

Modeling of steady state fault current contribution of inverter-connected generation

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Abstract

This paper presents 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. The proposed method is based on the Norton equivalent of the generators. The method basically adds a resonant admittance to cancel out the impact of the equivalent admittance for fault current computation. This way, iterative computations are avoided. The proposed method is simple to implement and it has been successfully applied to a simple and a real system consisting of planned wind farm on the Canary Islands.

1 Introduction

Short circuits should be studied both during planning and operation of electric networks. 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 for instance depends on the residual voltage, the reactive and active power output, the wind speed, and the control strategy including the fault ride through (FRT) operation mode. FRT mode is activated once the fault has been detected, occurring within 1 to 2 grid cycles. Further, state-of-the-art type 4 wind generators only inject symmetrical current under balanced or unbalanced faults [4]. In case of multiple stages of generators connected tandem to a common inverter, the inverter output will depend on the number of connected generators, which in turn is function of the wind speed [4]. Currently, steady state fault current contribution must be iteratively computed in software packages such as PSS/e or PowerFactory if current limitations of inverter-connected generation are considered [4]. In fact, conventional steady state fault current calculations are based on Thévenin equivalents of generators, which is a reasonable representation for synchronous generators but fails to reflect the current limiting functionality of inverters. In [5], 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 [5] 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 [6]. An equivalent Thévenin model for type 3 wind generators has been proposed in [7] to compute the magnitude of the short-circuit current generated by wind farms. In [8], an iterative procedure somewhat similar to [5] has been presented to compute the fault current

contribution of ENERCON full-converter wind generators by adjusting the internal reactance. It seems that already the first iteration yields to acceptable results. PV plants behave like type 4 wind generators.

This paper presents a new method to model the steady state fault current of inverter-connected generation such as type 4 wind and PV generators contribution during three-phase short-circuits. During faults, grid codes usually require the inverter-connected generation to inject reactive power as a function of the voltage. For rather severe faults, voltage controllers saturate and maximum reactive power is injected. Further, reactive power is usually prioritized over active power in case current reaches its limit. The proposed method is based on the Norton equivalent of the generators. Whereas the equivalent current source is supposed to be a constant current source, the paralleled equivalent admittance draws current as a function of the voltage. The method basically adds a resonant admittance to cancel out the impact of this equivalent admittance for fault current computation. Iterative computations can thus be avoided and the implementation is as simple as adding a shunt impedance in standard software packages.

The paper is organized as follows: the method for computing fault current contribution of inverter-connected generators is presented first. Subsequently, two examples illustrate the effectiveness of the proposed method.

2 Fault current contribution

Inverter-connected generation such as type 4 wind and PV generation behaves as a controllable current source. Typically, inverter-connected generators quickly reach the maximum current during short-circuits. For type 4 wind or PV generators it is however possible to avoid iterative methods and to compute the fault current contribution directly.

In software packages such as PSS/e [9], type 4 generators can be represented by their Thévenin equivalent as illustrated in Figure 1 a)¹. However, during switching events (such as faults), generators are modeled by their Norton equivalent as shown in Figure 1 b).

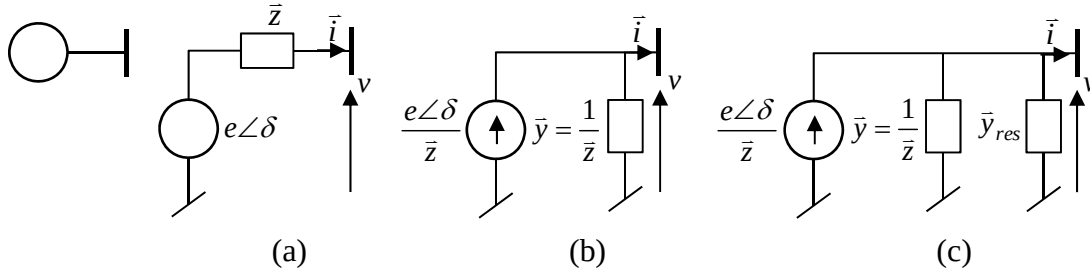


Figure 1: Generator representation: a) Thévenin equivalent, b) Norton equivalent, and c) proposed method.

