Journal of Computer Science and Cybernetics, V.30, N.4 (2014), 313–334
DOI: 10.15625/1813-9663/30/4/5762

REVIEW PAPER

GENERAL OVERVIEW OF CONTROL PROBLEMS IN WIND POWER PLANTS

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Abstract. Wind power plants can be realized with different generator types using different control principles. The choice of the generator regardless of control method, potentially destabilizes the grid, and can even lead to grid collapse. For independent grid (e.g. on islands) this risk is especially great. The report aimed at giving the reader a general overview of the control methods, and the developers a better understanding of each generator type to get the right choice for their wind power project.

Keywords. Wind power plant, DFIG, PMG, front-end converter, generator-side converter, grid voltage oriented control, linear control, exact linearization, flatness-based control

Abbreviations

DFIG	Doubly-fed Induction Generator	IG	Induction Generator
DPC	Direct Power Control	LLDG	Low-Load Diesel Generator
DTC	Direct Torque Control	MPPT	Maximum Power Point Tracking
ESS	Energy Storage System	PMG	Permanentmagnet Excited Generator
FC	Frontend Converter	SCADA	Supervisory Control and Data Acquisition
GC	Generator-side Converter	WPP	Wind Power Plant
GVOC	Grid Voltage Oriented Control	WT	Wind Turbine

1. INTRODUCTION

Currently the exploitation of wind energy receives increasing attention from the society in Vietnam. Many projects have been carried out, in parallel with both (more or less) successful and not yet successful results. The weaknesses that make exploitation of such systems more difficult are caused by insufficient understanding of the operating principles, especially the principle of control. Even the projects with (more or less) success also contain potential long-term risks to the national grid. On the one hand the paper presents an overview of the control methods in WPP system, on the other hand it points out the mistakes susceptible in WPP projects in Vietnam.

We know, energy can be extracted from the wind (Figure 1, [1]) by the following formula:

$$P = \frac{1}{2}\rho_w \, A \, v_w^3 C\left(\lambda,\, \beta\right), \tag{1}$$

where P: power; ρ_w: density of air; A: swept areas of blades; v_w: wind speed; λ: ratio of the rotational speed of the turbine to wind speed; β: angle of rotor blades

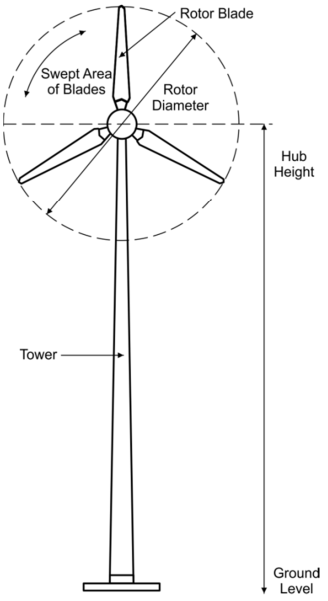


Figure 1: Exploiting the power from wind turbines

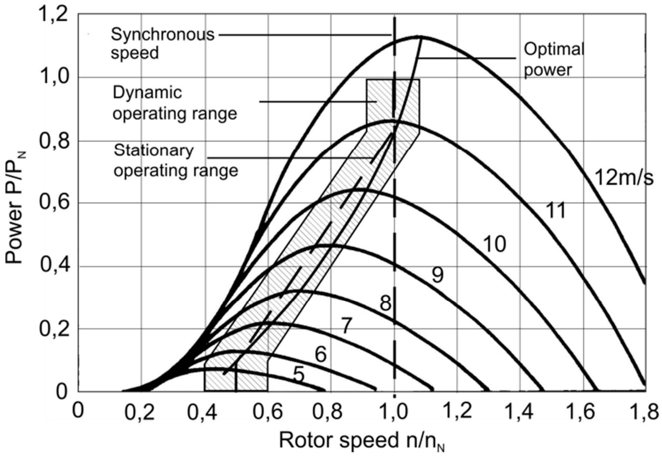


Figure 2: Characteristic curves for power extraction from wind

In formula (1), $C(\lambda, \beta)$ is the coefficient reflecting the characteristics (the ability to exploit energy) of wind turbines. This coefficient is also the secret of the manufacturer, making up the difference between the turbines of different manufacturers. However, all types of turbines always have one thing in common, that is, the coefficient $C(\lambda, \beta)$ can always be reflected by a class of power curves, which are identical in principle and have the form as in Figure 2. These characteristic curves are kept confidential by manufacturers and stored in a look-up table to control turbines.

