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Experimental Study and Performance Evaluation of the Renewable Energy Conversion Systems under Realistic Grid Conditions Using RTDS

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Abstract—**This paper presents a new approach to analyze the steady– state and transient behavior of grid connected renewable energy sources. For this case, a permanent magnet generator based variable speed wind turbine interfaced to the grid through back to back fully rated converters is considered. The salient feature of this paper is the introduction of the realistic grid into real time digital simulation such that practical effects can be examined prior to the experimental test stage. The effect of power quality phenomena present on the supply voltage waveforms on the performance of the variable speed wind turbine system is examined. It is noted that tuning the grid side converter voltage loop for successful low voltage transient operation might not be sufficient for operation under the non–ideal voltage waveforms of actual grids. Simulation and hardware implementation have been carried out by RTDS/RSCAD.**

Index Terms—**Frequency converter, Permanent magnet synchronous generator (PMSG), Real Time Digital Simulator (RTDS), Transient analysis, Voltage source converter (VSC).**

I. INTRODUCTION

WINDenergy is playing an increasingly important role in the world's energy market nowadays due to its clean and economical characteristics. According to the Global Wind Energy Council (GWEC) 2011 report [1], the total installed capacity has reached up to 240 GW till 2011. On top of this, there are predictions that wind energy will grow by 14-16% globally from its present status by the year 2020 [1]. Given the above statistics, it is clear that a large number of wind farms will be integrated into the electrical power network in the near future. It is therefore imperative to analyze the performance of grid connected wind farms and their ability to fulfill recent grid code requirements [2].

Variable speed wind turbines (VSWT) are prevailing in recent wind farm installations due to their increased energy capture [3] as compared to fixed speed systems. VSWTs are generally based on two main types of electrical generators, mainly the double fed induction generator (DFIG) and the permanent magnet synchronous generator (PMSG). Both generators require a power electronic converter to be interfaced to the electrical grid. The DFIG presents the advantage that it can be operated with a partially rated converter thus saving on the capital cost [4].The PMSG requires a full rated converter however it offers the possibility of a direct drive at low speed without the need of a gearbox, thus making the system simpler and also lowering both capital and operational costs [5].

As wind energy forms an increasing percentage of the energy mix for the supply of electrical energy, grid codes are imposing Low Voltage Ride through (LVRT) requirements such that the impact of the disturbance is not exacerbated [2]. Concentrating on the aforementioned variable speed generators, the LVRT requirements present different challenges. The DFIG is directly connected to the grid through its stator winding hence it directly experiences the low voltage transients [4]. The PMSG is connected through a converter stage which can be controlled to decouple the grid dynamics from the generator dynamics [6-7]. In some power system literatures, the modeling and control scheme for the operation of PMSG type wind generator in both normal and fault conditions are reported using offline simulation software [8-11].Real time simulation and control of variable speed wind turbine driven PMSG is reported in [12-13].Voltage transient analysis of PM type machine is reported in [14-15] using real time digital simulator where focus is given in controller-hardware-in-loop (CHIL) method. In all cases, the ideal grid waveforms are used in simulation, which is not realistic and indicates the necessity of conducting a detailed LVRT analysis of variable speed wind turbine driven PMSG considering realistic grid.

The active power fed from grid connected wind farms can exhibit significant fluctuations due to the wind speed variations. Depending on the type of electrical generator in use by the turbine, the active power variation may lead to voltage fluctuation and hence flicker at the point of connection. Such voltage fluctuation can be compensated using appropriate reactive power compensation. This can be achieved through the use of additional devices [16, 17] or through the control of the power electronic converter interfacing the wind turbine system to the grid [9, 10]. The grid voltage at the Point of Connection (PoC) may also itself show power quality phenomena resulting from nearby loads, particularly non–linear and unbalanced loads. The presence of the power quality phenomena imposes further requirements on the necessary reactive power compensation. This additional requirement is not sufficiently addressed in the literature as typically ideal grid waveforms are assumed. Considering the aforementioned issues, the effects of realistic grid in real time simulation of variable speed wind turbine driven PMSG including power quality and detail LVRT characteristics analysis are yet to be addressed adequately.

