DYNAMIC SYSTEM PERFORMANCE OF RENEWABLE POWER GENERATION UNITS - USEFUL AND DOUBTFUL GRID CODE REQUIREMENTS

Bernhard SCHOWE-VON DER BRELIE
FGH GmbH – Germany
bernhard.schowe@fgh-ma.de

Frederik KALVERKAMP
FGH GmbH – Germany
frederik.kalverkamp@fgh-ma.de

Julian LANGSTÄDTLER
FGH GmbH – Germany
julian.langstaedtler@fgh-ma.de

ABSTRACT

To maintain system stability and functioning and to ensure the quality of supply, system operators are responsible to set up transparent and commonly valid requirements for the usage and connection to their relevant grids. Facing the increasingly high penetration of dispersed power generators the requirements have been continuously updated and revised by TSOs and DSOs according to the new challenges of its transforming traditional operation procedures in all European Member States over the last decade. Based on gathered experiences in many years the reasonable needs for specifically designed and more stringent requirements with respect to system management and control schemes of renewable energy systems (RES) have evolved. However the accurate definition of advanced requirements is still ongoing and manufacturers are subjected to a rather dynamic technical as well as legislative framework in this context. In fact, ENTSO-E is currently working on a first pan-European grid code.

In some ways also DSOs are overcharged in choosing the most suitable solution with respect to their alternatives like reactive power contribution of RES. Hence the intention of this paper is to highlight the contemporary sophisticated requirements related to the dynamic performance of RES during system disturbances and their respective contribution to system recovery and voltage support. The investigation of the required capabilities shows for example that under specific system conditions and operation modes the intended support function of injecting reactive current during voltage dips may not lead to the anticipated but rather to unsolicited impacts on the system that even can contradict the intention of system recovery. The corresponding analysis is based on simulations performed in German wind farm certification procedures by using manufacturer-specific models that have been validated in accordance with German Technical Guideline TR4.

INTRODUCTION

Worldwide the growth rates of wind power installations have reached annually more than 20% in the last decade [1]. Following this rapid development and the simultaneously progressing structural paradigm shift in conventional energy supply the requirements for grid integration of renewable energies needed mandatorily to be adapted. They must go along with the dynamic expansions to ensure reliable system stability. Based on their responsibilities the system operators therefore adjusted and revised their grid codes and set up special conditions for the connection and operation of renewable energy systems (RES) in the past. Nowadays many grid codes take advantage of the flexible operation modes and modern system behaviour that RES are able to provide. Germany for instance was one of the first countries worldwide that elaborated clear technical standards for the dynamic performance of RES during system faults. Furthermore a compliance scheme based on type testing and certification was established to verify the respective standards of transmission and distribution systems with application to both unit and farm level.

However lessons learnt from the verification of grid code compliance have shown several shortcomings in requirements as well as various misinterpretations from manufacturers and power plant operators. As a matter of fact, this was also reasoned by the newly applied grid code requirements that have been updated according to an improved implementation and technical intention of their use. Nevertheless modern grid codes are still lacking in clear definition and the requirements for connection and operation of RES vary considerably on international level.

REQUIRED DYNAMIC PERFORMANCE

Next to regular voltage and frequency control functions, the modern requirements applied to RES in terms of fault performance basically comprise on the one hand the low-voltage-ride-through (LVRT) capability and on the other hand the injection of reactive current to stabilise the system and counteract the expansion of voltage drops. While the LVRT-capability is state-of-the-art and required by most TSOs, the latter requirement for voltage support however consists only in a few European countries yet.

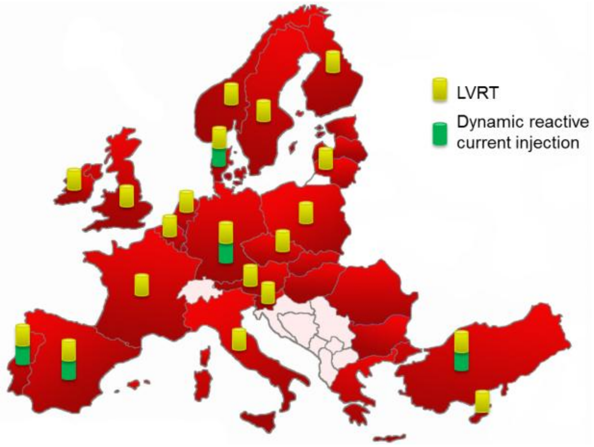

Fig. 1: Dynamic performance requirements in EU-27 plus Norway and Turkey

As it can be derived from Figure 1 especially countries with a high amount of RES installations connected to the electricity grids launched the concept of reactive current injection so far. With a further penetration of RES all across Europe it can be expected that an increasing number of TSO will make usage of this system support provided by RES as well, similarly to the recently observed developments of LVRT requirements. In fact the ongoing activities on European level to aim at establishing a pan-European grid code which is applicable to all connected generators in all Member States do consider a reactive current injection in its latest draft as well.

