Benchmarking of Voltage Sag Generators

Yang, Yongheng; Blaabjerg, Frede; Zou, Zhixiang

Published in:
the 38th Annual Conference of the IEEE Industrial Electronics Society

DOI (link to publication from Publisher):
10.1109/IECON.2012.6389164

Publication date:
2012

Document Version
Early version, also known as pre-print

Benchmarking of Voltage Sag Generators

Yongheng Yang, Frede Blaabjerg
Department of Energy Technology
Aalborg University
Pontoppidanstraede 101, Aalborg DK-9220, Denmark
yoy@et.aau.dk, fbl@et.aau.dk

Zhixiang Zou
School of Electrical Engineering
Southeast University
No. 2 Sipailou, Nanjing 210096, China
zou.zhixiang@seu.edu.cn

***Abstract*—The increased penetration of renewable energy systems, like photovoltaic and wind power systems, rises the concern about the power quality and stability of the utility grid. Some regulations for Low Voltage Ride-Through (LVRT) for medium voltage or high voltage applications, are coming into force to guide these grid-connected distributed power generation systems. In order to verify the response of such systems for voltage disturbance, mainly for evaluation of voltage sags/dips, a Voltage Sag Generator (VSG) is needed. This paper evaluates such sag test devices according to IEC 61000 in order to provide cheaper solutions to test against voltage sags. Simulation and experimental results demonstrate that the shunt impedance based VSG solution is the easiest and cheapest one for laboratory test applications. The back-to-back fully controlled converter based VSG is the most flexible solution for the system test under grid faults but also the most expensive one.**

I. INTRODUCTION

The highly increased penetration of renewable energy systems, especially photovoltaic (PV) systems and wind turbine (WT) power systems, stirs up research on the integration and control of such environmentally-friendly power generation units. However, it may also cause some negative impact on the power quality, stability and availability of public grids. Some national grid codes, mainly fault ride-through and grid support capabilities, have been issued by the Transmission System Operator (TSO) to regulate the distributed generations connected to medium-voltage or high-voltage networks [1]. These requirements are also expected to be updated for low-voltage level applications, because the impact of the fast growth of distributed generation systems, especially PV systems, connected to low-voltage grids can not be neglected at this level either.

It is stated in the grid codes that the grid-connected power systems should not disconnect from the grid within a certain time during voltage drops, also known as low voltage ride-through operation. The voltage profiles for the low voltage ride-through capability for wind power systems from different national grid codes can be depicted as shown in Fig. 1. The renewable generation systems must stay connected above these curves with a defined time.

The goal of these grid requirements for renewable generation systems when connected to the utility grid is to maintain the power quality and stability of the public networks. As it is mentioned above, the distributed power generation systems are required to feed reactive current into the network during

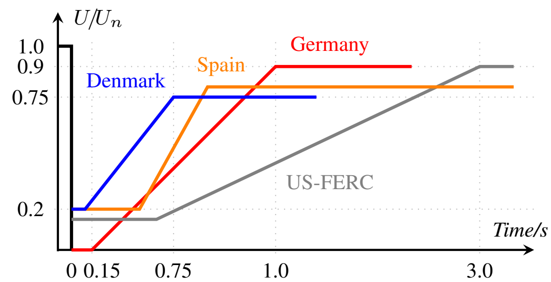


Fig. 1. Low voltage ride-through requirements of wind power systems in different countries [1].

such voltage disturbance in some cases. Many distributed power generation system models have been developed with the purpose to study the LVRT behavior and grid support capability before the approval of grid access. Normally, a grid emulator which can simulate a grid fault is needed to evaluate such kind of models in simulations or pre-tests [2]–[4].

Therefore, along with the grid requirements, it is necessary to carry out tests under standardized procedures such as IEC 61000-4-11 in order to verify a distributed generation model using specific devices [2], [3]. A simplified voltage sag test system is shown in Fig. 2. A Voltage Sag Generator (VSG) is such a device that could be used to simulate different grid faults in a laboratory or to produce voltage sags in a field-test environment. According to IEC 61000-4-11, a generic three-phase VSG should have the following functionalities:

1) produce unbalanced and balanced voltage sags,
2) control the depth and duration of such sags,
3) provide a programmable recovery voltage profile.