This work concerns the performance of renewable energy conversion systems operating under realistic grid conditions. It is focused on the performance of a PMSG based VSWT connected to a realistic grid through fully rated power electronic converters. The system model is implemented on a real time digital simulator (RTDS) platform and studies the performance of the wind farm in the presence of power quality phenomena that might be exhibited by the grid voltage. Real power quality phenomena are introduced by interfacing real grid voltage waveforms into the model. Moreover additional effects emulating an industrial supply are introduced. It is shown that through appropriate tuning, the VSWT PMSG farm connected to the grid through fully rated converters can successfully overcome the grid power quality phenomena while satisfying the imposed LVRT requirements.

II. SYSTEM MODELING

A. *Wind Turbine*

For wind turbines equipped with blade pitch mechanism, the mechanical power extracted from the wind can be expressed mathematically by (1) [18],

$$P_w = 0.5\rho(\pi R^2)C_p(\lambda,\beta)V^3 \quad (1)$$

P_w is the extracted power from the wind, ρ is the air density, R is the wind turbine radius, C_p is the power coefficient and V is the wind speed. As shown in (1), C_p is not constant but is a function of the tip speed ratio λ and the blade pitch angle β. The pitch angle is set by the pitch angle controller while the tip speed ratio depends on the turbine rotational speed ω_r, as shown in (2). For the calculation of the resulting C_p, the approximation shown in (3) is used based on β and the λ_t parameter defined in (4). It is assumed for this work that ρ is constant as its variation can be compensated through appropriate measurements.

$$\lambda = \frac{\omega_r R}{V} \quad (2)$$

$$C_p(\lambda,\beta) = 0.73\left[\frac{151}{\lambda_t} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right]e^{-18.4/\lambda_t} \quad (3)$$

$$\lambda_t = \frac{1}{\frac{1}{\lambda+0.02} - \frac{0.003}{\beta^3+1}} \quad (4)$$

VSWTs allow increased energy capture due to their broader speed range. The wind turbine control employs a maximum power point tracking algorithm that sets the optimal operating point at the current wind speed conditions. Due to the nature of the wind speed measurement, it is generally difficult to accurately measure the wind speed experienced by the turbine. A typical solution is to base the optimal operating point on the rotational speed of the turbine, which can be easily measured. For the case of power controlled turbines, the optimal power P_{opt} is given by (5), where C_{p_max} is the maximum attainable C_p and λ_{opt} is the tip speed ratio at which C_{p_max} is achieved.

$$P_{opt} = 0.5\rho\pi R^5 \frac{C_{p\_max}}{\lambda_{opt}{}^3}\omega_r{}^3 \quad (5)$$

The modeled VSWT is rated at 5 MW.The values of C_{p_max} and λ_{opt} corresponding to (3) are at 0.44 and 5.9 respectively. The wind turbine is assumed to have a pitch mechanism that is used to limit the maximum power to rated (1.0 pu).

B. *Permanent Magnet Synchronous Generator*

Permanent magnet synchronous generators are proving to be an alternative solution for large scale wind energy conversion systems. PMSGs allow designs using a high number of poles enabling the generator to be coupled directly to the turbine. The direct connection removes the need of the gearbox, improves the conversion efficiency and reduces the need for maintenance. The use of permanent magnets also greatly simplifies the excitation requirements of the generator. The modeled PMSG is set to match the speed variation of the VSWT, which ranges from 5 rpm to 16 rpm.

C. *Grid Interfacing*

Various solutions are available for the grid connection of large scale renewable energy sources to the grid. The directly coupled permanent magnet synchronous generator is typically interfaced to the grid through fully rated back to back converters. This topology decouples the generator dynamics from the grid. Both converters are modeled as 2-level voltage source units. Pulse width modulation is used to control the switches due to the fixed switching frequency; well defined harmonic spectrum and low current ripple. There are various PWM schemes to shape the output voltage waveforms which facilitate operation at different voltage levels.For this case, the carrier based PWM technique is used for both converters with a switching frequency of 1050Hz.

III. SYSTEM IMPLEMENTATION ON THE REAL TIME DIGITAL SIMULATOR

A. *RTDS Platform*

The RTDS is a power system simulator that solves electromagnetic transient simulations in real time. RTDS is based on parallel processing hardware architecture organized in racks. Each rack consists of the processor cards, communication cards and a number of interface cards. The RTDS has two main software elements: the RSCAD software suite and the Component Model Libraries. RSCAD provides the facility to set up and run the simulation, and to capture and analyze the resulting data.RTDS provides various power system and control system models apart from other models that can be used directly in the simulation. Triple Processor cards (3PC) and Giga Processor cards (GPC) are used for solving the power and control circuits. The 3PC card allows the connection of an OADC card, which provides six optically isolated 16 bit analogue to digital converter channels. This allows the introduction of real waveforms into the simulation.