It can be clearly seen that the Norton current source depends on the internal voltage e and the stator impedance $\bar{z}$. The internal voltage is given by:

$$\begin{aligned} e\angle\delta &= v + \bar{z} \cdot \bar{i} \\ &= v + \bar{z} \cdot \frac{\bar{s}^*}{v} \quad (1) \end{aligned}$$

¹ Alternatively, it has been a common practice to represent wind and PV generation as negative loads. Such modeling does however not allow for representing fault current contribution by these kind of generation.

where v is the generator voltage, $\bar{s}$ the apparent power and $\bar{i}$ the current. The equivalent Norton current source $\bar{i}_{cs}$ can then be written as:

$$\bar{i}_{cs} = \frac{e \angle \delta}{\bar{z}} = \frac{v}{\bar{z}} + \frac{\bar{s}^*}{v} \quad (2)$$

Inverter-connected generators behaving as controllable current sources are naturally represented by a Norton equivalent. During faults, voltage controllers usually saturate and according to the prioritization of active or reactive power in the control strategy, this current is at most equal to the maximum current $i_{cs,max}$ (typically between 1.1 and 1.5 pu ([4], [10])):

$$i_{cs,max} = \left| \frac{v}{\bar{z}} + \frac{\bar{s}^*}{v} \right| \quad (3)$$

Equation (3) however only provides the magnitude of the maximum current and thus of the impedance. Note that inverter-connected generators might set reactive current set points according to a proportional control where the input is the voltage deviation with respect to a reference voltage v^{ref} as shown in equation (4) [11].

$$i_q^* = K \cdot (v^{ref} - v) \quad (4)$$

Typically, the proportional gain K is between 5 and 20 pu; congruently, voltage deviations between 0.05 and 0.2 pu might lead to nominal reactive current set point. Further, inverter-connected generators are usually required to increase reactive power injection during faults, limiting active power eventually (see for example [12], where reactive power current is at least 90% of the nominal current for voltages below or equal to 0.5 pu). Manufacturers sometimes provides such low voltage-current characteristics [4]. From equation (2) and by acknowledging that maximum current $\bar{i}_{cs,max}$ has both magnitude and phase according to the control strategy, the impedance can be defined as in equation (5):

$$\bar{z} = \frac{v^2}{v \cdot \bar{i}_{cs,max} - \bar{s}^*} \quad (5)$$

Equation (5) allows determining the impedance guaranteeing that the current is at most $\bar{i}_{cs,max}$. Under classical fault current calculation assumptions, generators work under no load conditions and if maximum current is a purely reactive power current, the reactance x of the impedance $\bar{z}$ becomes:

$$x = \frac{v}{i_{cs,max}} \quad (6)$$

According to Figure 1, the total current is the sum of the Norton current source and the current flowing through the parallel admittance $\bar{y}$. To cancel the current contribution through the admittance, a resonant admittance y_{res} should be connected in parallel as shown in Figure 1 c). The resonant admittance is given by equation (7):

$$\bar{y}_{res} = -\bar{y} = -\frac{1}{\bar{z}} \quad (7)$$

which results in a total current equal to the Norton current source. The resonant admittance is necessary since otherwise the current $\bar{i}$ flowing out of the inverter-connected generator is different from $\bar{i}_{cs,max}$, the current actually imposed by the current limiting functionality of the inverter.

3 Application

The proposed method to compute the fault current contributions of inverter-connected generators is applied to two systems of different size and features. The first system is a very simple test system consisting of two generators connected through a line. The second system corresponds to a wind farm on the Canary Islands under construction. Both systems are modelled in PSS/e [9].

3.1 Simple test system

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

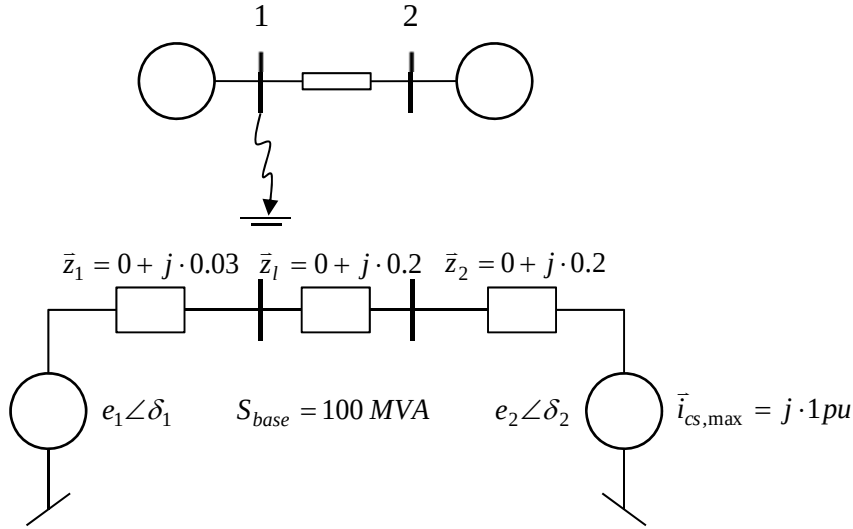


Figure 2: Single line diagram of the simple test system.

