Transformer Based Voltage Sag Generator to test Renewable Energy Systems during Grid Faults in the Laboratory

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Abstract
A transformer based voltage sag generator to test renewable energy systems is presented. Design considerations concerning overvoltages and overcurrents during switching action are addressed. Measurement results of a 30 kW laboratory prototype testing a line side PWM converter and a DFIG are presented. Both measurement results for investigations on the transformer based sag generator at the line side converter and the DFIG show the superb functionality of the sag generator. Voltage dips of variable depth, duration time and fault type can be generated without overvoltages or voltage interruptions.

1 Introduction
With the increased amount of installed wind power transmission system operators are forced to tighten their grid connection requirements to guarantee a stable and safe operation of the energy network. A detailed review of international grid code requirements can be found in [1]. A fault ride through of voltage dips for renewable energy systems (RES) is required in the grid codes and in international standards as [2]. For research and development of RES voltage sag generators are needed to test the systems under defined, repeatable voltage sags of different voltage depth, fault duration and fault type. There are four main solutions to build a voltage sag generator, which are generator based [3], shunt impedance based [4], [5], transformer based [6], [7], [8] or full converter based as described in [9], [10], and [11]. In this paper design and testing of a 30 kW transformer-based voltage sag generator are described. It is easy to build in a laboratory and suitable to test renewable energy systems during voltage dips of variable depth, duration time and fault type. The paper is structured as follows. In section 2 requirements for renewable energy systems are highlighted concentrating on voltage dips. Section 3 gives an overview on four different solutions to realize a voltage sag generator. In section 4 the experimental setup of a 30 kW transformer based voltage sag generator prototype is described. Design issues concerning overvoltages and overcurrents are addressed. The laboratory equipment consisting of a line side PWM converter and a 22 kW doubly-fed induction generator (DFIG) that are tested by the sag generator are described in this section as well. Finally, in section 5 measurement results for the sag generator testing the line side converter and the DFIG are shown. A conclusion closes the paper.

2 Requirements for renewable energy systems
Renewable energy systems have to fulfill international standards and grid codes to be connected to the energy network. Grid codes for wind turbines cover the steady state and transient state operation
as well as the communication and power dispatch. In steady state operation the wind turbine must provide active power to stabilize the grid frequency and reactive power to perform a grid voltage control. The main dynamic requirements concern the fault ride through capability of wind turbines. Transmission system operators have specified their recent requirements, so that wind turbines must offer ride through capability under abnormal conditions. Instead of disconnecting from the grid the turbines have to stay connected and supply reactive power to the grid continuously to support the voltage level. One Low Voltage Ride Through requirement from the german transmission code is shown in Fig. 1. A detailed review on international grid code requirements can be found in [1].

The International Electrotechnical Commission (IEC) developed and released the IEC-standard 61400-21 for testing and assessing power quality characteristics of grid-connected wind energy converters [2]. The standard stipulates the measurement of the turbine electrical behaviour under symmetrical three phase and asymmetrical 2 phase voltage dips of different amplitudes (90 %, 50 % and 20 %) and duration (0, 2 ms to 0, 5 ms).

However, to predict the behavior of renewable energy systems under voltage dips and to fulfill international standards like the IEC 61400-21, voltage dip generators are needed.

3 Overview on voltage sag generators

In summary there are four different types of voltage dip generators, which are 1) generator based, 2) shunt impedance based, 3) transformer based and 4) full converter based. An overview on the four voltage sag generator types is shown in Fig. 2.

![Figure 2: Overview on the four different types of voltage sag generators](image)

Figure 1: LVRT in german VDN Transmission Code
3.1 Generator based voltage sag generators

In [3] a diesel powered 15 kW synchronous generator is presented as sag generator for testing electrical equipment. The synchronous generator has been modified to give controlled symmetrical voltage sags by changing the field excitation. The hardware expense is high due to the weight and scale of the diesel engine and the synchronous generator. Only symmetrical voltage sags can be emulated with this topology. Field tests show symmetrical voltage sags with a rather slow decrease of voltage within several grid periods. To emulate more realistic transient grid faults symmetrical and asymmetrical 1- and 2-phase dips or even phase voltage shifts and harmonics as well as a more dynamic decrease in the voltage within milliseconds is desirable.

3.2 Shunt impedance based voltage sag generators

A voltage dip can also be created by switching an impedance in parallel to the line. The current flow in the additional path causes a voltage drop across the impedance, that leads to the voltage dip. In [4] a thyristor controlled reactance consisting of an inductance, a bidirectional thyristor and a step-down transformer is presented. The step-down transformer is used to reduce the voltage rating of the thyristors. The current through the impedance, and though the voltage dip depth, can be controlled by the method of firing delay angle control. This kind of control causes significant undesired harmonics that must be reduced by additional harmonic filters, increasing the hardware expense of the system. A voltage sag generator consisting of one shunt and one series impedance to test wind turbines up to the 5 MW range is presented in [5]. The shunt impedance is used to decrease the line voltage while the series impedance immunizes the grid from the fault. The depth of the voltage dip can be adjusted by changing the value of the impedance. Though an impedance bank is necessary. A switch to connect the line directly to ground is included to produce voltage dips down to 0 % voltage. Summarizing the shunt impedance voltage sag generator solution allows the generation of one to three phase voltage sags of variable depth. No controllable generation of harmonics is possible. For the thyristor controlled reactor solution the undesired harmonics must be reduced by filters.