B. *Modeled System*

A block diagram of the modeled system is shown in Fig. 1. A PMSG is directly driven by a VSWT equipped with a blade pitch mechanism. The PMSG is interfaced to the grid via back to back fully rated converters and a step up transformer. The wind energy conversion system is supplied through a double circuit transmission line (TM) with circuit breakers at both ends. In the dc link between the machine side converter (MSC) and the grid side converter (GSC) a braking resistor is connected to dissipate the excess energy during the voltage dip at grid side. Discharging the excess energy limits the dc link voltage rise, hence, safeguarding the switches.

The wind turbine is modeled as presented in Section II. The RSCAD library model is used for the PMSG. Both the machine side and the grid side converters are modeled using ideal switches. A capacitor of 10,000 μF is connected across the dc link, which is set to 2.3kV. The 5MVA, 1.25kV/6.6kV transformer with an impedance of 0.1pu steps up the voltage level to the grid voltage at the PoC.The double circuit transmission line is modeled by a short TM line model with an X/R ratio of 6. A three phase generator model from the RSCAD library is used for the grid. The generator impedance is set very low to represent a stiff grid.

The PMSG, MSC, GSC, and DC link including the braking resistor are modeled in the VSC small time step environment of RTDS and are solved on GPC cards.The wind turbine model, TM lines, the grid, and the control loops are modeled in the large time. The VSC large– and small– time steps are interfaced through the interface transformer model from the RSCAD library. The small– and large– time steps are set at 2.7μs and 50μs, respectively.

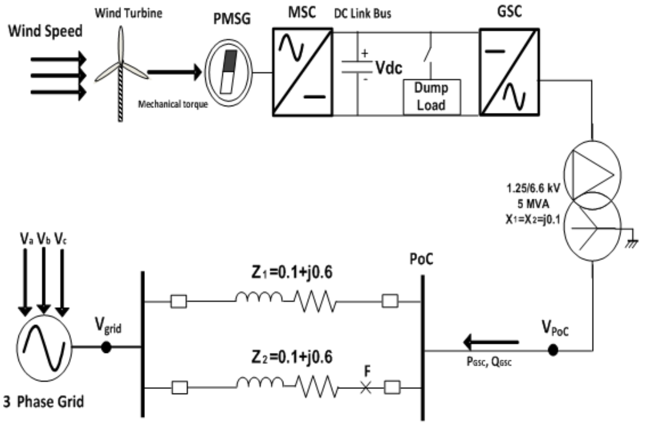

Fig. 1.Block diagram of the modelled system.

IV. INTRODUCTION OF THE REALISTIC GRID

Simulation study is a very effective tool in testing the performance of a system. However operating the system under real conditions might expose the system to additional effects that were not modeled in the simulation. The focus of this paper is to test the performance of a VSWT interfaced through fully rated back to back converters in the presence of realistic grid waveforms. Real grid voltage waveforms can exhibit a number of power quality phenomena including: unbalance between the different phases, harmonics, voltage level fluctuation and voltage notching effects. Apart from such phenomena, the introduction of actual measurements will introduce some noise in the system. The presence of any or a combination of these effects will act as a disturbance to the PoC voltage control loop.

A. *Interfacing the Grid Waveforms*

This work uses the interfacing capability of the RTDS platform to integrate the real voltage waveforms in the simulation. The three instantaneous grid voltage waveforms are stepped down through three identical voltage probes. The low voltage signals are then fed into the simulation through the OADC card and are used as external voltage waveforms to three phase generator model simulating the grid. The captured waveforms are scaled such that they show the same peak value as the simulated supply. The calibration is done on phase A only and applied to the other phases such that any unbalance between the phases is preserved.

Captures of the voltage waveforms showed some voltage fluctuations. Due to the large infiltration of nonlinear loads, it was opted to make the grid waveforms more realistic by introducing voltage notching effect.This was done by connecting a nonlinear load, basically a three phase rectifier feeding a resistive inductive load from a variable transformer.

