Chapter 14
Generic DSL-Based Modeling and Control of Wind Turbine Type 4 for EMT Simulations in DIgSILENT PowerFactory

Abdul W. Korai, Elyas Rakhshani, José Luis Rueda Torres and István Erlich

Abstract In this chapter, to cope with new challenges arising from the increasing level of power injected into the network through converter interfaces, a new wind turbine (WT) as well as a VSC–HVDC control concept, which determines the converter reference voltage directly without the need for an underlying current controller, is presented and discussed. Additionally, alternative options for frequency support by the HVDC terminals that can be incorporated into the active power control channel are presented. The implementation steps performed by using DSL programming are presented for the case of EMT simulations. Simulation results show that the control approach fulfills all the operational control functions in steady state and in contingency situations supporting fault ride through and emergency frequency support, without encountering the problems arising from current injection control.

Keywords DIgSILENT EMTP simulation · DSL programming
Wind turbine control · HVDC control

14.1 Introduction

Application of proper software, like DIgSILENT PowerFactory, for analyzing the future grids with power electronic-based generation like wind turbine (WT) generation considering the fact that future WT will be required to participate on active and reactive power management systems, is the motivation of presented material in this chapter. Future WT should be able to contribute on reactive power

A. W. Korai · I. Erlich
Institute of Electrical Power Systems, University Duisburg-Essen,
Duisburg, Germany

E. Rakhshani · J. L. Rueda Torres (✉)
Department of Electrical Sustainable Energy, Delft University
of Technology, Delft, Netherlands
e-mail: j.l.ruedatorres@tudelft.nl

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management and be involved in continuous voltage control like the synchronous machines currently are. Furthermore, how and in what form the converter-based generations may be involved in primary frequency control or even providing virtual inertia is still a challenging issue.

This chapter provides a control approach which achieves all the standard control objectives without encountering the problems arising from current injection control from the conventional control of WT. On the basis of these new control approaches, the implementation of coordinated var-voltage control and alternative frequency support schemes will be presented and simulation results that demonstrate the feasibility of the new approach will be provided. All the simulation are presented and discussed using the functionalities of DIgSILENT simulation language (DSL) for EMT-based models.

This chapter is organized as follows: In Sect. 14.2, a review on wind model and its mathematical equations is presented briefly while in Sect. 14.3 the background on the current injection-based control for WT is reviewed. Then, in Sect. 14.4, details of the proposed generic control approach for WT is presented and discussed. In Sect. 14.5, DSL-based control implementation in DIgSILENT PowerFactory is explained and finally in Sect. 14.6 the performance of the proposed control for WT modeling in DIgSILENT is simulated and analyzed for one power system case study with different contingencies. Summary and main conclusions of this chapter are also presented in Sect. 14.7.

14.2 Wind Turbines Technologies

There are four main technologies for wind turbine (WT), such as fixed-speed, variable speed, doubly fed induction generator (DFIG)-based WT and variable speed full converter wind turbine (FCWT). The first concept is a fixed-speed wind turbine equipped with a squirrel cage induction generator. The second one is a variable speed wind turbine with variable rotor resistance, which usually is used by Vestas [1]. This type of wind turbine technologies is using a wound rotor induction generator which is equipped with variable rotor resistances. The rotor resistances are regulated by means of a power converter. This concept is known as the limited variable speed concept. The third technology for WT is based on a variable speed wind turbine with a partial power converter or a wind turbine with a doubly fed induction generator (DFIG).

The fourth technology will be a variable speed FCWT. This concept can use different type of generators, like induction generator or a synchronous generator, with permanent magnets or external electrical excitation.

In case of FCWT, its functionality is more adaptable with the stringent grid codes which are currently required wind turbines to have high immunity against grid faults. In addition, FCWT type wind turbines can provide more reactive power support which are highly preferable. For these reasons, FCWTs are increasingly penetrating the market.

Normally, the turbine concept will be consisted of one generator which is interfaced directly to the grid with a back to back converter. This generator can be a synchronous generator, with or without a gearbox, or an induction generator type including its gearbox. The converter part is normally made of IGBTs [2] while the grid/line-side converter, which mainly acts as a current-regulated, voltage-fed inverter, can provide reactive power support to the grid. In case of FCWT, different types of generators can be used like a permanent magnet synchronous generator (PMSG), an electrically exited synchronous generator and an induction generator. As it is explained, modern wind turbines are able to control active and reactive current and thus active and reactive power independently. In the wind turbine concept with a fully rated converter (so-called Type 4 wind turbine, Fig. 14.1), the grid or line-side converter (LSC) is fully responsible for the control actions toward the power system and rotor-side converter (RSC) is responsible for converter control actions [3, 4]. Therefore, the LSC is usually equipped with decoupled current control in which the active power output is controlled via the DC voltage and the reactive power, alternatively power factor or terminal voltage, is regulated via other external control loops.