If line was lossless, fault contribution from generator 1 is 33.41 pu and fault contribution from generator 2 is 2.56 pu when modeling both sources as synchronous generators and considering the pre-fault loading conditions. Under classical short circuit assumptions, fault currents are 33.33 and 2.5 pu, respectively. However, if generator 2 was an inverter-connected generator, the obtained result would be misleading since such kind of generation can only provide a current of up to 1.5 pu.

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 (5):

$$\bar{z}_2 = \frac{v^2}{v \cdot j \cdot 1 - p} = 0.78 \angle -128.7^\circ \quad (8)$$

The resonant susceptance is then:

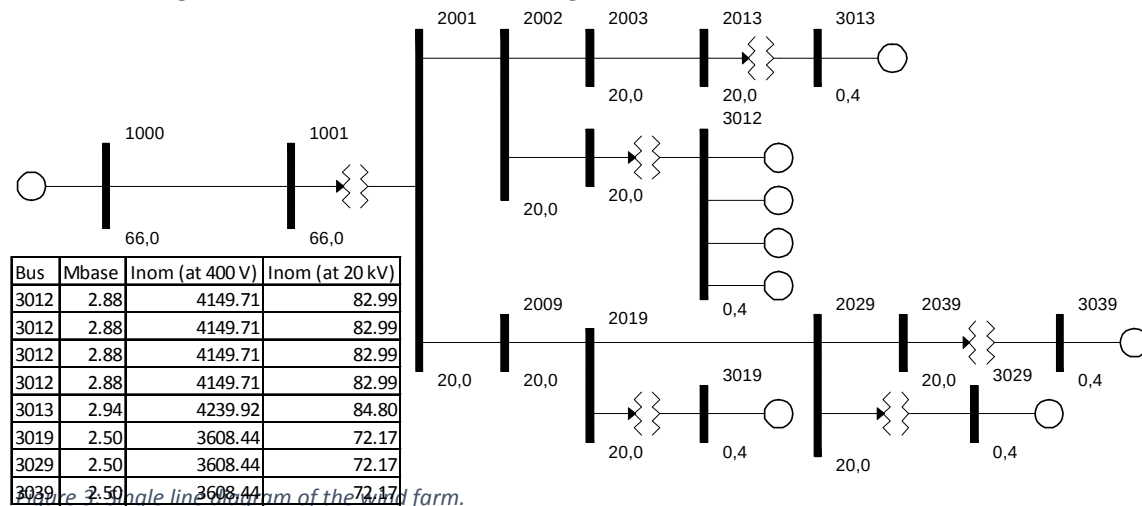
$$\bar{y}_{res} = -\frac{1}{\bar{z}_2} = 1.28 \angle -51.3^\circ \quad (9)$$

Note that for example PSS/e reads the resonant susceptance in Mvar and conversion to the actual susceptance is based upon the actual bus voltage magnitude. Further, if no load conditions are supposed, 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 $S_{base} \cdot b_{res}$ Mvar (= 100 Mvar). Now, if generator 2 was a type 4 wind generator and under classical short circuit assumptions,

fault contribution of generator 1 is still 33.33 pu , but fault contribution of generator 2 is now 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.

3.2 Wind farm on the Canary Islands

The proposed method is now applied to a wind farm on the Canary Islands. The wind farm consists of 26 type 4 wind generators and its installed capacity amounts to 59.25 MW. Figure 3 shows a single line diagram of two of the nine feeders. Each of the wind generator of 400V is connected to the 20 kV wind farm network, which is connected through a transformer to the 66 kV grid. Machine rating and rated current at both the LV and MV side of the step-up transformer of each wind generator are also indicated in Figure 3.



Three-phase solid short-circuits at buses 2001 and 2003 have been consecutively simulated by using the proposed method for computing the fault contribution of the wind generators directly. Figure 4 shows the line currents, whereas Figure 5 shows the bus voltage magnitude. It can be easily seen for lines 2029-2039 and 2003-2013 that wind generators at buses 2039 and 2013 inject nominal current (72.2 and 84.8 A at MV side, respectively). The line 2009-2019 should carry three times 72.17 A (equal to 216.51 A), which can be confirmed in Figure 4.