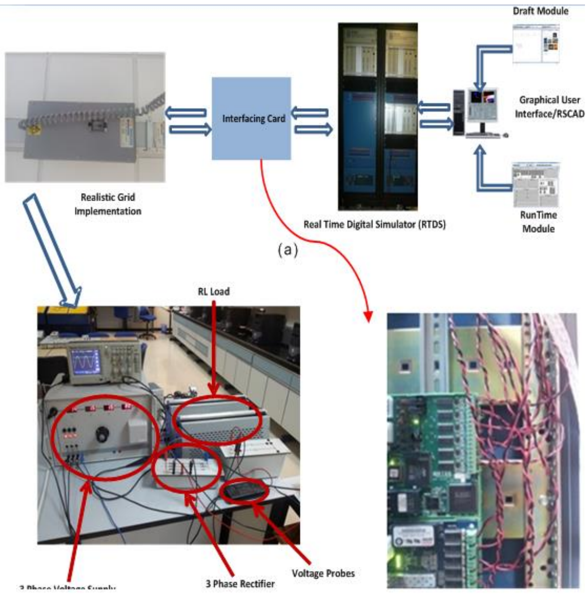

Fig. 2.Experimental voltage waveform capture with introduced notching effects.

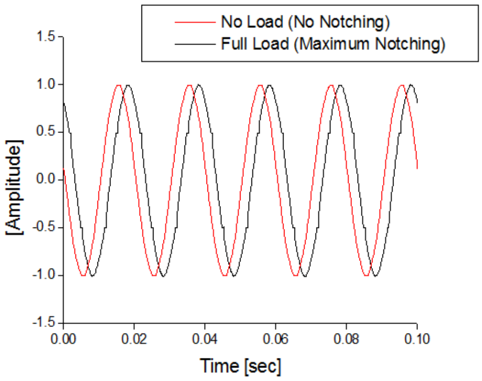

Fig.3. Captured voltage waveforms showing the introduced notching effect.

The voltage waveforms at the output of the variable transformer were then used for the realistic grid waveforms. The load can be changed to vary the intensity of the resulting notching effect. To counteract possible voltage drops across the transformer due to different loading, the scaling factor is calibrated before each run. The voltage waveform capture together with the nonlinear load is shown in Fig. 2. Captured waveforms scaled to 1.0puare shown in Fig. 3 for no load case (no notching) to the maximum loading used.

B. *Effect of the realistic grid on the system performance*

The power quality phenomena present in the realistic grid waveforms are coupled into the grid side control loops mainly through the PoC RMS voltage measurement. They also influence the GSC reactive power Q_{GSC} and current components that are also fed back to the control system. The voltage RMS measurement is done using a standard RSCAD function and then low pass filtered by a first order lag of 10ms. The RSCAD three phase meter uses (6) for the RMS calculation.

$$RMS = \sqrt{\frac{{v_A}^2+{v_B}^2+{v_C}^2}{3}} \tag{6}$$

The voltage loop is typically tuned such that the necessary reactive power is provided during low voltage transients and to shape the voltage profile as it recovers from the transients. Tuning the loop for these requirements might not be sufficient to provide a satisfactory reactive power response to mitigate power quality disturbances at the PoC. Simulation studies showed that despite excellent LVRT performance, the tuning can lead to oscillations in the reactive power and hence the PoC voltage in the presence of supply voltage fluctuations. To this effect the voltage controller was tuned to also allow mitigation of low frequency effects such as voltage fluctuations.

V. RESULTS

This section presents the real time simulation results of the grid connected wind energy conversion system operating under realistic grid conditions. Real grid waveforms with imposed notching effect are used. This section is divided into three parts. In the first part, the effect of non–ideal grid voltage waveforms is simulated. In the second part, the system is simulated with the introduced realistic grid waveforms under steady state conditions. In the third part, the transient operation of the system under the introduced waveforms is tested.