In steady state, the priority of the LSC control is on the feed in of active power delivered by the wind turbine. However, the wind turbines are also able to supply reactive power within a certain range in addition to the active power.

In case of large voltage drop or voltage rise, converter switches from active current priority to a reactive current priority. This means that the active current and thus active power will be reduced, if necessary, in favor of reactive current. The aim of injecting capacitive or inductive current during large voltage deviations is the stabilization of the voltage [5].

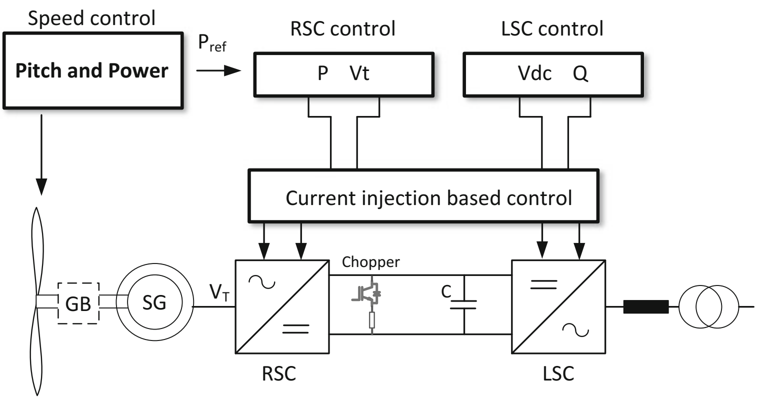


Fig. 14.1 Type 4 full converter wind turbine

14.2.1 Full Power Converter Wind Turbine with PMSG

Since in a permanent magnet synchronous generator the excitation can be provided by the permanent magnets, it does not require a separate rotor excitation. Thus, no rotor winding is needed. This advantage can significantly reduce the excitation losses as well as the torque density of the generator [6].

In the PMSG model, it is assumed that the flux is sinusoidally distributed along the air gap and therefore, no damping winding is considered. The mathematical equations can be made by aligning the d-component of machine vectors to the rotor flux. Therefore, voltage equations of the machine will be as follows:

$$v_{sd}^r = R_s i_{sd}^r - \omega_r \psi_{sq}^r + \frac{d\psi_{sd}^r}{dt} \tag{14.1}$$

$$v_{sq}^r = R_s i_{sq}^r - \omega_r \psi_{sd}^r + \frac{d\psi_{sq}^r}{dt} \tag{14.2}$$

with the stator flux components obtained from

$$\psi_{sd}^r = X_{sd} i_{sd}^r + \psi_{pm}^r \tag{14.3}$$

$$\psi_{sq}^r = X_{sq} i_{sq}^r \tag{14.4}$$

where v_{sd}^r and v_{sq}^r are the d and q components of the terminal voltage vector, respectively; i_{sd}^r and i_{sq}^r are the d and q components of the stator currents, respectively; R_s is the stator resistance; X_{sd} and X_{sq} are the d and q components of the stator reactances, respectively, and ψ_{pm}^r is the permanent magnet flux linkage. Superscript r will indicate the corresponding variable which is related to the rotor flux reference frame.

The electromagnetic torque of PMSG can be also expressed by

$$T_e = i_{sq}^r \left(i_{sd}^r \left(X_{sd} - X_{sq} \right) + \psi_{pm}^r \right) \tag{14.5}$$

For a non-salient pole machine, the stator inductances X_{sd} and X_{sq} can be assumed to be equal. Consequently, the d-component of the stator current i_{sd}^r does not influence the electromagnetic torque.

14.2.1.1 Rotor-Side Controller

Typically, the generator/rotor-side converter will regulate generator speed and power [7, 8]. The converter can be also employed to control the dc-link voltage [2]. In addition to these control actions, the converter can be used to control the reactive power exchange with the generator. The controller can be implemented using the vector control technique, in a way that the *d*-axis is aligned to the rotating stator flux. Using this control method, various control strategies like full torque control or constant stator voltage can be implemented.

14.2.1.2 DC-link and Line-Side Controller

The line-side converter equations can be expressed in *dq*-components aligned with the grid voltage vector. Normally, the line-side converter is assigned to maintain the dc-link voltage level and reactive power injection into the grid [7, 8]. Otherwise, the line-side converter can also be used to control the active power of the wind turbine. An independent control of active power or the dc-link voltage on one side, and reactive power on the other side, can be realized using a vector control aligned with the grid voltage vector.

Finally, the complete model of WT will have several order but sometimes it is possible to reduce the order of such model or make some simplification depending on the objectives of the analysis. Complete details of turbine modeling and mechanical components can be found in [4]. For further simplification, mechanical equations can be also omitted and DC input can be considered with a controlled current source. It should be mentioned that the aerodynamic model is, in fact, the same as those in wind turbines with doubly fed-induction generators as described in [4]. The main purpose of the pitch controller is to limit generator speed and power output at rated value.