Characteristic curves in Figure 2 show: Each wind speed curve has a point with maximum capacity to exploit P. Therefore, if the consumer (the grid) is able to accept unlimited P, the control system is responsible for changing the turbine rotational speed (the working point) to reach and to maintain maximum power point. However, if the turbine is only permitted to generate a capacity of $P = \text{const}$, despite the fluctuation of the wind. Then, the rotational speed of the turbine would have to change constantly and the control becomes more difficult due to large inertia of the rotor blades [1].

2. CONTROL HIERARCHY

2.1. Operating modes of wind turbines

We can distinguish two modes of operation, and therefrom the two control modes of wind power generation systems.

2.1.1. Operating mode with the national grid

This operating mode is characterized as follows:

- The national grid can be seen as hard grid with extremely large P, with stable voltage and frequency.

- The active power is controlled following the curve with optimal power (Figure 2), to extract maximum power from the wind.
- The power factor $\cos\varphi$ is often fixed by value nearly 1. That means the WPP will neither generate nor consume a reactive power Q.

2.1.2. Independent operating mode without the national grid

Specific examples for this operating mode are WPPs on islands with following characteristics:

- Local grids are built by a group of diesel generators with small active power P. These are the so called *wind based hybrid power systems*.
- Local grids are soft grid whose voltage and frequency are unstable.
- The load is divided between the group of diesel generators and the WPP. The WPP may generate only a fixed active power $P = \text{const}$ (Figure 2) specified by the rate of distribution.
- The power factor $\cos\varphi$ of WTs should be set flexibly in the appropriate value to ensure safe and efficient exploitation of the diesel generators.

2.2. Control hierarchy of a WPP

Regardless of the used type of generator, the control system of a WPP is always structured by a 3-level hierarchy as in Figure 3.

2.2.1. Control level I

This control level has *the task of a SCADA system* serving the goal of WPP integration with the grid (national, local). Dependent on the operation mode this level decides the set points for P and Q. For large-scale systems (*wind park*), the level plays the role of the supervisory control equipped with the ability to communicate between members of wind park and the dispatching center. With the characteristics of a SCADA system, on this level we can specify our principles of energy management.

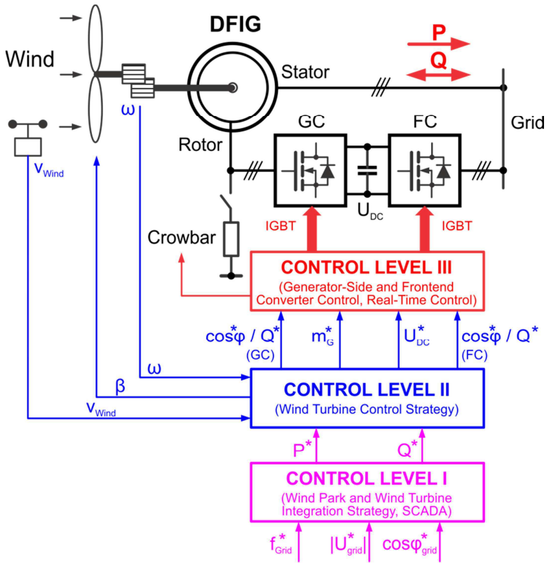


Figure 3: Control hierarchy of wind power plants

2.2.2. Control level II

This level realizes the *task of turbine control* with a feedback closed loop for the turbine rotor speed ω. Based on the measured wind speed v_{wind} and on the pre-selected operating mode, the system uses a *look-up table* to find the set points for the rotor speed ω which can be controlled by varying the blade pitch angle β. There are two things to note:

- In operating mode with extraction of maximum wind power the system uses a MPPT algorithm to reach the rotor speed ω on the top of the wind characteristics (Figure 2) dependently on the measured wind speed v_{wind}. MPPT algorithm is always a secret of turbine manufacturers, and users do not have the opportunity to intervene at this stage.