A. *Tuning the grid side voltage loop*

The first simulation assumes ideal grid waveforms as in conventional simulation studies. The three phase generator RSCAD model used to represent the grid allows the introduction of a fluctuation on its ideal sinusoidal waveforms. In line with the observed fluctuation, the voltage magnitude of the three phases was modulated by a sinusoidal signal of magnitude 0.01pu and a frequency of 1Hz. In order to focus on the effect of the disturbance, the wind speed is assumed steady and close to the rated speed. Waveforms of the grid side RMS voltage V_{grid}, the reactive Q_{GSC}, the PoC RMS voltage V_{PoC}, and the active power P_{GSC} are shown for the ideal grid and for the case of introduced voltage fluctuations in Fig. 4 and Fig. 5, respectively. In Fig. 4, all the plotted quantities are relatively smooth due to the ideal voltage waveforms. In Fig 5, it can be seen that due to the revised tuning, the power flow and the PoC voltage are still smooth despite the supply voltage fluctuations. It can also be observed that the reactive power flow fluctuates to counteract the supply voltage fluctuations.

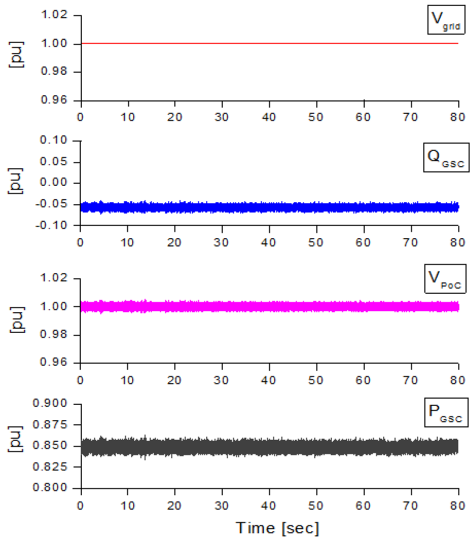

Fig. 4.Ideal voltage waveforms.

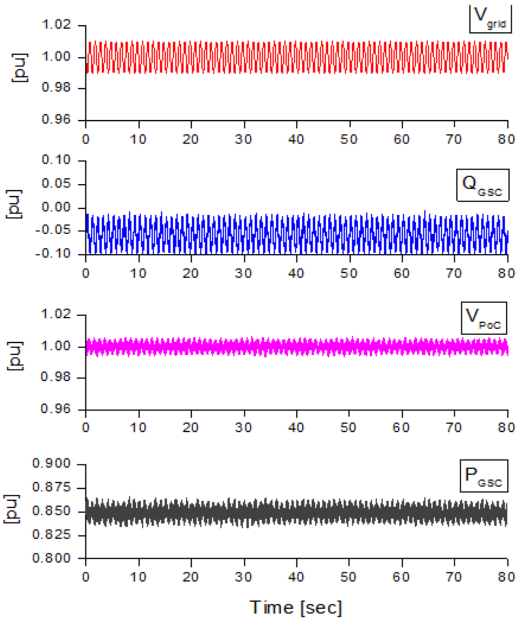

Fig.5. Simulated voltage fluctuations.

B. *Steady State Results*

In this set of simulations, the ideal waveforms of the three phase generator simulating the grid are replaced with the realistic grid waveforms introduced before. Wind speed scenario remains the same. Two cases of voltage notching intensity are considered, ranging from no nonlinear load to the maximum loading used.

Figure 6 shows the case where no nonlinear load is added. The plots, from top to bottom, show the grid side RMS voltage V_{grid}, the reactive power flow Q_{GSC}, the PoC RMS voltage V_{PoC} and the active power flow P_{GSC}. It can be clearly seen that V_{grid} is below 1.0pu and shows some variation, especially in the time range from circa 60s onwards. The V_{PoC} voltage is however steady at 1.0 pu through the reactive power flow that counteracts the variation, as can be observed from the low pass filtered Q_{GSC} waveform. The active power flow P_{GSC} is also steady. It can also be observed that both the P_{GSC} and Q_{GSC} are noisier than the corresponding waveforms in Figs 6 and 7.