3.3 Transformer based voltage sag generators

A transformer in combination with appropriate switching devices can also be used to generate different voltage sags. The switch changes the output voltage from nominal to sag voltage by connecting another transformer output level to the load. In [6] a low cost single phase transformer-based voltage sag generator as laboratory prototype is presented. In [7] three single phase variacs with adjustable output voltage are used to generate symmetrical and unsymmetrical voltage dips. The duration of the voltage decrease is approximately 100 milliseconds which is a rather slow performance for a voltage dip. Thus, a step transformer combined with switches should be used to generate dynamic, transient voltage dips. The transformer based solution is suitable for building a low cost laboratory type voltage sag generator because standard components like a step transformer and power electronic switching devices as well as a simple control scheme can be used and the grid perturbation like harmonics or overcurrents is low.

3.4 Full converter based voltage sag generator

A fourth solution to build a voltage sag generator is a full converter setup. A back-to-back converter is connected in between the grid and the load. By controlling the load-side output voltage all kinds of grid faults can be emulated. In [9], [10], and [11] such devices are described. The hardware is expensive and the control algorithm is complicated compared to the other sag generator solutions. A comparison between a full converter based and a transformer based sag generator can be found in [8]. It is concluded, that the full converter setup is powerful in creating all kinds of grid faults,
but due to the disadvantages of the complex control, high cost and less reliability due to the limited overvoltage and overcurrent capabilities of the IGBT’s the transformer based sag generator with bidirectional switches is the preferred solution for laboratory type application. A series connected FACTS (flexible AC transmission system) converter also known as dynamic voltage restorer is normally used to mitigate voltage dips in power systems. By generating an appropriate voltage this device can also be used to generate voltage sags and swells. Note, that as a fifth class of voltage sag generators a waveform generator can also be used to create output voltages with desirable characteristics as varying magnitude, frequency, duration and harmonics but they are not available or very expensive in the comparable power rating of renewable energy systems and thus not included here.

4 Experimental setup design and description

4.1 Transformer based voltage sag generator

According to the advantages of the transformer based voltage sag generator topology highlighted in the previous section, such as simple realization and relative low cost a 30 kW laboratory type sag generator was built and is described in this section. The one phase equivalent circuit is shown in Fig. 3.

![Figure 3: One phase equivalent of transformer based voltage sag generator topology](image)

A 30 kW 3-phase delta-star connected, variable ratio, isolating transformer (primary side: $V_N = 400 V/ I = 43 A$) was used that allows the adjustment of five different output voltages which are 12.5 %$V_N = 50 V$, 37.5 %$V_N = 150 V$, 62.5 %$V_N = 250 V$, 80 %$V_N = 320 V$ and 100 %$V_N = 400 V$. By using appropriate switching devices a voltage dip can be emulated by switching another output level to the load by switching on switch 2 and switching off switch 1 (see Fig. 3). To conduct current in both directions bidirectional switches have to be chosen. There are three different possibilities to realize a switch as described in [8], which are a relay, bidirectional thyristors or bidirectional IGBT’s. A high power rating can be achieved using a relay but due to the inherent physical conditions it is difficult to control precisely the action time of the relay which will cause short-term voltage interruptions and high peak voltages, which is unfavorable when testing sensible electronic equipment precisely. Compared to a relay, a bidirectional switch composed of thyristors has many advantages such as fast switch speed, noise-free action, no spark, long life, vibration resistance and high reliability. But the thyristor is a half-controlled device and switching can only occur at the zero-crossing point of the current. Thus, for a three phase system two- or three-phase-faults will not occur simultaneously. This problem can be solved using full-controllable IGBT switches in bidirectional topology that allow fast turn-on and turn-off and precise phase control of one- to three-phase voltage sags. In the laboratory prototype twelve (four per phase) Toshiba MG500Q1US1 devices are used that have a maximum rating of $V_{CE} = 1200 V$ and $I_C = 500 A$, which is quite overrated for the 30kW power rating of the sag generator but eventually occurring peak voltages or currents can be studied safely. The voltage sag duration and the gate signals for switch 1 and 2 are emulated by an ATMEL 8 bit microcontroller. Simultaneous switching from switch 1 to switch 2 must be avoided due to the short circuit peak current in the IGBT’s. Thus, switch 2 is turned on after a given delay time. The delay time must be designed precisely to avoid overcurrents. In the laboratory setup it was designed experimentally. An overvoltage at the output of the transformer can be caused by switching off large
load currents if the load contains inductances like machines that have an inductive characteristic or converters that are typically connected by line filters to the grid. To avoid a fast decrease of the current \( \frac{dI}{dt} \) slow switching of the IGBT’s was implemented by choosing large gate series resistances. Note that during the slow switching of the device high power losses are produced that may decrease its lifetime. Thus an overrating of the power modules is necessary.