- Rotor and rotor system weigh many tons, resulting in a huge moment of inertia which limits the dynamic control of the blade pitch angle β in both operating modes $P = \text{const}$ or $P = \max$ (Figure 2).

2.2.3. Control level III

This control level contains the *real-time algorithms of the generator control structure* to control the flows of active power P (electric torque m_G) and reactive power Q (power factor $\cos\varphi$), fulfilling the demands of the level I. To control P and Q, the system uses a *back-to-back converter* with two parts GC and FC. The implemented control methods depend on:

- the type of the generator, and
- the operating mode (connected to the national or local grid).

It can be confirmed that the level III is responsible for the control system of WPP (characterized by rapid dynamics and small inertia, small sampling periods and small modulation periods), which is connected with grids (characterized by slow dynamics and large inertia), is really a challenge for investors. The incomplete understanding of this level is the potential risks mentioned from the beginning of the paper.

3. CONTROL PROBLEMS OF THE LEVEL III

3.1. Overview about control of generators

Figure 4 gives an overview of the control problems for generator types IG, DFIG or PMG ([2–4]) used in WPP. It can be seen:

- *In the case DFIG*: Because the back-to-back converter is located on the side of rotor circuit (not between the stator and grid like the cases IG and PMG), the power electronic converter must only be sized with nearly 1/3 power of the generator. The cost of systems using DFIGs is always lower than the cost of systems with PMGs.
- *In the cases IM, PMG*: Because the back-to-back converter is located between the stator and grid, the system cost is higher than the cost of DFIG systems, but easier to control.

We can divide the generator control problems into 2 groups: FC control and GC control with a lot of issues that need to be addressed, but not possible to be introduced in the limited framework of this paper. Depending on the type of generator DFIG or IG/PMG, the group of GC control can also be split into different solutions.

3.1.1. FC control

The control problems of this group are basically the same in all three cases IG, DFIG and PMG. It can be summarized as follows ([3, 7]):

- The main method is the GVOC. Some works have tested the method DPC inspired by the DTC of electric three-phase AC drives.
- The control must ensure the decoupling between P and Q, as well as the flexible setting of $\cos\varphi$. It only needs a linear control structure [7].