Nevertheless the requirements of the dynamic voltage support slightly differ in its implementations. Normally it is claimed that the reactive current shall be fed-in commensurate with the decrease of voltage. This leads to a corresponding fixed constant of proportion meaning that every percentage of voltage decrease goes along with a corresponding percentage increase of reactive current (in relation to the nominal current). Fixed constants for the reactive current injection can be found in Denmark and Spain, for instance. In Germany as well as in the ENTSO-E Network Code (NC) however this constant (the so called k-factor) can additionally be adjusted according to the locally varying system operators' need and preferences. In this relation a wide range of different k-factors shall be provided by the RES although experiences and respective studies do not exist so far.

Grid Code Requirements in Germany

Since 2009 it is required in Germany that wind turbines contribute to dynamic voltage support. During significant voltage deviations of more than +/-10% of nominal voltage the wind turbine shall back up the voltage by adjusting additional reactive current. In this context it is spoken of a reactive current deviation (ΔI_B) which must be proportional to the relevant voltage deviation at the single turbine (ΔU_r). The proportional factor "k" must variably be adjustable ($0 \leq k \leq 10$) and will be optionally determined by the relevant system operator.

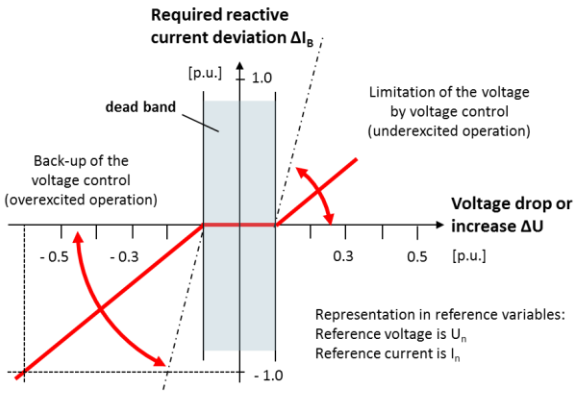

Fig. 2: Voltage back-up in the case of network faults in wind energy generating units [2]

Furthermore the German "Ordinance on System Services by Wind Energy Plants" defines specific time periods for the step response of the additional reactive current [2]. The response time is defined when the reactive current firstly enters the tolerance band at -10% of its stationary end value (Figure 3). It shall not exceed a value of 30 ms after the voltage had left its normal operation ranges. The transient time is the time at which the transient processes have abated and the reactive current remains in the tolerance band at +20% of its stationary end value. The time limitation here are 60 ms. Further specifications on the control design and behaviour is not given in this context.

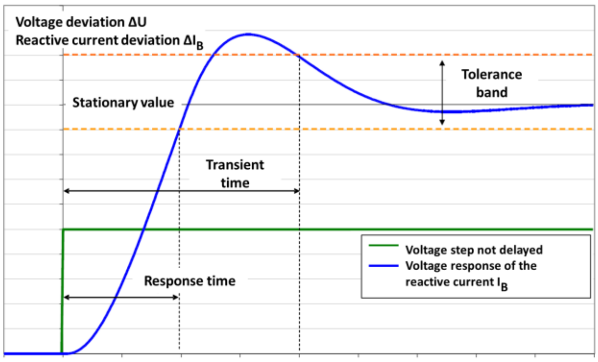

Fig. 3: Characteristic variables for the step response of the reactive current [2]

ENTSO-E Network Code

The Third Energy Package of the European Commission is intended to reinforce competition and liberalisation towards an internal European electricity market. The newly founded EU Agency for the Cooperation of Energy Regulators (ACER) has therefore implemented framework guidelines that instruct ENTSO-E to create a new and firstly-designed pan-European network code for the grid connection requirements applicable to all generators. Due to its wide scope ENTSO-E's NC is affecting also small generation units connected to low and medium voltage grid with therefore significant impact on distribution level as well.