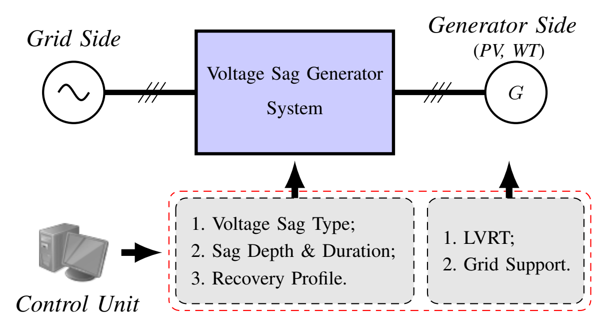


Fig. 2. Simplified voltage sag test system.

The scope of this paper is first to give a thorough description of the existing VSG topologies, followed by a discussion of bidirectional switches which are commonly used in a VSG system. With the purpose to provide cheaper solutions to test against voltage sags, the focus will be put on a comparison of these voltage sag generators based on the simulation and experimental results in terms of performance and cost. Finally, a single-phase system is demonstrated in grid faulty mode operation.

II. Voltage Sag Generator Solutions

Many voltage sag generator solutions have been reported in the literature [5]–[14]. There are mainly three different types of voltage sag generators: shunt impedance sag generator, transformer based voltage dip generator and fully controlled converter based voltage sag generator, as it is shown in Fig. 3. In the following, an overview of these sag generators will be presented. For simplicity, the voltage sag generators are described for single-phase tests in the followings.

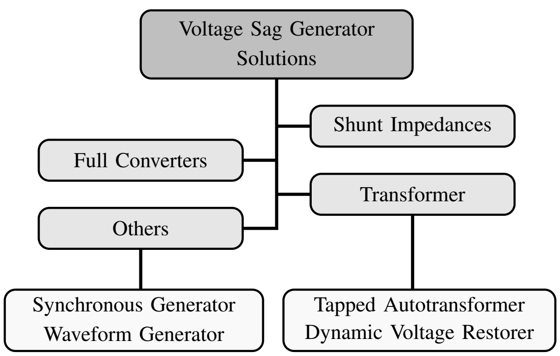


Fig. 3. Overview of voltage sag generator solutions for distributed generation systems.

A. Shunt Impedance Voltage Sag Generator- SVSG

The easiest and the most intuitive solution of a voltage sag generator is to short-circuit the grid by a shunt impedance as shown in Fig. 4. In order to generate voltage dips with different depths, a shunt impedance bank is used. The series impedance Z_s is designed to reduce the short-circuit effects on the up-stream grid [2], [3], [5].

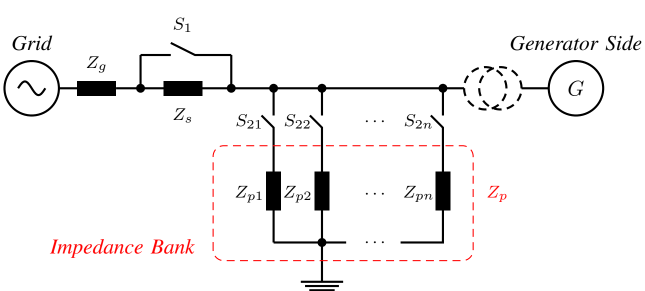


Fig. 4. Shunt impedance based voltage sag generator.

In the normal operation, the switch S_1 should be closed and the shunt switches (S_{21}, S_{22}, $\cdots$, and S_{2n}) should be open. In grid faulty mode operation, desirable voltage sags can be generated by opening the switch S_1 firstly and then switching the shunt impedances (Z_{p1}, Z_{p2}, $\cdots$, Z_{pn}), because the current flowing through the equivalent shunt impedance Z_p is changed automatically. The switching time interval up to 100 μs is acceptable [2]. A 100% voltage drop can be obtained by short-circuiting the voltage to ground directly.

According to IEC 61400-21, the size of the series impedance Z_s should be selected so that the voltage drop testing is not causing an unacceptable situation (greater than 5%) at the upstream grid [3], [5], [9]. This constraint can be expressed as:

$$|Z_s + Z_p| \geq 0.95\,|Z_s + Z_p + Z_g|, \tag{1}$$

where Z_g is the grid short-circuit impedance.