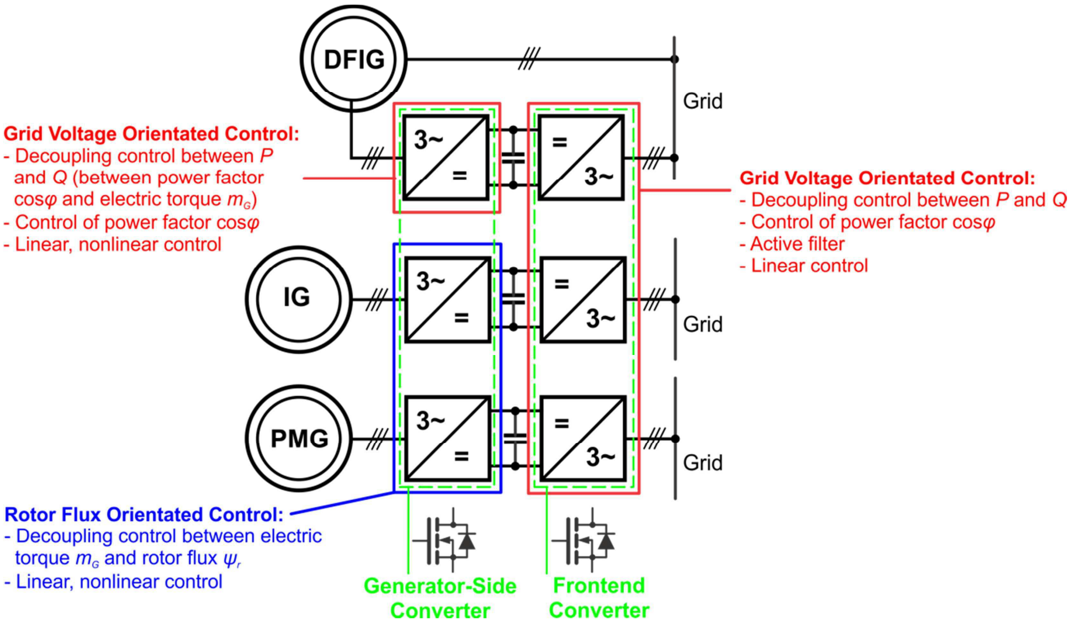


Figure 4: Overview of the control problems for generator types DFIG, IG and PMG

- The control must satisfy the regulations of the grid harmonics. In some cases the FC control can be extended by an active filter function.

3.1.2. GC control in the case DFIG

Because the stator of DFIG is directly connected to the grid, therefore this is the case with most challenge regarding to the generator control.

- The main method is the GVOC.
- The control must ensure the decoupling between P and Q (decoupling between m_G and $\cos\varphi$), as well as the flexible setting of $\cos\varphi$.
- The control structure can be either linear or nonlinear.
- Crowbar control.

3.1.3. GC control in the cases IG, PMG

In practice, the generator type IG is no longer used. Currently we can not find on the market this generator type used by turbine manufacturers, but only PMG. For PMG, there are 2 possible solutions for GC as follows:

- *GC is a simple non-controlled rectifier*: In this case following characteristics are to note.
    + The amount of the input energy on the primary side (wind energy) is decided only by the turbine control system (control of rotor speed ω). The input energy must be totally transferred to the grid.

  + A DC-DC boost converter must be used on the DC link to increase the magnitude of the DC voltage to the level of the FC input.

- *GC is a controlled rectifier*:

  + In combination with the turbine control, the GC can effectively control the energy flow from the primary side. The often used principle is the pole flux oriented control.
  + Decoupling control between the electric torque m_G and the pole flux ψ_p.
  + The control structure can be either linear or nonlinear.

3.1.4. Related control problems for both groups FC and GC

Beside separate control problems only for GC or FC, there are a lot of control task related to the complete system WPP:

- Fulfilling the *grid code* (more in section 4): While symmetrical or nonsymmetrical voltage dips, the WTs should be able to stay on grid and to handle without disconnection.
- The standard output voltage of WTs is 690V AC. The wind turbines must be equipped with 690V/22kV (or 690V/110kV) transformer to synchronize with the grid. This leads to problems to be solved:

  − The *neutral-point voltage* of the primary side varies. A neutral-point voltage control must be implemented to ensure that the DC current is zero.
  − *Common-mode voltage stress*: The switching action of the rectifier and inverter normally generates common-mode voltages which are essentially zero-sequence voltages superimposed with switching noise. This voltage is very harmful for the winding insulation, and causes ignition through the parasitic capacitance C_p which reduces the life of bearings.