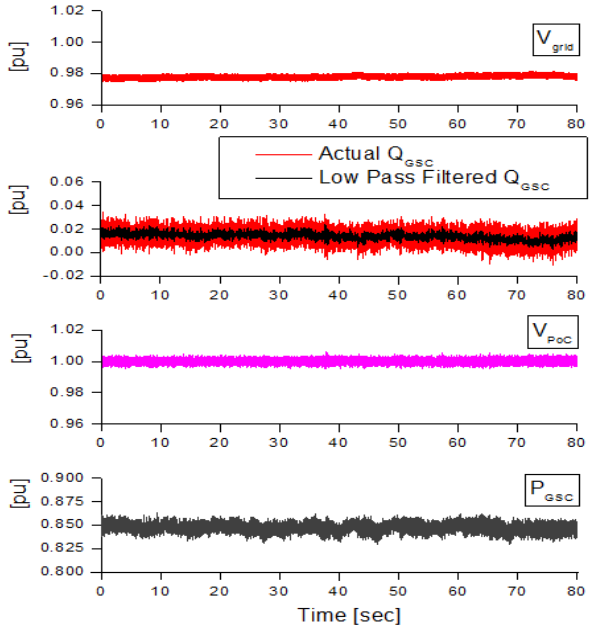

Fig. 6. Steady state response under realistic grid conditions with no introduced notching effect. Grid RMS voltage V_{grid}; and Q_{GSC}: actual and low pass filtered; PoC RMS voltage V_{PoC} and P_{GSC}.

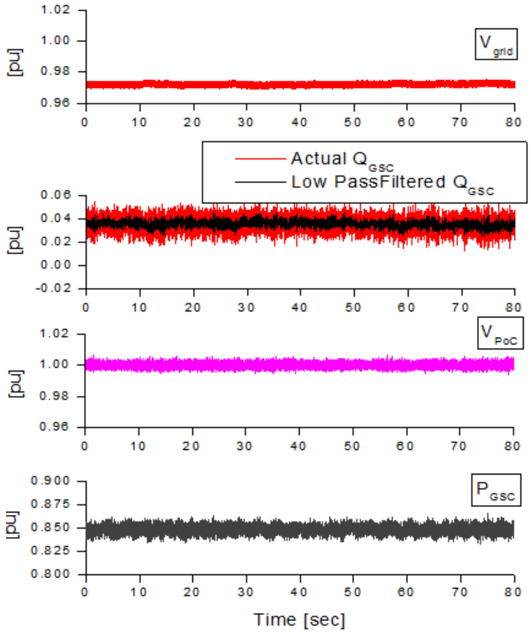

Fig. 7. Steady state response under realistic grid conditions with more severe notching effect. Grid RMS voltage V_{grid}; and Q_{GSC}: actual and low pass filtered; PoC RMS voltage V_{PoC} and P_{GSC}.

Figure 7 shows the case when the voltage notching effect is introduced. The plots follow the same order as for Fig. 6. It can be observed that V_{grid}, apart from the variations, is also reduced reflecting the introduced notching effect. However the V_{PoC} is also steady at 1.0pu. It can be seen that the average Q_{GSC} is higher than the previous case to counteract the notching effect.

C. Transient Results

A Wind farms are required to conform to sets of requirements following transients on the grid. In particular, following the TenneT TSO GmbH (formerly EON Netz) grid code (herewith referred to as grid code), a wind farm is required to stay online when the line voltage drops to zero for a period less or equal to 150 ms and should recover to 90% of its voltage within 1.5 s from the time of occurrence of the fault [2]. Faults on the grid cause the wind farm PoC voltage to drop. The severity of the drop depends on the location of the fault and on the protection arrangement. A voltage sag or interruption will hinder the ability of the wind farm to transfer active power to the grid.

Given the grid code requirements the modeled system introduced in Fig. 1, operating with realistic grid conditions, is also tested under transient operation. The wind speed is also kept constant for this case as the wind speed is not expected to vary greatly within the short time period of interest. A bolted symmetrical three line to ground (3LG) fault is applied at the converter end of one of the transmission lines. The fault location is marked as *F* in Fig. 1.The applied fault is cleared after 150 ms, corresponding to the maximum period in the grid code, by tripping the circuit breakers at both ends of the line. The fault is assumed to be temporary and the breakers are then reclosed after 1s after the occurrence of the fault.