It is also pointed out in the IEC 61400-21 that the voltage sag generated by VSG is defined when the test unit (wind turbine, PV generator) is absent. Thus, the residual voltage U_{sag} can be calculated as:

$$U_{sag} = \left| \frac{Z_p}{Z_g + Z_s + Z_p} \right| U_g, \tag{2}$$

where U_g is the nominal grid voltage. The design of a voltage sag generator must comply with the above constraints. Some special requirements are also given in the grid codes, like the specification in the Spanish grid code in which the short circuit power in the test point must five times greater than the test unit rated power [5].

Due to the switching behavior, this kind of VSG may generate undesirable harmonics which means that additional filters are required. Another disadvantage of a shunt impedance based VSG is that, in three phase applications, many switching devices are needed and should be controlled in order to generate different kinds of voltage dips, which means that the control system will be more complicated. Nevertheless, this kind of voltage sag generator might be a favorable solution because the impedances and switches are readily available in a laboratory.

B. Transformer Based Voltage Sag Generator- TVSG

A combination of a step-down auto-transformer and some switches is another implementation option of a voltage sag generator. The structure of a typical transformer based VSG is shown in Fig. 5. Appropriate control sequences can be applied to the switch S_2 in order to produce a voltage sag with desirable depth. By opening the switch S_1, a 100% voltage dip is generated. The output sag voltage of the transformer based VSG can be expressed as:

$$U_{sag} = \frac{1}{n} U_g, \tag{3}$$

where n is the transformer turns ratio.

The transformer based voltage sag generators can be found in recent literature [2], [6]–[8], [10], [15]. Since an auto-transformer can be smaller, lighter and cheaper than a standard dual-winding transformer, this solution based on tapped autotransformer is very suitable for building up a low-cost laboratory VSG [8]. The ease of use (simple control) and low cost make this kind of voltage sag generator to be another highly favored one. Another advantage of the transformer based VSG is that it can limit the harmonics and inrush currents in the voltage sag recovery cases [6], [8]. However, in three-phase applications, there may be three single-phase tapped autotransformers, which makes the system bulky.

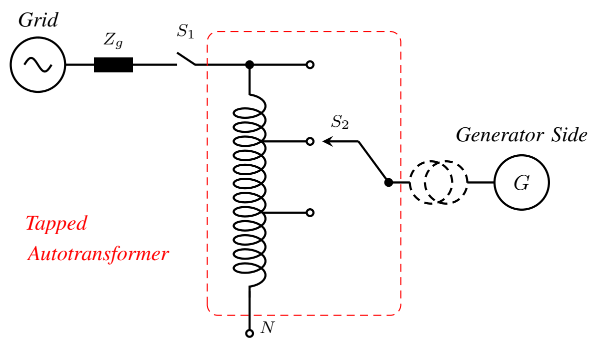


Fig. 5. Autotransformer based voltage sag generator.

It should be noted that a series connected dynamic voltage restorer (DVR), which is usually used as a voltage sags and swells mitigation device, could be used to produce voltage sags or swells by appropriate and precise control [7], [8], [16], [17]. The DVR structure diagram and its vector diagram are shown in Fig. 6. Such a system consists of a series transformer, a DC capacitor and an inverter which is the reason that it is seen as a transformer based voltage sag generator.

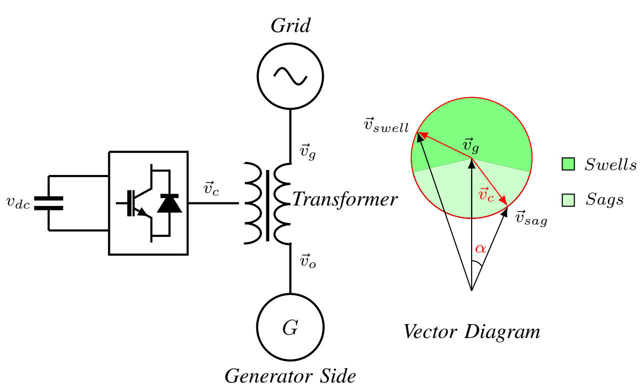


Fig. 6. Dynamic voltage restorer system.

The significant characteristics of a DVR based voltage sag generator are the controllability and the programmability. The output voltage $\vec{v}_o$ can be derived by applying the second cosine law [7], as it is shown in (4).

$$|\vec{v}_o| = |\vec{v}_g|\, cos\alpha \pm \sqrt{|\vec{v}_g|^2\, cos^2\alpha - |\vec{v}_g|^2 + |\vec{v}_c|^2}. \quad (4)$$

It can be seen in Fig. 6 and (4) that the output voltage can be controlled either by the amplitude of $\vec{v}_c$ or by the angle α.