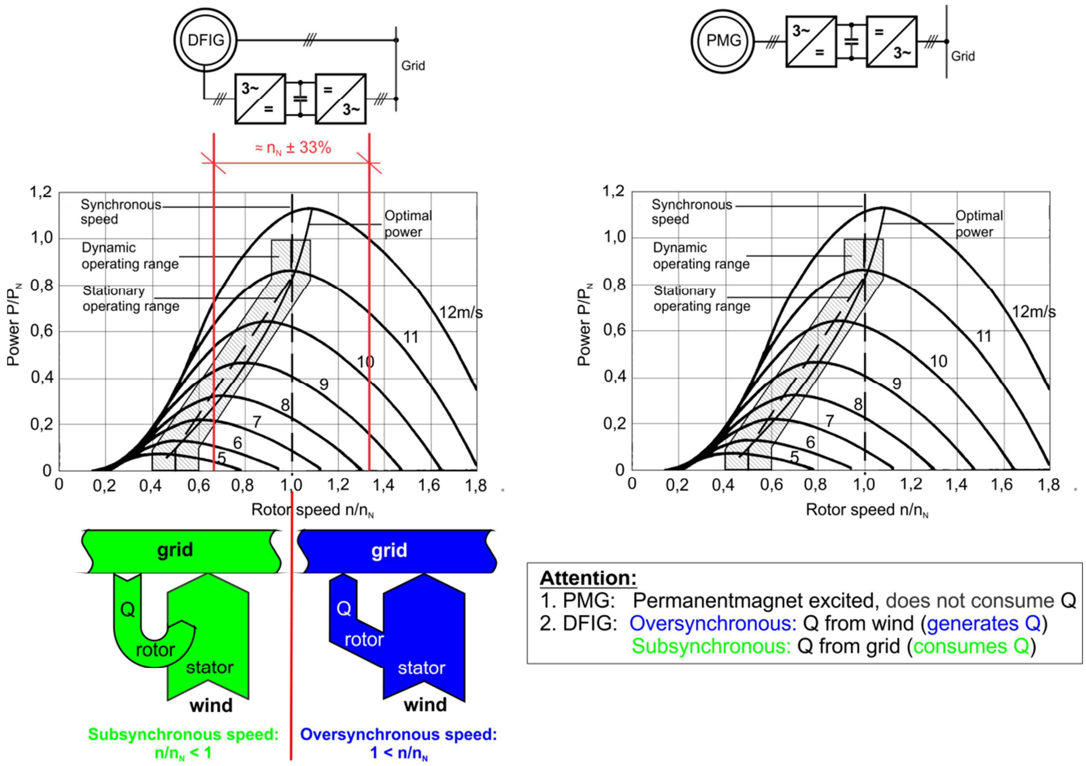
- Equipments supporting to stabilize the grid voltage in case of independent operating mode. The equipments can be either *energy storage systems* or *low-load diesel generators.*

  − The ESSs with the ability to charge or discharge energy very quickly can help to stabilize the grid voltage while *wind fluctuation.*
  − The main task of LLDGs is the generation of reactive power Q, and therefore the *generation of the grid* for WTs with DFIG. This equipment is not able to compensate the wind fluctuation.

3.2. Main difference between the DFIG and PMG control

To illustrate the difference between 2 generator types, we should begin with DFIG in Figure 5a. Because the stator of DFIG is directly connected with the grid, the turbine rotor speed ω as well as the rotational speed of the DFIG is bounded in the range ±33% compared with the synchronous speed. A brief statement of the main points of DFIG control can be given as follows [7]:

- *Range of oversynchronous speed*: Figure 5a illustrates clearly that in this range the energy, flowing through the rotor winding, is generated by the wind. That means, the reactive power Q is generated by the wind.



a) b)

Figure 5: Regarding to the rotational speed: a) the control of DFIG is dependent on range of oversynchronous or subsynchronous speed, and b) the control of PMG is nearly unlimited

- *Synchronous speed*: At the point of synchronous speed, corresponding to the stator frequency 50Hz, the rotor frequency is zero. A DC current flows in the rotor circuit. Special attention for this point in control concept is necessary, to avoid damages of the rotor.
- *Range of subsynchronous speed*: In this range Q is supplied by the grid. This is the main disadvantage, which limits the use of DFIGs for WPPs on islands.

In contrast to DFIG, Figure 5b shows that:

- PMGs are excited by permanent magnets and do not consume reactive power Q.
- The stator of PMGs is not directly connected with the grid. The rotor speed is not dependent on grid frequency, and this fact allows the power extraction from wind in a relatively wide range.
- WPP using PMGs is the only type of system, which can operate independently without grid (national and local).