14.3 Review on Current Injection-Based Control of WT

The common current control approach shown in Fig. 14.2 uses two current feed-forward terms and two PI control blocks. Furthermore, the grid voltage is added to the d-channel output which represents an additional feed-forward term.

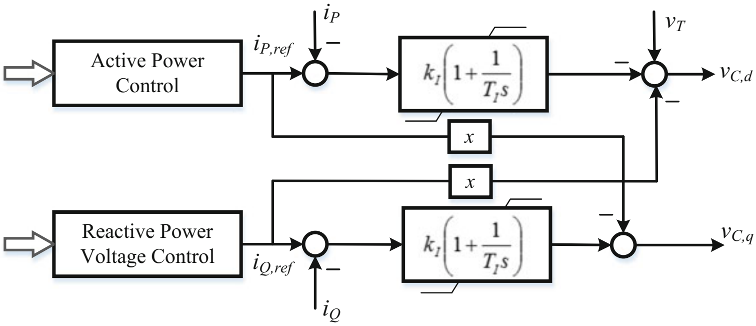


Fig. 14.2 Classical control approach

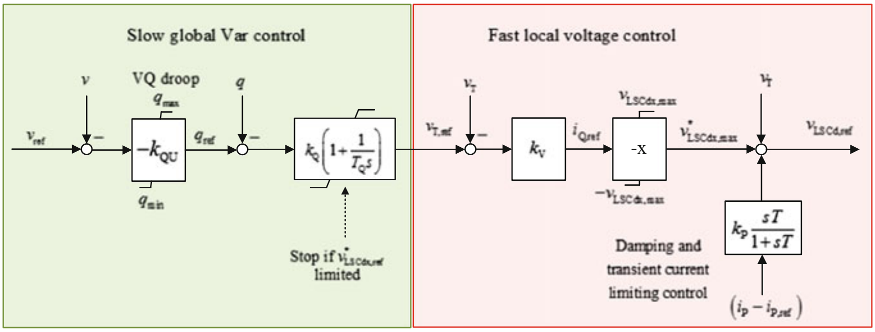


Fig. 14.3 Var-voltage control approach for WT

Control input of the active current controller is the active current reference forwarded from the DC voltage control.

Feedback signal is the measured active current. Control input for the reactive current controller is the reactive current set point from outer reactive current set-point calculation (see Fig. 14.3). The feedback is the measured reactive current where k_I and T_I are controller parameters which act as a filter, i_P and i_Q denote the grid current components, v_T is the grid voltage, $v_{C,d}$ and $v_{C,q}$ denote the converter voltage vector components.

The output of both PI controllers is ideally zero because the feed-forward terms take care of the main control actions. The PI controllers account for parameter and measurement uncertainties and are normally limited to the nominal current of the LSC. Output of the current control is the reference voltage of the converter [4].

With the projected future scenarios ranging from 50 to 100% renewables, it is obvious that a new converter control scheme is required which adapts automatically to the current depending on the grid conditions by trying to fulfill the main objectives of voltage and frequency control.

14.4 Proposed Generic Control Scheme for WT Application

In this section, a generic control technique for grid forming WTs is proposed. In the presented control for WT, on the one hand, it does not necessitate current injection for the controller to function properly, and on the other hand, it is capable of mitigating some of the problems arising from the presence of converters in large number.

The main control loops of the presented control approach are var-voltage and active power/frequency control loops.

14.4.1 Var-voltage Control Channel

As shown in Fig. 14.3, the reactive power reference, in the proposed solution for the var-voltage control channel, is based on a droop characteristic. The response time of this controller is set 5–30 s, large enough to avoid significant control action during network short circuit and small enough to preclude unnecessary tap movement in on-load tap changing (OLTC) transformers.

This control approach consists of a slow global controller, as explained, and a fast local controller for voltage control and damping.

The damping term replaces the proportional component of the PI block in the standard implementation at the moment. It offers also additional possibilities in terms of selective damping, and for the converter required current limitation is achieved through output voltage limitation. After the addition of the controlled terminal voltage (the feed-forward term), the d-component of the inverter voltage is determined. As can be seen, the reactive current no longer appears explicitly in this scheme, and as a result, there is no risk of integrator windup in the event of an unforeseen islanding. The current adjusts itself according to the network conditions in response to a changing converter voltage. The output of the voltage controller is also limited for taking into account the current limitation of the converter. The maximum value $v_{\mathrm{LSC,max}}$ was calculated depending on the selected active or reactive current priority. The limited output is then added to the measured grid voltage (see Fig. 14.3). The result represents the LSC voltage reference in the d-axis. This maximum value calculation of those limiter can be also applied for active power controller of the next subsection.