Another merit of a DVR based voltage sag generator is that it can generate not only sags and swells but also flickers which is another power disturbance defined in IEC 61400 and IEEE 1149. Therefore, this kind of voltage sag generator is very useful and flexible for power disturbance condition tests. The harmonics injected in the system can be alleviated by connecting an *LC*-filter between the inverter and transformer.

C. Fully Controlled Converter Based Sag Generator- FCVSG

When it comes to the programmability, the full power converter based voltage sag generator could be the most promising one. This fully controlled system consists of two back-to-back converters. The topology of fully controlled converter based VSG is shown in Fig. 7. It can be used to generate all kinds of voltage sags as long as appropriate control method is adopted in this system [18]. In literature [18], a rectifier is used as grid side converter *CON1*. Normally, both converters are fully controlled power converter in order to control the power flow in this system by regulating the DC-link voltage v_{dc}.

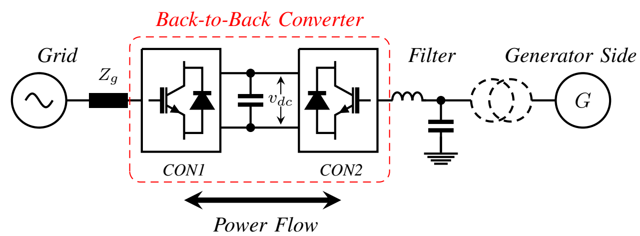


Fig. 7. Fully controlled power converter based voltage sag generator.

The attractiveness of the fully controlled power converter based VSG is that it has small size, light weight and precise control, but the control might be very complicated. Although it is convenient to generate a voltage sag with a desirable voltage sag depth, appropriate fault duration and variable sag types, the thermal cycling of the power devices under high voltage stress, which is quite related to the reliability, is also a challenge for high voltage applications [19]. Moreover, the dynamic behavior of such a sag generator system are also quite questionable [11], [14].

This kind of structure is a main favorable solution of grid emulators [20]. Nowadays, some commercial products are available in the markets, like the California Instruments MX Series AC Power Source [21], which can be used to simulate grid voltage variations and frequency variations. Thus, this implementation of a voltage sag generator is the most powerful one but also the most costly one.

D. Benchmarking of Voltage Sag Generators

In order to find the best VSG solution for different applications, a comparison is given as shown in TABLE I in terms of cost, size (transportability), controllability (sag depth and duration), the ability of generating recovery profile, and etc.

It can be concluded from TABLE I that the combination of switches with impedances might be the cheapest option for a laboratory setup. The performance of these implementations depends on the control system and the switching behavior. Thus, it is necessary to compare the bidirectional switches that can be used in voltage sag generators.

TABLE I
COMPARISON OF VOLTAGE SAG GENERATORS

	COST	SIZE	CONTROLLABILITY	RECOVERY PROFILE GENERATION	FAULT TYPES	MAINTENANCE
SVSG	$	Small	Easy	Difficult	Some	Easy, Cheap
TVSG	$$	Medium	Easy	Difficult	Some	Easy, Cheap
FCVSG	$$$	Small	Complicated	Easy	All	Difficult, Costly

III. SWITCHING DEVICES

As it can be seen in the last paragraph, the switching devices play an important role in the implementation of voltage sag generators. Typically, there are three different bidirectional switches that could be used in voltage sag generator systems:

- Relays, including contactor relay, solid-state relay, machine tool relay, and etc.;
- Thyristor based switching devices;
- IGBT and MOSFET based bidirectional devices.

A. Relays

A contactor is one type of relay that can handle higher VSG power rating (eg. MV level applications) which is required in most renewable energy generation systems, but it can be extremely loud in operations. Compared to such kind of relay, a solid-state relay (SSR) has no moving parts but can also achieve high currents. This application of such a relay with tapped transformer is reported in [6] with high cost-effectiveness and better performance. In order to control the sag duration time, the programmable logical controller (PLC) can be used to displace the electromechanical relay or SSR in the voltage sag generator applications.