4. CONTROL DURING GRID FAULTS

Previously, in order to protect itself when grid faults occur, the control system may separate WTs out off the grid. In recent years, the exploitation of wind power has reached the scale of the plant (*wind parks*); WPPs separation out off the grid potentially causes local oscillations. These local oscillations can spread out and lead to the risk of grid collapse.

To prevent this negative scenario, many countries have made regulations which strictly prohibit the separation out off the grid in some cases of grid faults. The WTs must have the ability to "*ride through*" during grid faults ([18–22]), and must be able to generate reactive power Q for supporting the grid stability as well as for avoiding the spread of voltage oscillations.

4.1. The term "grid code"

The mentioned ability to "*ride through*" during grid faults is standardized by the term "*grid code*" illustrated in Figure 6, in which the definition of the group E.On Netz (Germany) is clearly explained.

Here in words:

The grid voltage amplitude suddenly drops from 100% to 15% of the nominal level. The level 15% maintains approximately 500ms (25 grid cycles), then the grid voltage recovery increases steadily back to 90% (the allowed low level). In the whole process of grid faults 3000ms (150 grid cycles), the WPP is not allowed to separate itself out off the grid. The WPP must be able so to control that its output voltage exactly follows the grid voltage. During this control process the generation of active power P is not necessary.

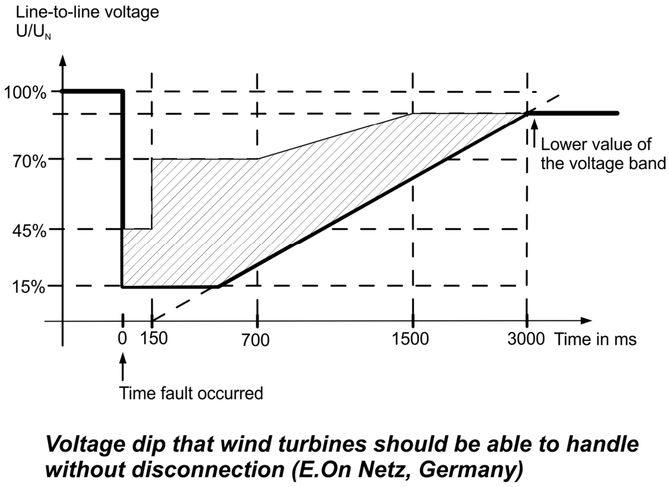


Figure 6: The ability "ride through" is defined by the term "grid code" ([21])

Fulfilling the grid code is the required condition for grid connection of WPPs. At begin this issue has created new challenges for control design. In recent times this issue has been investigated also at the HUST very intensively.

4.2. WPP control with grid tracking

In section 3, all control problems in WPPs are listed. The main challenge for manufacturers is to find a solution for both problems to design the control structure and to fulfill the grid code (section 4.1). This is particularly difficult for the system using DFIG, and it can be confirmed: Not any commercial DFIG system on the market can meet this requirement.

To visualize the level of difficult or easy to meet the requirement "grid code" between the generator types DFIG and PMG, we only have to take a closer look for Figure 7.

- Because the *stator of PMG is not directly connected to the grid*, it will be relatively easy the FC (a DC-AC converter) so to control that its output voltage exactly follows the grid voltage during grid faults, as required by grid code.
- Because the *stator of DFIG is directly connected to the grid*, the control efforts from the rotor side only have indirect effects. In addition, when the grid voltage is suddenly decreased,