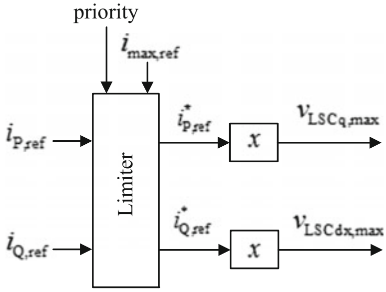
The converter current is limited through the voltage thresholds $v_{\mathrm{LSCdx,max}}$ and $v_{\mathrm{LSCq,max}}$. Calculations can be made as follows:

14.4.1.1 Part 1: Limiting of the Real Current (Current Limiting Control)

If $\left(|i_d + j\, i_d| - i_{\mathrm{max0\_ref}}\right) > 0 \rightarrow i_{\mathrm{max\_ref}} = i_{\mathrm{max0\_ref}} - k_{\mathrm{red}} \cdot \left(|i_d + j\, i_d| - i_{\mathrm{max0\_ref}}\right)$
else $i_{\mathrm{max\_ref}} = i_{\mathrm{max0\_ref}}$

14.4.1.2 Part 2: Limiting of the Current Reference

As long as the reference current is not limited $v_{\mathrm{LSCd,\,max}} = v_{\mathrm{LSCq,\,max}} = x.i_{\mathrm{max,\,ref}}$
otherwise $v_{\mathrm{LSCd,\,max}} = x \cdot i^{*}_{Q,\,\mathrm{ref}}$; $v_{\mathrm{LSCq,\,max}} = x \cdot i^{*}_{\mathrm{P,\,ref}}$



Considering current priority in reference current limitation:

14.4.2 Active Power Control Channel

The proposed control schema is shown in Fig. 14.4. The structure of DC voltage controller with the PI characteristic is the same as in previous controller schemes. The output of the DC voltage controller is the active power injected into the network:

$$p = v_T i_P = -v_t \frac{v_{cq}}{x} \tag{14.6}$$

As can be seen in (14.6), the active power can be controlled using the q-component of the converter voltage, which can also be used to limit the current. Please note that no integral current injection is used, and the actual active current adjusts itself in accordance with the power flow equations of the network. For frequency control, three options are given in Fig. 14.5. As it has been explained, the current magnitude limitation is also possible according to the selected priority.

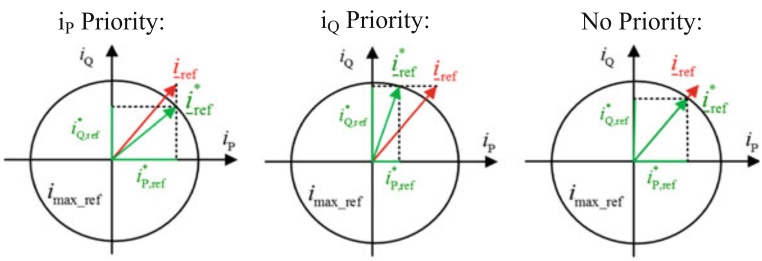


Fig. 14.4 Current priority limitations

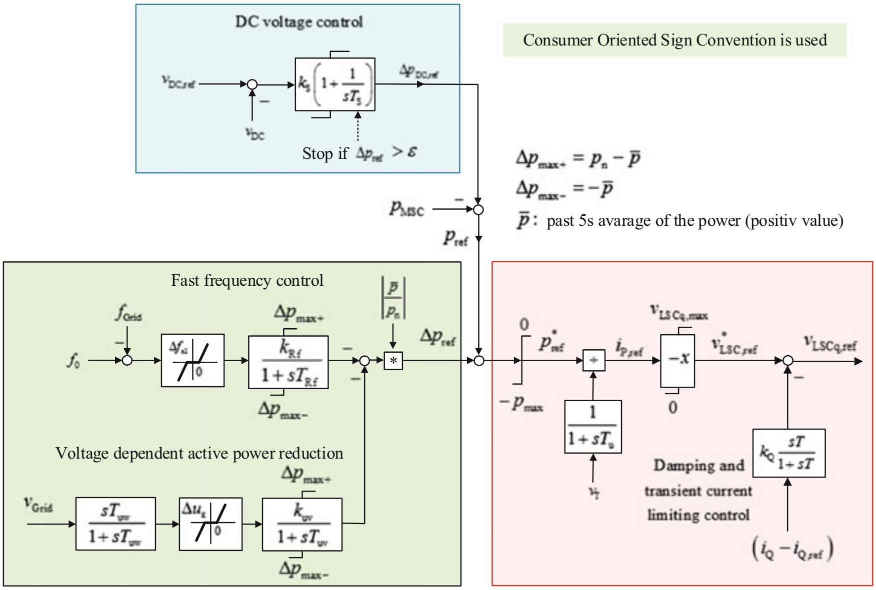


Fig. 14.5 Proposed control schema in active power control channel

14.4.2.1 Option A: Over-frequency Emergency Control (OFEC)

The control is activated when the frequency exceeds a preset threshold value, e.g., 50.2 Hz in the example in this paper. The gain k_{Rf} defines the frequency deviation at which the power reduction corresponds to the total power p_{ref} (e.g., 51.5 Hz). The time constant T_{Rf} is small totally with the fast response time of converters. One can also define in the delay block a limitation of rate of change, the effect of which will be demonstrated in the next section.