It seems that the electromechanical relay is suitable for implementation of a cheap voltage sag generator with easy control methods. However, it has a slow switching speed and long-term erosion may make it unreliable. Even for SSRs, which can overcome the above disadvantages, the reliability is the main problem that must be taken into consideration. A solid-state relay can have malfunction due to transient behaviors, causing a connection between the contacts, which should be avoided in VSG applications.

B. Thyristor Based Switching Devices

A thyristor based bidirectional device, also known as TRIAC, can be used in VSG applications with higher reliability and very fast turn-on and turn-off speeds when compared to contactors or relays. A thyristor controlled reactor is successfully used to implement a voltage sag generator in [7]. As it can be seen in [7], this kind of voltage sag generator will produce undesirable harmonics which may be needed to be filtered. Moreover, the vital disadvantage of thyristor based bidirectional switches is that the conducting switch can only occur at the zero-crossing points of output voltage and current [2], [11], as it is shown in Fig. 8. This characteristic makes it possible for single-phase voltage sag generators, but it is unfit for three-phase applications.

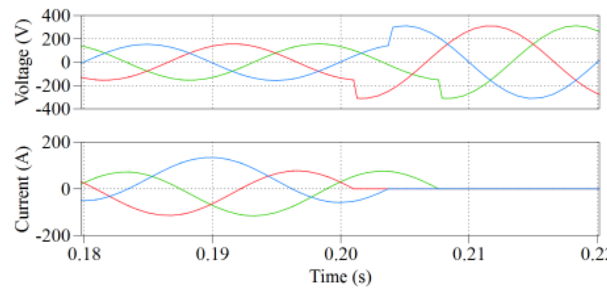


Fig. 8. Transient behavior of voltage sag generators using triacs.

C. IGBT and MOSFET Based Bidirectional Switches

In order to solve the aforementioned problems, fully controlled devices can be used as bidirectional switches by configuring two common-emitter IGBTs or MOSFETs and two diodes in order to provide instantaneous voltage sags. This bidirectional switches can turn on and turn off at a fast speed without the limitation of zero-crossing current conducting [11], which can be used in three-phase voltage sag generators.

However, this kind of switches requires detailed snubber circuits and driving systems which is shown in Fig. 9 and as they operate in shunt impedance based voltage sag generator systems. Thus the control methods are impacted. The cost and the reliability also limit the application of fully controlled devices in voltage sag generators. Nevertheless, the combination of such fully controlled devices with a PLC, a DSP or a computer based control system (dSPACE system) might be a favorable choice for voltage sag generators in the future. The detailed design of snubber circuits can be found in [12].

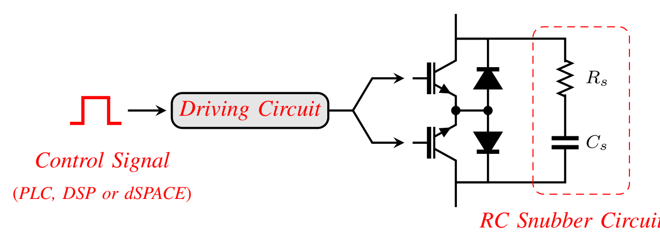
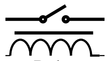
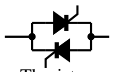
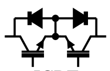


Fig. 9. Diagram of a typical IGBT based bidirectional switch for voltage sag generation systems.

D. Comparison of Bidirectional Switches

A comparison of the above bidirectional switches is given as shown in TABLE II for the convenience to choose the best devices in different applications.

TABLE II
COMPARISON OF BIDIRECTIONAL SWITCHES FOR VSG SYSTEMS

 Relays	■ High rating power ■ Very cheap ■ Easy to control	■ Low reliability (have malfunction) ■ Slow response ■ Noisy
 Thyristors	■ Fast, high reliability ■ Low noise, no sparks ■ Long life	■ Turn-off at the current zero-crossing (unfit for three-phase VSG systems)
 IGBTs	■ Precisely, fully controlled	■ Require detailed snubber circuits and driving systems

IV. SIMULATION AND EXPERIMENTAL RESULTS

Simulations are done in MATLAB using PLECS toolbox for a three-phase system. The shunt impedance based voltage sag generator as shown in Fig. 4 is tested with the grid parameters shown in TABLE III. The simulation results of different voltage sags are presented and shown in Fig. 10, in which the voltage sag lasts for 100 ms. This kind of voltage sag generator using manual switches is also verified experimentally and the results are shown in Fig. 11.