In the recent draft a very similar reactive current injection like in Germany is assigned to RES during system disturbances [3]. Although the characteristic is basically the same as shown in Figure 2, small differences can be identified in the definitions. On the one hand the value of the k-factor can be adjusted from 2 to 10 ($2 \leq k \leq 10$) and on the other hand it is not spoken of additional but only reactive current. Moreover the NC defines a control response time of maximum 40 ms when the RES shall feed the required reactive current after the fault inception into the network [3]. In common with the German grid code there are no additional specifications given if the control of reactive current has to work on its constant reference value or in a continuously regulating manner.

CASE STUDY SIMULATIONS

Based on gained experiences in the German certification process of grid connection of RES a reference case of a typical wind farm connected to the medium voltage level is introduced. The wind farm consists of 5 single wind turbines with fully rated converters and 2 MW rated power each. For their simulation validated manufacturer models in accordance to German TR4 are used [4]. The total capacity of 10 MW is connected at the point of common coupling (PCC) to a 20 kV medium voltage system which is represented by a grid equivalent with voltage source and network impedance. Its values can be derived from the network characteristics of 155 MVA net short-circuit power and an impedance angle of 82°. The internal cable connections in the wind farm have in total a length of 1.5 km and the connection cable to the PCC has a default value of 5 km but will be changed later on. For the investigation of the impact of reactive current in-feed and respective voltage support, different initialisations of the k-factor in the wind turbines and different depths of voltage dips are examined. The wind farm simulations and performance comply with the German requirements.

Intended functioning in appropriate conditions

In a first stage the results of the regular dynamic behaviour of the wind farm response during a three-phase voltage dip in RMS simulation is presented.

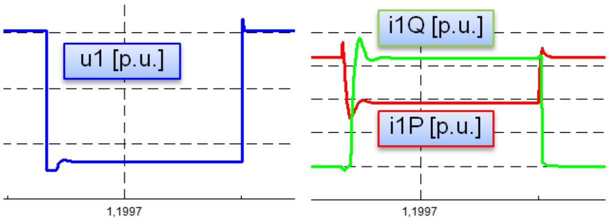

Fig. 4: Active (i1P) and reactive (i1Q) current response on a voltage dip in positive sequence p.u. values

Figure 4 illustrates qualitatively the proper injection of reactive current during the voltage dip in accordance with an initialised proportional constant (here: k = 2). The scaling has been removed to outline the basic principle. Before the system fault occurs the voltage is constantly remaining on its nominal value. The wind farm is controlled to regulate a unique power factor at the PCC (cosφ = 1). Depending on the wind conditions the wind turbines generate active power. In the event of the fault the voltage drops to a remaining value outside of the voltage dead band of normal operation. Following the disturbed voltage value the wind turbine detects a common failure mode and sets internally the reference value of the corresponding reactive current provided by the current controller. Since the reactive current injection is given priority during the failure mode the active current needs to be reduced due to the limitation on the nominal current in the power converter. An impact of the reactive current in-feed can be seen in the raise of the voltage in the disturbed condition. In case that the voltage dip is deep enough (at k = 2 below 40% of nominal voltage) the converter would be fully saturated by injecting reactive current whereas active current is reduced to almost zero. When the voltage returns in its normal operation ranges the wind turbines detect fault clearance and continue with the pre-fault operation mode within the required time.

High values of k-factor

The net short circuit power gives information about the robustness of the system at a specific location of the grid, e.g. the PCC. The higher its value is the stronger the grid and its capability to withstand disturbances in the grid. Due to the possible wide range of the k-factor a system operator with a relatively weak power system at the PCC may choose a high k-factor to be initialised at the wind turbines to maximise the voltage support of the wind farm during the fault. Hence, the wind farm has a rather high influence on the system.

Derived from this consideration a scenario is created where the net short-circuit power at the PCC is reduced to 120 MVA and the system operator chooses a high initialisation for the reactive current contribution. In Figure 5 the impact of the wind farm in the event of a voltage dip to a value of 75% of nominal voltage with a predefined k-factor (k = 5) is shown.