14.4.2.2 Option B: Direct Frequency Control

This method is similar to Option A with the only difference that frequency control takes place for frequency errors in both directions, i.e., at both under frequency as well as over frequency. Normally, this control is significantly slower than Option A and contains only a small dead band (e.g., 20 MHz).

It is intended to contribute to frequency regulation in normal operation and is also a requirement in ENTSO-E.

14.4.2.3 Option C: Inertia Control

This option represents the well-known inertia control with extension in both frequency change directions. This means the controller can also contribute to the stabilization of the frequency by reducing the power at the expense of a speed increase in wind turbines during an over-frequency event. In the case of grid frequency drop, the controller will increase the power temporarily. The activity of this controller is restricted to a narrow time band due to the washout filter at the frequency input.

14.5 DSL-Based Control in DIgSILENT PowerFactory

Figure 14.6 shows the model of the grid side converter, which was built as a composite model and contains the following components: (a) converter used in wind farm model which includes the PWM converter (ElmVsc), (b) DC voltage and power controller (Udc_PQ controller, ElmDsl); (c) current controller (ElmDsl), (d) DC model (ElmDsl), (e) AC voltage measurement (StaVmea), (f) AC current measurement (StaImea), (g) power calculation block (ElmDsl), (h) Park transform (ElmDsl), model of current source used in simplified WT (ElmDsl), PLL: angle measurement (ElmPhi_pll), and (i) Mod Limiter (ElmDsl).

Correct initialization of a model in a power system simulation tool avoids fictitious electrical transients and makes it possible to evaluate correctly the real dynamic performance of the system. Therefore, the initialization equations of important dynamic block of this composite model are presented below:

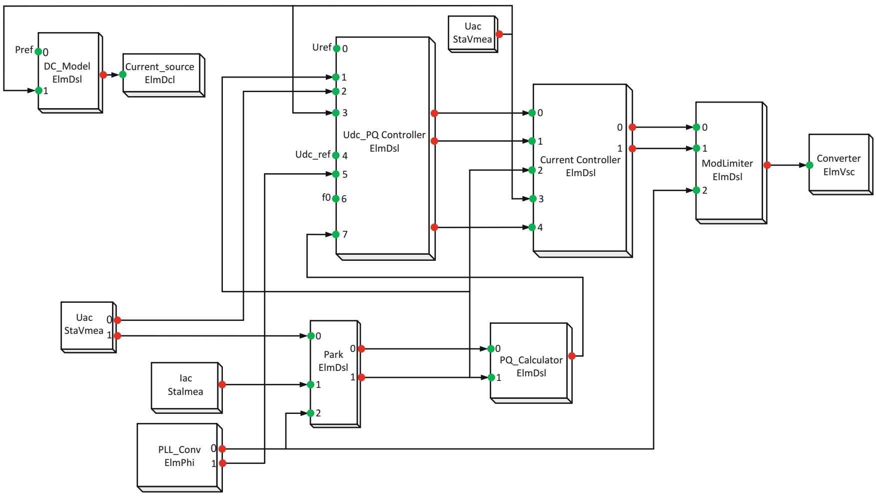


Fig. 14.6 Structure of the grid side converter model in PowerFactory

DC Model initialization:

```
vardef(VdcN)='kV';'Nominal DC Voltage'
vardef(Vdcmax)='kV';'Max DC Voltage'
vardef(Pnom)='MW';'Nominal active power of the converter'

inc(xr)=1
inc(vdc)=1
inc(pref)=-1
```

Mod Limitation initialization:

```
inc(ud_ref)= ur*cos(phi) + ui*sin(phi)
inc(uq_ref)=-ur*sin(phi) + ui*cos(phi)
inc(ur)=Pmr /0.612
inc(ui)=Pmi /0.612
```

Current controller initialization:

```
vardef(Kw) = '-';'Washout out filter gain'
vardef(Tw) = 's';'Washout filter time constant'
vardef(Un) = 'V' ; 'Nominal AC voltage of converter'
vardef(UDCn) = 'V' ; 'Nominal DC voltage of converter'
vardef(ud_min) = 'pu' ; 'Minimum modulation index d-channel'
vardef(uq_min) = 'pu' ; 'Minimum modulation index q-channel'
vardef(ud_max) = 'pu' ; 'Maximum modulation index d-channel'
vardef(uq_max) = 'pu' ; 'Maximum modulation index q-channel'

inc(uq_set)=0
inc(xdw)  =0
inc(xqw)  =0
inc(ulsc_d)=1

inc(id_ref_)=id
inc(iq_ref)=iq
Ksin = 2*sqrt(2)*Un/(sqrt(3)*UDCn)
```