TABLE III
SIMULATION PARAMETERS

Phase-to-ground Grid Voltage	$V_{rms} = 230\ V$
Grid Frequency	$f_g = 50\ Hz$
Grid Impedance	$R_g = 0.1\ \Omega,\ L_g = 2\ mH$

As it can be seen in these figures, the shunt impedance based voltage sag generator can produce the desired voltage sag types with controlled voltage sag depths using readily available devices in the laboratory. Moreover, with the help of bidirectional IGBT switching devices, this kind of voltage sag generator can simulate three-phase voltage sags since the switches conduct simultaneously, as it is shown in Fig. 10.

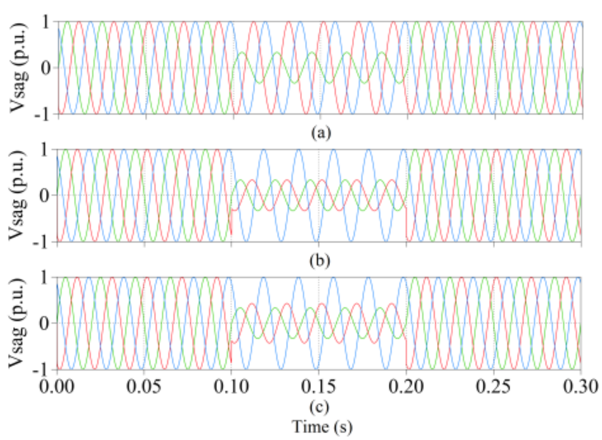


Fig. 10. Simulation results of shunt impedance based voltage sag generator using bidirectional IGBT switches: (a) 1-phase sag; (b) 2-phase symmetrical sag; (c) 2-phase asymmetrical sag.

It is worth to point out that the experimental results shown in Fig. 11 present an over-voltage during the voltage sag recovery because manual switches are used as the bidirectional switches in this experiment. It means the snubber circuits should be designed appropriately.

For comparisons, the fully controlled converter based voltage sag generator is also tested experimentally. The nominal line-to-line voltage in this system is set to be $50\sqrt{3}$ V for safety and the line-to-line voltages are measured. The test results shown in Fig. 12 demonstrate the flexibility of generating various voltage sags on the basis of an appropriate control method. However, besides a good control strategy, additional filters are also needed to enhance the quality of the output voltage sags, which increases the whole complexity and cost of this system and may make the control system apt to be unstable.

V. CASE STUDY BY EXPERIMENTS

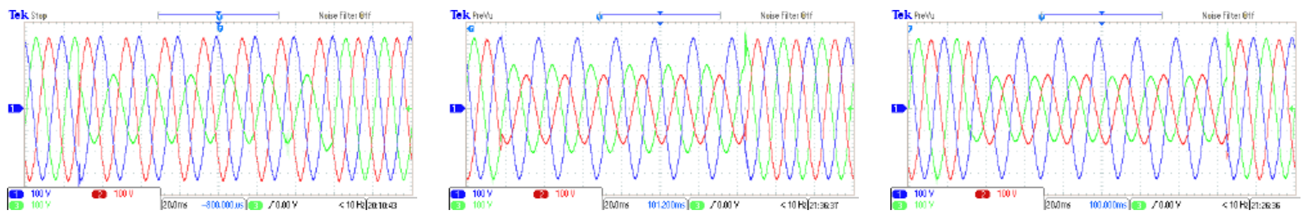
A 1 kW single-phase grid-connected system is tested and the results are shown in Fig. 13. A 0.45 p.u. grid fault is generated by short-circuiting a series resistance and switching a shunt resistor. During the grid fault, the system injected some reactive power (about 300 Var) to support the grid and limited active power output (about 100 W) according to the depth of the voltage sag in such a way to prevent the inverter from over-current and overheating. As it is shown in Fig. 13 (a), the grid current is limited below the rated maximum value (8 A). This case shows that the shunt impedance based voltage sag generator is suitable for laboratory low voltage ride-through and grid support tests.

VI. CONCLUSION

This paper presents the existing solutions to voltage sag generators. A thorough comparison of voltage sag generators and an evaluation of switching devices were done. It can be concluded that the implementation based on a combination of fully controlled switching devices and auto step-down transformer might be the most promising solution. However, using cheap traics or SSRs, the shunt impedance based voltage sag generator is the most low-cost and easiest candidate for a laboratory setup. This kind of voltage sag generator could be used in renewable energy generation systems to test LVRT behaviors as demonstrated by a simple case of a single-phase grid-connected system in grid faulty mode operation.

