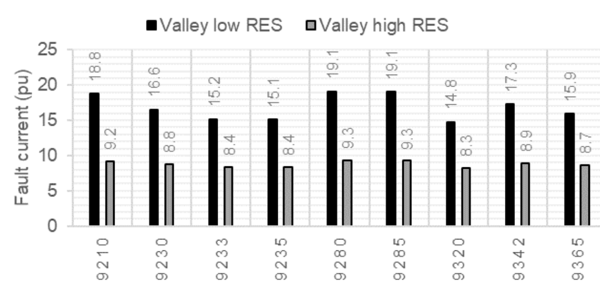

Figure 7. Fault currents in pu on a 100 MVA system basis.

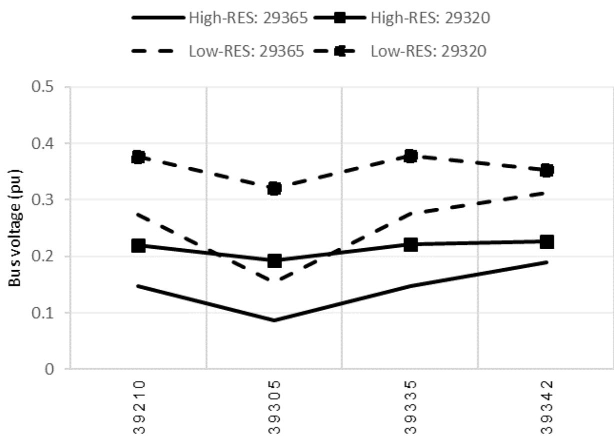

Figure 8. Voltage at 66 kV buses of selected inverter-connected generators for faults at 220 kV buses 29365 and 29320 in both penetration scenarios.

Finally, the impact of increasing RES penetration on distance relaying is analyzed. Figure 9 magnifies the 220 kV grid around bus 29280. A fault at 20% of the line between buses 29342 and 29280 is simulated. Figure 9 also shows the relay locations and indicates zone 1 and zone 2 relays (RZ1, RZ2) for this fault.

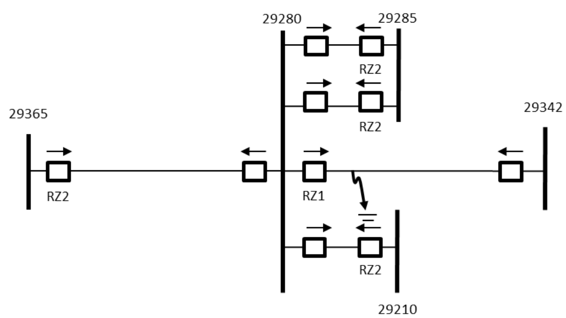

Figure 9.- Magnification of the 220 kV grid around bus 29280 with a fault on the line between 220 kV buses 29342 and 29280.

Figure 10 shows the impedance magnitude as measured by zone 1 and zone 2 distance relays. Impedances measured at bus 29285 vary significantly for the two considered scenarios, being higher for the high RES penetration scenario. The measured impedance basically increases because less current flows through the line between buses 29285 and 29280 and into the fault. This is due to the fact that less synchronous generation is available at bus 29233. In other words, both dispatch variation due to the increased RES penetration and the limited current injection capability of inverter-connected generation amplifies the infeed effect of distance relaying under the considered fault.

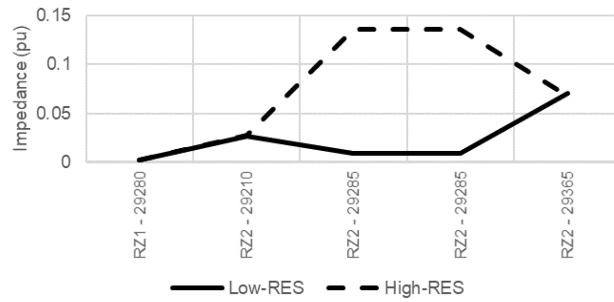

Figure 10. Magnitude of the impedance as measured by a distance relay for a fault at the 220 kV bus 29365 in both penetration scenarios.

IV. Conclusions

This paper has presented a new method to model the steady state fault current contribution of inverter-connected generation such as type 4 wind and PV generators during three-phase short-circuits in PSS/e. The proposed method is based on the Norton equivalent of the generators and can be applied to other software packages. It basically adds a resonant admittance to cancel out the impact of the equivalent admittance for fault current computation. The proposed method has been implemented in PSS/e, which does consider current limiting functionality of inverter-connected generation in steady state short circuit analysis. The main advantages of this method are that it avoids iterative computations and that its implementation is as simple as adding a shunt impedance. Further, the computation of the resonant admittance only depends on the operation point but not on the fault location, i.e., the same setup is valid for the computation of different faults at different locations. In other words, the method is simple and effective. The proposed method has been firstly applied to a simple system and later to two real systems: a PV plant and a Spanish isolated power system. These examples showcase the accuracy of the proposed approach. The application to the isolated power system has further shown how RES penetration reduces fault currents and thus short circuit power and how distance relaying is affected by the growing presence of inverter-connected generation.

V. References

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