Udc_PQ Controller initialization:

```
vardef(Kv) = '-' ; 'Global Var control P.constant'
vardef(Tv) = 's' ; 'Global Var control Integral time constant'
vardef(Kdc) = '-' ; 'DC link control P.constant'
vardef(Tdc) = 's' ; 'DC link control Integral time constant'
vardef(uDC_CHon) = 'pu' ; 'Chopper activation voltage level'
vardef(uDC_CHoff) = 'pu' ; 'Chopper deactivation voltage level'
vardef(iChopper) = '-' ; 'Chopper active [1]- inactive[0]'
vardef(Ku) = 'pu' ; 'Fast voltage control P.constant'
vardef(db_spannung_VDACR) = 'pu' ; 'deadband for VDAPR'
vardef(irmax) = 'pu' ; 'Maximum converter current'
vardef(Tuu) = 's' ; 'Voltage measurement delay'
vardef(T_rate_limit_freq) = 's' ; 'Frequency control time delay'
vardef(l) = 'pu' ; 'Converter reactance'
vardef(T) = 's' ; 'VDAPR washout filter time constant'
vardef(qmax) = 'pu' ; 'Maximum reactive power in steady state'
vardef(Kvdapr) = '-' ; 'Gain of the VDAPR'
vardef(Tvdapr) = 's' ; 'Time delay of the PT1 filter of VDAPR'
vardef(Tp_aver) = 's' ; 'Time constant for the calcualtion of p average'
vardef(Kqu) = '-' ; 'Static gain of the reactive power control'

inc(ulsc_d)=1
inc(xv)= 1.01
inc(qref)=q
inc(xu)=ulsc_d
inc(id_ref)=-0.95/us
inc(idref)=-0.95/us
inc(uref)=us
inc(xdc)=id
inc(udc_ref)=1
inc(xtst)=-0.95
inc(xuuu)=0
inc(xuu)=us
inc(x)=us
inc(f0)=50
inc(xp_avg)=p
inc(xf)=0
```

14.6 Performance Evaluation in DIgSILENT PowerFactory

As shown in Fig. 14.7, wind farm model used in this chapter is a simplified model including controlled current source, wind IGBT-based converter, chopper, series reactor and compensation and grid side transformer.

An example of a grid model is also depicted in Fig. 14.8. It contains the connection of the wind farms with 25 MW and five units of 5 MW farms to the main grid. The connection of the wind turbine to the station is modeled by the actual physical component models from DIgSILENT library (transformer, line, load, bus bar), while the remaining power system is represented by simplified equivalents, as, e.g., a Thevenin equivalent models the grid. This is a reasonable approximation for

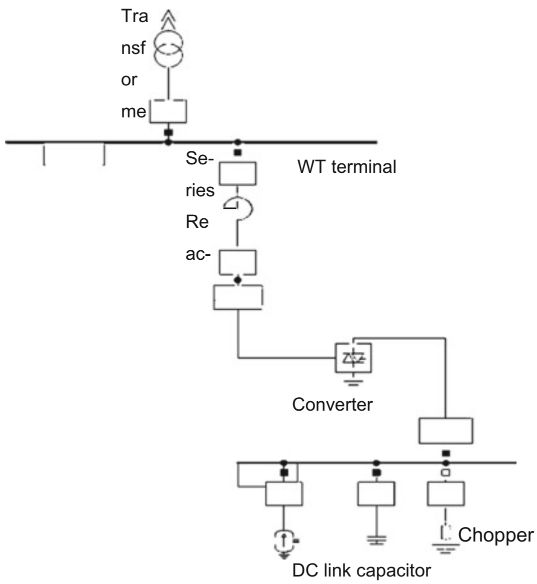


Fig. 14.7 Single line diagram of the full converter model in DIgSILENT

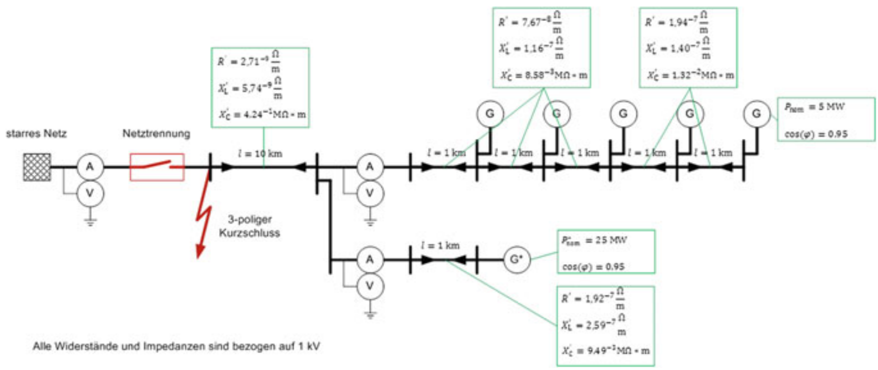


Fig. 14.8 Test system used for simulations with wind farms

power quality studies, as the grid is assumed very strong as compared to the power capacity of the wind turbine.