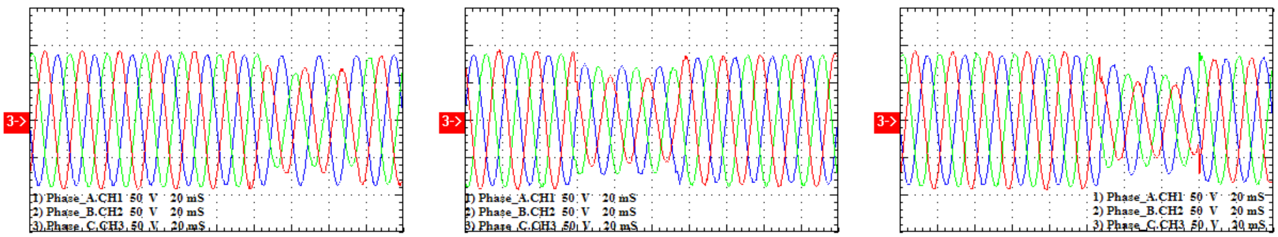
REFERENCES

[1] F. Iov, A. D. Hansen, P. E. Sørensen, and N. A. Cutululis, "Mapping of grid faults and grid codes," Risø National Laboratory, Technical University of Denmark, Tech. Rep., 2007.
[2] "Electomegnetic Compatibility (EMC)- Part 4-11: Testing and measurement techniques- voltage dips, short interruptions and voltage variations immunity tests," *IEC Std 61000-4-11*, 2004.
[3] "Wind Turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines," *IEC Std 61400*, 2008.
[4] EM Test, *Power Fail Simulator 503N Series Datasheet*, April 2012. [Online]. Available: http://www.emtest.com/
[5] I. J. Gabe, H. A. Grundling, and H. Pinheiro, "Design of a voltage sag generator based on impedance switching," in *Proc. of IECON'11*, pp. 3140–3145, Nov. 2011.



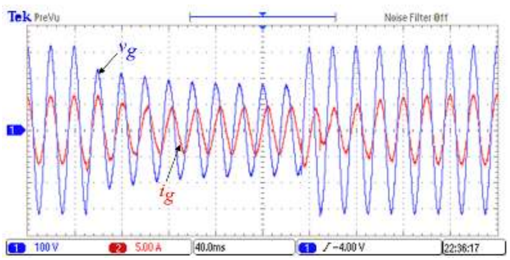
(a) 1-phase to ground sag (b) 2-phase to ground symmetrical sag (c) 2-phase to ground asymmetrical sag

Fig. 11. Experimental results of shunt impedance based voltage sag generator using manual switches: voltage [100 V/div], time [20 ms/div].

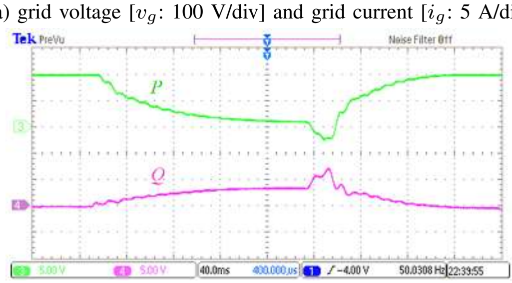


(a) 1-phase to ground sag (b) 2-phase to ground symmetrical sag (c) 2-phase to ground asymmetrical sag

Fig. 12. Experimental results of back-to-back converter based voltage sag generator: voltage [50 V/div], time [20 ms/div].



(a) grid voltage [v_g: 100 V/div] and grid current [i_g: 5 A/div]



(b) active power [P: 500 W/div] and reactive power [Q: 500 Var/div]

Fig. 13. Experimental results of a single-phase system under a 0.45 p.u. voltage sag using shunt impedance based sag generator, [t = 40 ms/div].

[6] O. S. Senturk and A. M. Hava, "A simple sag generator using SSRs," *IEEE Trans. Ind. Appl.*, vol. 48, no. 1, pp. 172–180, Jan.-Feb. 2012.

[7] Y. H. Chung, G. H. Kwon, T. B. Park, and K. Y. Lim, "Voltage sag and swell generator for the evaluation of custom power devices," in *Proc. of IEEE-PES General Meeting*, vol. 4, pp. 2503–2507, July 2003.