To protect the IGBT’s from overvoltages additional varistors are installed across each device. The described transformer based sag generator was built in the laboratory and shown in Fig. 4.

Figure 4: Picture of transformer based voltage sag generator laboratory prototype

For laboratory tests it is connected to a wind energy test system comprising a 22 kW doubly-fed induction generator. The rotor of the machine is fed by a back-to-back converter via slip rings. Investigations using the sag generator have been done separately on the line side converter of the back-to-back converter and on the stator of the DFIG. Both systems are described in the following subsections.

4.2 Test devices

4.2.1 Line side converter

The experimental setup of the sag generator connected to the line side converter is shown in Fig. 5.

Figure 5: Experimental setup with sag generator connected to line side converter

The line side converter is a 2-level PWM converter with a DC link capacitance of \( C_{DC} = 8mF \). The six pack module is an Infineon BSM100GD120DN2 with a maximum rating of \( V_{CE} = 1200V \) and \( I_C = 100A \). The converter is connected to the grid by a line filter consisting of a three phase inductance of \( L = 3mH \). To control the line side converter a standard voltage oriented control with an outer DC voltage PI controller and inner PI current controllers as described in [12] is applied and implemented on a dSpace 1104 board. The DC voltage is controlled to 320 V and limited to 375 V by a DC-chopper for security reasons. Tests are performed at a line-to-line voltage of \( V_N = 160V \). The voltage level is chosen to adapt the converter to the low rotor voltages of the doubly
fed induction generator that loads the converter. For this purpose the DC link is connected to the rotor side converter of the DFIG. Experimental results are taken at a DC link power of 3 kW.

### 4.2.2 Doubly-fed induction generator (DFIG)

The experimental setup of the sag generator connected to the stator of the doubly-fed induction generator is shown in Fig. 6. The DFIG is a 22 kW machine connected via slip rings to a back-to-back converter. The line side converter is described in the previous subsection and connected to a faultless grid and not connected to the sag generator. The rotor side converter has the same topology but is controlled by a separate dSpace 1006 board. The DFIG shaft is powered by an inverter fed 18.5 kW squirrel cage induction machine (SCIM) modelling a wind turbine. The DFIG topology for wind turbine applications is described in [13] and [14], whereas the dynamic behavior of the DFIG is presented in [15] during three phase voltage dips and in [16] during asymmetrical voltage dips. Experimental results are taken at an apparent stator power of $S = 12.5$ kVA, a line-to-line stator voltage of $V_N = 400$ V and a slip of 10% subsynchronous which results in a mechanical speed of 1350 r/min.

### 5 Measurement results

Measurement results using the transformer based voltage sag generator have been performed at the research laboratory for power electronic generator systems in wind turbines described in [17]. The sag generator was tested at a 22 kW DFIG and a line side converter described in the previous section. Results are recorded using a Dewetron data acquisition device. It will be shown, that the transformer based voltage sag generator allows testing power electronic equipment under voltage sags of variable duration, amplitude and faulted line.

#### 5.1 Line side converter

The results shown in Fig. 7 - 9 show a three, two and one phase voltage sag for the duration of 200 ms. There are no voltage interruptions or spikes. The output voltage decreases from nominal voltage to sag voltage within less than one millisecond. By regulating the ratio of the transformer and controlling the IGBTs, the required voltage sag depth, duration time and fault types can be changed.

To show the reaction of the line side converter to the different voltage sags the DC link voltage and the line currents are shown as well. The active load is the rotor side of the DFIG, generating a power of 3 kW. Due to the voltage sag the power cannot be fed into the grid immediately which leads to an increasing DC voltage. The DC voltage controller adjusts the voltage by increasing the line currents. The converter is overrated, so no current limitations have to be activated. To decrease the DC voltage ripple due to the negative sequence voltage during unsymmetrical grid faults the control can be improved significantly as shown in [18] and [19] but is not scope of this paper.
5.2 Doubly-fed induction generator

Measurement results for DFIG operation under nominal and single phase 67% voltage sag are shown in Fig. 10 and 11 respectively. The three phase stator voltages, stator and rotor currents of phase a and the accordant current spectra are shown. During nominal operation the apparent power of 12.5 kVA is generated. The rotor current oscillates at 10% slip frequency. Both frequency components are shown in the lower graph. During one phase voltage dip a \((2 - s)\omega_s = 95Hz\) (as theoretically analyzed in [16]) frequency component is superimposed on the rotor current (see Fig. 11).

6 Conclusion

The design of a transformer based voltage sag generator to test renewable energy systems is described. Design considerations concerning overvoltages and overcurrents during switching action are adressed. Measurement results of a 30 kW laboratory prototype testing a line side PWM converter and a DFIG are presented. Both measurement results for investigations of the transformer based sag generator at the line side PWM converter and the DFIG show the superb fuctionality of the sag generator. Voltage dips of variable depth, duration time and fault type can be generated without overvoltages or voltage interruptions.
References