Three-phase short circuit and islanding action are used for testing the performance of the proposed model. The time response in terms of grid frequency, bus voltage magnitude as well as injected currents to the grid (i.e., the point of common coupling of the FSC-based WT) for a three-phase grid fault for a duration of 150 ms is analyzed for illustrative purposes.

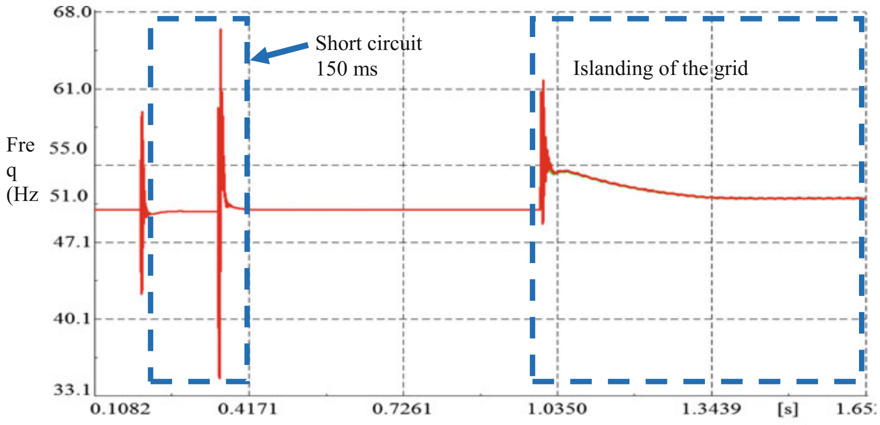


Fig. 14.9 Frequency of the grid

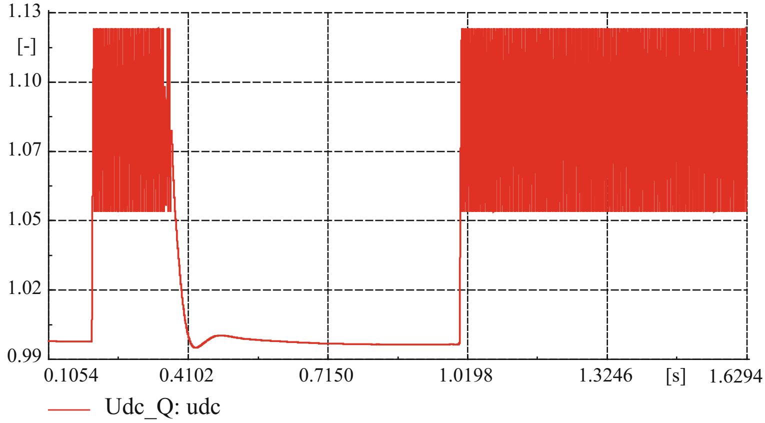


Fig. 14.10 DC-link voltage of the WT

Figures 14.9 and 14.10 show the variation of the frequency of the grid and the DC-link response following the interruption of the connection to the external grid for these scenarios.

Current response of the converter, comparing the measured and reference currents, during three-phase short circuit and for islanding action is also presented in Figs. 14.11 and 14.12, respectively.

Instantaneous voltages and currents are plotted for both the short circuit and islanding events in Fig. 14.13.