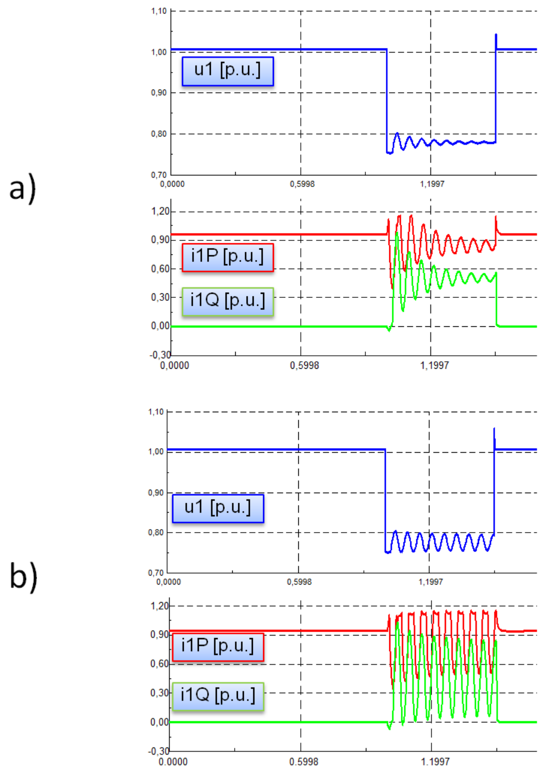

Fig. 5: Wind farm response at high k-factor and cable connection length of a) 15 km b) 25 km

The oscillations are a result of the lacking clarification and specification of the reactive current injection requirement in the grid code. If the voltage drops to values where the reactive current saturation of the power converter has not completely been reached, the shown behaviour might occur. The turbines generate the specific reactive current which leads to a voltage increase and the intended support. However due to the resulting higher value of the voltage the reactive current reference value of the current controller of the wind turbine will be recalculated and reduced because the failure mode control of the wind turbine is regulating continuously. Since the k-factor is comparatively high this means that due to the steep gradient in the characteristic the reactive current will be reduced disproportionally to the voltage increase. This again causes a drop in the voltage during the dip because the wind farm has a strong influence on the weak power system and so on.

The effect of the oscillations becomes even worse when the length of the wind farm connection cable is increased. To avoid this behaviour the current controller should determine the reference value of the reactive current based on its first set point when the fault is detected and remain there until the system is restored. That however could not be desired if the voltage decrease continues. Therefore high values of k-factors in practice must be analysed carefully.

Very low k-factors

Additionally dangerous system conditions might occur if very small values of k-factors are used ($k < 1$). A value of zero means preferably a continuously high active power production whereas no additional reactive current is injected. Practically the RES do not support the voltage anymore. This setting and configuration respectively becomes progressively instable the lower the voltage drops. Instabilities can especially occur when the wind farm operates at rated power and the voltage dip is in addition very deep e.g. below 20% of nominal voltage. Then the in-feed of active power may not be feasible anymore. For these situations the wind turbine itself is normally equipped with a self-protection mode which ignores the external difference in voltage angles and a synthetic angle reference is used as base value. However there are also constellations where instabilities appear before the threshold value for activating the protection mode is reached. That is also the reason why system operators often desire a rather passive behaviour of RES without any power in-feed during the voltage dip. Derived from the experiences in certification of the electrical characteristics of dispersed power generators in Germany this is demanded in the majority of projects where the farms are connected to medium voltage levels [5]. This performance mode however is technically only feasible by a few manufacturers of RES.

CONCLUSION

The provided analysis focused on the stipulated characteristics of RES to withstand voltage dips (LVRT) and dynamic current injection during grid faults with special consideration of wind farms. Purpose of these requirements is on the one hand to maintain a balanced share of connected generators for frequency stability in case of voltage dips while on the other hand RES shall moreover counteract the expansion of the fault by contributing to voltage stability. In contrast to the advantages and sense of its basic idea this requirement lacks in clear definition of references and terms. Additionally there are also undefined requirements according to the regulation behaviour of the controller itself. In this context it has be shown that in certain configurations a high value of the k-factor can lead to instabilities as well as voltage and power oscillations at the PCC. These operation conditions shall categorically be prevented otherwise it will impair the system state and affect its stability. Thus the wide range of high values of the k-factor as well as the neglecting of the smaller ones needs to be questioned and its technical benefit can be doubted e.g. in protection matters or distribution networks with low net short circuit power. Consequently any sensitively designed grid code especially with a pan-European scope should take these shortcomings carefully into account. Therefore the study provides a critical analysis with the aim of investigating and evaluating modern grid code requirements to contribute to an improved and coherent system integration of RES.

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