[8] C. Wessels, R. Lohde, and F. W. Fuchs, "Transformer based voltage sag generator to perform LVRT and HVRT tests in the laboratory," in *Proc. of EPE/PEMC'10*, pp. T11–8–T11–13, Sept. 2010.

[9] M. Garcia-Gracia, M. P. Comech, J. Sallan, and et al, "Voltage dip generator for wind energy systems up to 5 MV," *Applied Energy*, vol. 86, no. 4, pp. 565–574, Apr. 2009.

[10] C. Veganzones, J. A. Sanchez, S. Martinez, and et al, "Voltage dip generator for testing wind turbines connected to electrical networks," *Renewable Energy*, vol. 36, no. 5, pp. 1588 – 1594, 2011.

[11] S. Hu, J. Li, and H. Xu, "Comparison of voltage sag generators for wind power system," in *Proc. of APPEEC'09*, pp. 1–4, Mar. 2009.

[12] C. Venkatesh, D. V. S. S. S. Sarma, and M. Sydulu, "Dynamic voltage sag/swell compensator for industrial distribution system," *Journal of Electrical Systems*, vol. 6, no. 4, pp. 530–547, Dec. 2010.

[13] J. Dai, D. Xu, B. Wu, and N. R. Zargari, "Unified DC-link current control for low-voltage ride-through in current-source-converter-based wind energy conversion systems," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 288 –297, Jan. 2011.

[14] D. Li, H. Zhou, S. Xiao, and G. Yang, "A new voltage sag generator base on power electronic devices," in *Proc. of PEDG'10*, pp. 584–588, June 2010.

[15] Power Standards Lab, *Industrial Power Corruptor Manual Rev 1.00*, 2005. [Online]. Available: http://www.powerstandards.com/IPC.php

[16] J. G. Nielsen, M. Newman, H. Nielsen, and F. Blaabjerg, "Control and testing of a dynamic voltage restorer (DVR) at medium voltage level," *IEEE Trans. Power Electron.*, vol. 19, no. 3, pp. 806 – 813, May 2004.

[17] J. G. Nielsen and F. Blaabjerg, "A detailed comparison of system topologies for dynamic voltage restorers," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1272–1280, Sept.-Oct. 2005.

[18] R. Zeng, H. Nian, and P. Zhou, "A three-phase programmable voltage sag generator for low voltage ride-through capability test of wind turbines," in *Proc. of ECCE'10*, pp. 305–311, Sept. 2010.

[19] F. Blaabjerg, K. Ma, and D. Zhou, "Power electronics and reliability in renewable energy systems," in *Proc. of ISIE*, pp. 19–30, May 2012.

[20] R. Lohde and F. W. Fuchs, "Laboratory type PWM grid emulator for generating disturbed voltages for testing grid connected devices," in *Proc. of EPE/PEMC'09*, pp. 1–9, Sept. 2009.

[21] California Instruments, *MX Series AC and DC Power Source User Manual Series I/Series II*, Mar. 2010. [Online]. Available: http://www.californiainstruments.com/

[22] J. C. Ausin, D. N. Gevers, and B. Andresen, "Fault ride-through capability test unit for wind turbines," *Wind Energy*, vol. 11, no. 1, pp. 3–12, 2008.

[23] M. Mohseni, S. M. Islam, and M. A. S. Masoum, "Impacts of symmetrical and asymmetrical voltage sags on DFIG-based wind turbines considering phase-angle jump, voltage recovery, and sag parameters," *IEEE Trans. Power Electron.*, vol. 26, no. 5, pp. 1587–1598, May 2011.

[24] X. Yan, G. Venkataramanan, Y. Wang, Q. Dong, and B. Zhang, "Grid-fault tolerant operation of a DFIG wind turbine generator using a passive resistance network," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2896–2905, Oct. 2011.

[25] E. Gomez, J. Alvaro Fuentes, A. Molina, and et al, "Results using different reactive power definitions for wind turbines submitted to voltage dips: Application to the spanish grid code," in *Proc. of IEEE PSCE'06*, pp. 768–775, 2006.

[26] Y. Yang, F. Blaabjerg, and Z. Zou, "Benchmarking of grid fault modes in single-phase grid-connected photovoltaic systems," in *Proc. of ECCE'12*, to be published, 2012.