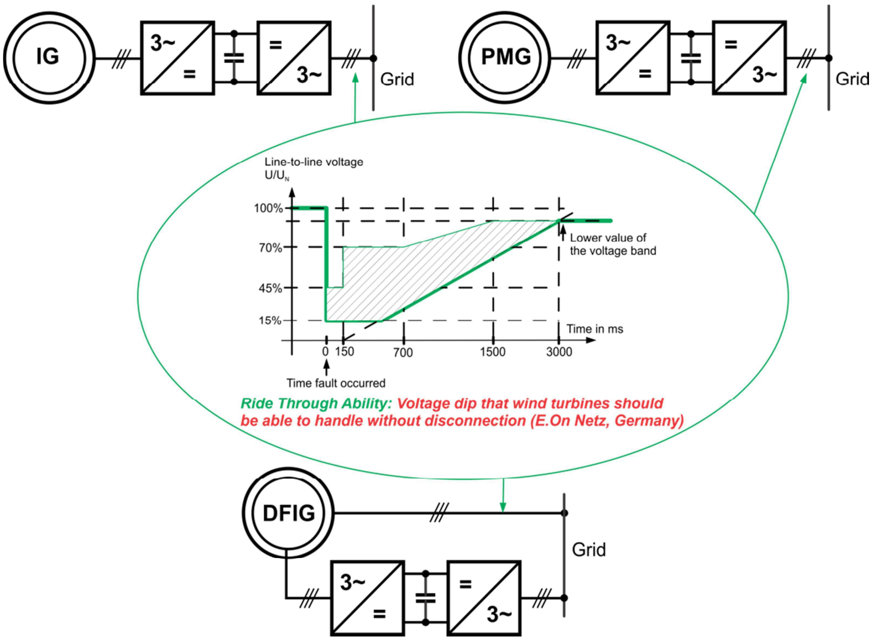


Figure 7: DFIG so to control that WPP fulfills the grid code is much more difficult than PMG control

the DFIG operation will change into the nonlinear operating mode. These are the two main causes of difficulty in case DFIG control to meet the grid code.

5. CONTROL STRUCTURES FOR DFIG

The preceding sections have highlighted the difficult problems of DFIG control. This section presents the investigation results of recent years to overcome this.

The most implemented principle is the grid voltage oriented control thereby the d-axis (the real axis) is the axis of the grid voltage vector (Figure 8). Starting from the following machine equations (2):

$$\left\{\begin{array}{lll} \mathbf{u}_s & = & R_s\mathbf{i}_s + \frac{d\psi_s}{dt} + j\omega_s\psi_s \\ \mathbf{u}_r & = & R_r\mathbf{i}_r + \frac{d\psi_r}{dt} + j\omega_r\psi_r \end{array}\right. \tag{2}$$

The state space model of DFIG in the grid voltage oriented reference frame (3) will be obtained as follows [7]:

$$\frac{d\mathbf{x}}{dt} = \mathbf{A}\,\mathbf{x} + \mathbf{B}_s\mathbf{u}_s + \mathbf{B}_r\mathbf{u}_r \tag{3}$$

where:

$$\mathbf{A} = \begin{bmatrix} -\frac{1}{\sigma}\left(\frac{1}{T_r} + \frac{1-\sigma}{T_s}\right) & \omega_r & \frac{1-\sigma}{\sigma T_s} & -\frac{1-\sigma}{\sigma}\omega \\ -\omega_r & -\frac{1}{\sigma}\left(\frac{1}{T_r} + \frac{1-\sigma}{T_s}\right) & \frac{1-\sigma}{\sigma}\omega & \frac{1-\sigma}{\sigma T_s} \\ \frac{1}{T_s} & 0 & -\frac{1}{T_s} & \omega_s \\ 0 & \frac{1}{T_s} & -\omega_s & -\frac{1}{T_s} \end{bmatrix};$$

$$\mathbf{B}_s = \begin{bmatrix} -\frac{1-\sigma}{\sigma L_m} & 0 \\ 0 & -\frac{1-\sigma}{\sigma L_m} \\ \frac{1}{L_m} & 0 \\ 0 & \frac{1}{L_m} \end{bmatrix}; \quad \mathbf{B}_r = \begin{bmatrix} \frac{1}{\sigma L_r} & 0 \\ 0 & \frac{1}{\sigma L_r} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