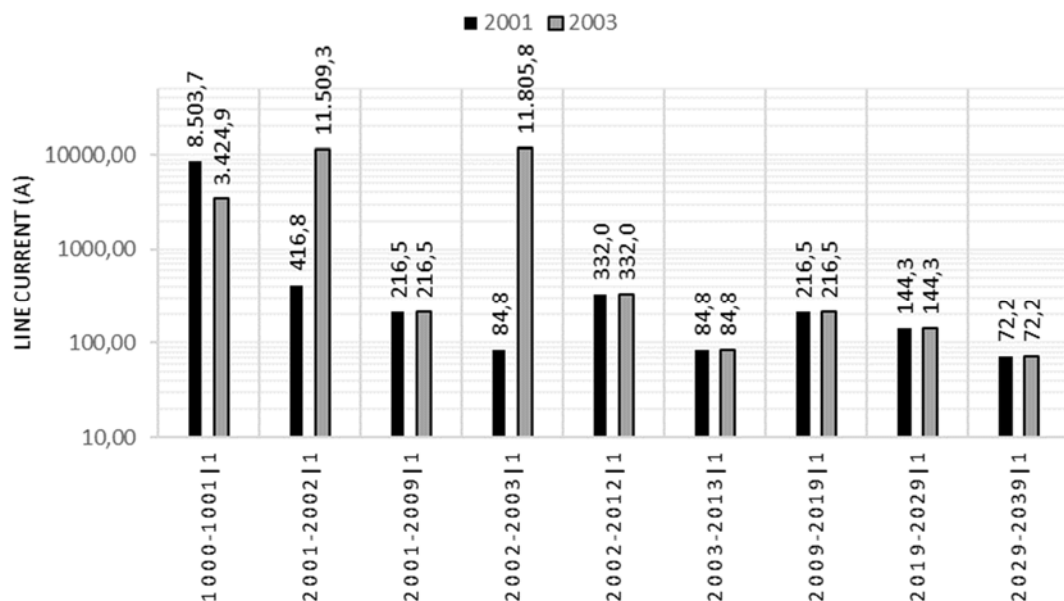


Figure 4: Line current for faults at buses 2001 and 2003.

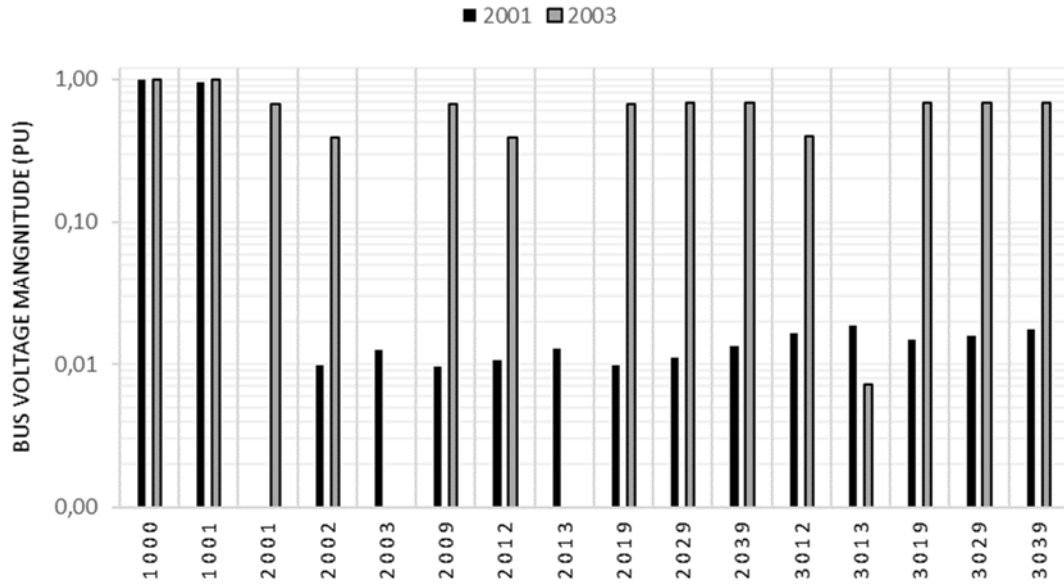


Figure 5: Voltage profile for faults at buses 2001 and 2003.

Voltage profile in Figure 5 shows voltage deviations above 0.3 pu, for which for instance voltage controllers with proportional gains higher than 5 pu will make the reactive current set point equal to 1 pu. In these cases, the wind generator will inject nominal current providing reactive power only.

4 Conclusions

This paper has presented a new method to model the fault current contribution of inverter-connected generation such as type 4 wind and PV generators during three-phase short-circuits. The proposed method is based on the Norton equivalent of the generators. It basically adds a resonant admittance to cancel out the impact of the equivalent admittance for fault current computation. The proposed method has been successfully applied to a simple and a real system. The main advantages of this method is that it avoids iterative computations and that its implementation is as simple as a shunt impedance in standard software packages. Further, the computation of the resonant admittance only depends on the operation point but not on the fault location. However, asymmetrical faults have not been contemplated, but the proposed method could be extended to asymmetrical faults as long as this kind of generation only injects symmetrical currents. Further, optimistic results will be obtained if voltage deviations are small since inverter current will not necessarily saturate.

5 References

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