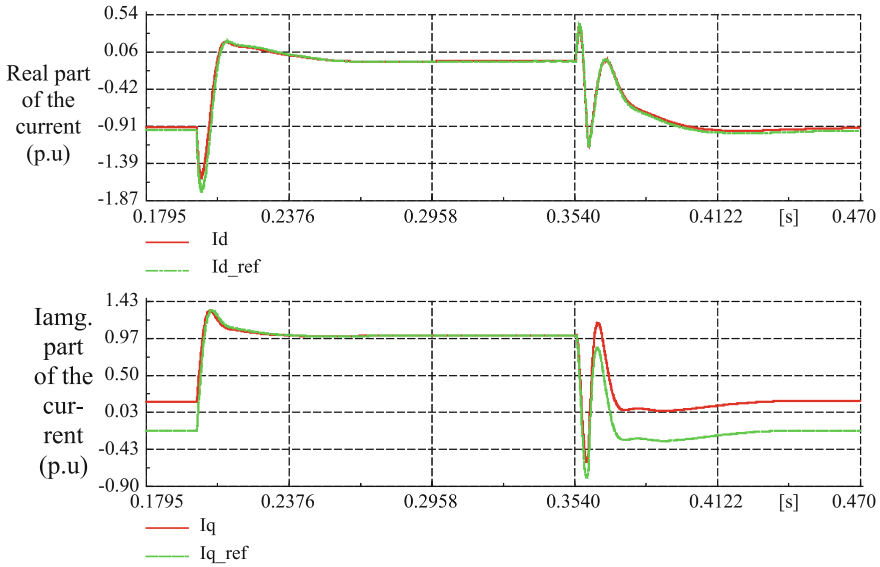


Fig. 14.11 Converter current during three-phase short circuit

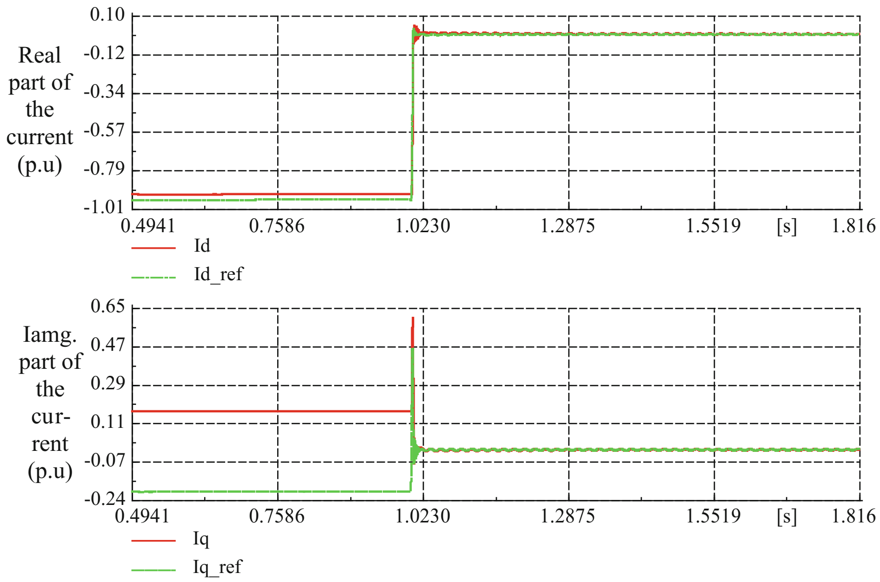


Fig. 14.12 Converter current after islanding

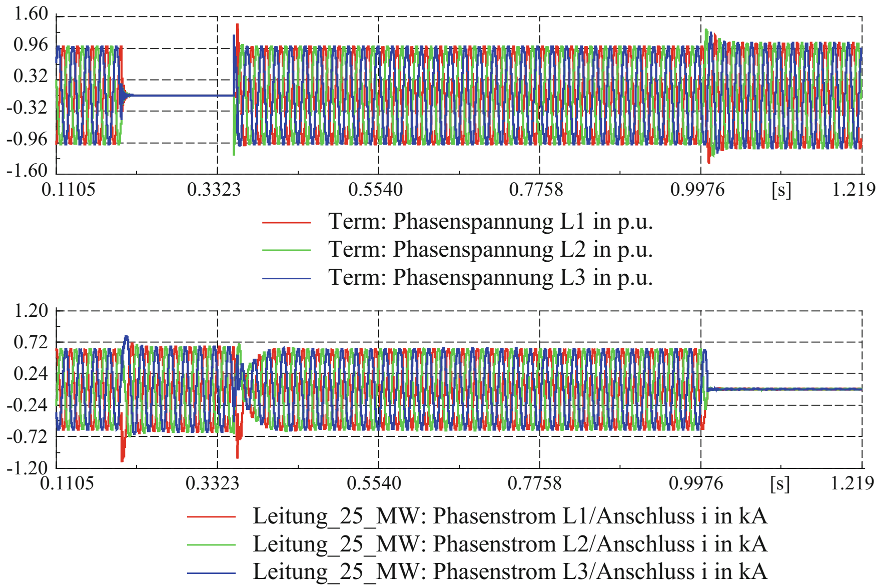


Fig. 14.13 Instantaneous voltages and currents (1 Mvar capacitive, three-phase short circuit at 0.2 s, Islanding at 1 s)

14.7 Conclusions

In this chapter, the implementation of generic model of WT type 4 for dynamic simulations in DIgSILENT PowerFactory was presented. The control implementation and its initialization in PowerFactory were also explained.

Due to the problems raised by classical PI blocks in the current injection-based controller, a new generic control considering both active power and var-Q control is performed. Active power control is performed using the DC voltage controller. For var-voltage control, a hierarchical scheme is suggested based on a slow var controller with PI characteristic and a local fast voltage controller with proportional characteristic. To achieve sufficient damping, two damping control blocks are included to the output of the controllers. These controllers are only active in the transient period due to the wash-out filter implemented.

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