As shown in Fig. 1, the excess power during the occurrence of the fault is discharged in the barking resistor connected across the dc link. The switch connected in series with the braking resistor is controlled through conventional hysteresis control. The main priority of the GSCcontrol during the low voltage disturbance is to provide the necessary reactive power to support the system overcome the disturbance. It is also recognized that the ability of the GSC to transfer power to the grid decreases with the increasing severity of the voltage drop. For this reason, the active power transfer is temporarily suspended when the PoC voltage drops below a lower hysteresis boundary (0.07pu for this case). At the same time, in order to avoid windup of the controllers, the integral terms are disabled till the PoC voltage recovers up to an upper hysteresis boundary (0.14pu in this case). The active power transfer is delayed by a further specified time period (0.1s) to give priority for the voltage shaping. The integral terms are also disabled when the dc link voltage falls below 0.6pu.

The two cases corresponding to the steady state results of Figs. 6 and 7 are subjected to the LVRT transient. The

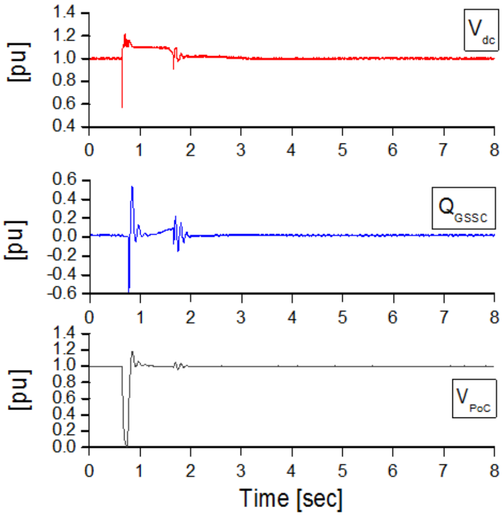

Fig. 8. LVRT response under realistic grid conditions with no introduced notching effect. DC link voltage V_{dc}; reactive power Q_{GSC} and PoC RMS voltage V_{PoC}.

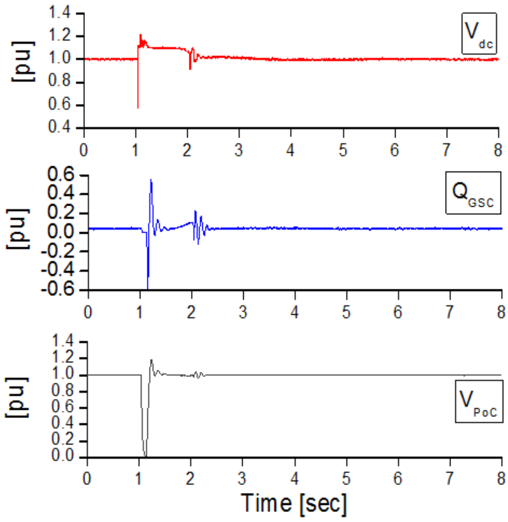

Fig. 9. LVRT response under realistic grid conditions with more severe notching effect. DC link voltage V_{dc}; reactive power Q_{GSC} and PoC RMS voltage V_{PoC}.

corresponding LVRT responses are shown in Fig. 8 and Fig. 9 respectively. For both cases, the plots from top to bottom show the dc link voltage V_{dc}, the reactive power Q_{GSC} and the PoC RMS voltage V_{PoC}. It can be seen that in both cases the system successfully meets the grid code requirements. The responses for the two cases are similar – this is expected as the reactive power flow in the steady state tests to overcome the effects of the realistic grid is low due to the relatively clean grid waveforms. The difference in the average steady state Q_{GSC} between the two cases is however still evident, which can clearly be observed from Figs. 6 and 7.

VI. CONCLUSION

Unlike conventional simulation studies, the paper proposes the interfacing of real signals such that the model is driven by realistic grid waveforms. In addition to the effects present on the actual supply, voltage notching with varying intensity was introduced. The analysis covers both steady state and transient operation. The introduction of the realistic grid in the simulation study allowed the examination of effects that are not usually considered in conventional simulation studies but are then faced when the system is implemented experimentally. It was noted that tuning the grid side converter loops for the system to meet the grid code LVRT requirements might not be sufficient if the voltage at the PoC exhibits significant power quality phenomena. The role of the GSC voltage control loop in providing the necessary reactive power for overcoming the power quality phenomena and during transients was clearly seen. The setup presented in this paper is well suited to allow hardware in the loop experiments for grid connected megawatt lass wind farms. It allows the examination of real phenomena without the cost and time required for an experimental prototype. It is proposed that the realistic grid interfacing methodology with real time digital simulation used for the analysis of the wind farm can be used in other renewable energy and smart grid applications.

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