With: state vector $\mathbf{x}^T = \left[i_{rd},\, i_{rq},\, \psi^{/}_{sd},\, \psi^{/}_{sq}\right]$; stator voltage vector $\mathbf{u}_s^T = [u_{sd},\, u_{sq}]$ as input vector on stator side; rotor voltage vector $\mathbf{u}_r^T = [u_{rd},\, u_{rq}]$ as input vector on rotor side. The used symbols in system matrix $\mathbf{A}$, rotor-side input matrix $\mathbf{B}_r$ and stator-side input matrix $\mathbf{B}_s$ mean: T_r, T_s: time constants of rotor and stator circuit; L_m: mutual inductance; L_r: rotor-side inductance; ω: mechanical rotor angle speed; ω_r, ω_s: angle speed of rotor and stator circuit; σ: total leakage factor.

Outgoing from the model (3) the following physical relations (4) can be easily derived, and then illustrated in Figure 8:

$$\sin\varphi = \frac{|\psi_s|/L_m - i_{rq}}{|\mathbf{i}_s|}; \quad m_G = -\frac{3}{2} z_p \frac{L_m}{L_s} \psi_{sq} i_{rd} \tag{4}$$

The *main conclusion* following the equation (4) is that the current component i_{rd} *plays the role of torque control or active power control* and the current i_{rq} *is the reactive power forming component.* This conclusion means that *the most important control loop in the structure is the inner loop.* The variety of the inner current loop extends from linear to nonlinear controller whose successful designs will be presented in the next sections. The outer loop normally contains two PI-controller for active power P as well as reactive power Q or power factor $\cos\varphi$. Figure 9 shows the control hardware of WPPs.

5.1. Linear control

Since the two rotor current components i_{rd}, i_{rq} play the role of P and Q control variables an inner control loop to impress the rotor current vector is needed. The discrete model of the rotor current can be derived by iterative integration of the equation (3):

$$\mathbf{i}_r(k+1) = \Phi_{11}\mathbf{i}_r(k) + \Phi_{12}\psi'_s(k) + \mathbf{H}_{s1}\mathbf{u}_s(k) + \mathbf{H}_{r1}\mathbf{u}_r(k) \tag{5}$$

or in component form:

$$\left\{ \begin{array}{lcl} i_{rd}(k+1) & = & \Phi_{11} i_{rd}(k) + \Phi_{12} i_{rq}(k) + \Phi_{14}\psi^{/}_{sq}(k) + h_{11s} u_{sd}(k) + h_{11r} u_{rd}(k) \\ i_{rq}(k+1) & = & -\Phi_{12} i_{rd}(k) + \Phi_{11} i_{rq}(k) + \Phi_{13}\psi^{/}_{sq}(k) + h_{11r} u_{rq}(k) \end{array} \right. \tag{6}$$

In equations (5) and (6) the stator flux and the stator voltage might be regarded as disturbances to be compensated by a feed-forward control on the one side. On the other side, these values are nearly constant and therefore can be compensated exactly and fast enough by the implicit integral part of the controller, so that their feed-forward compensation may be omitted.

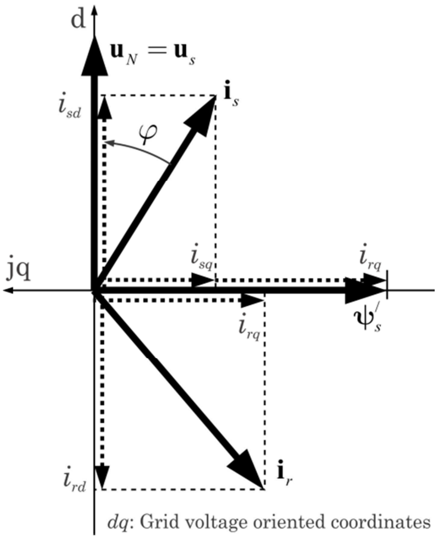


Figure 8: Vector diagram of DFIG in grid voltage oriented coordinates [7]

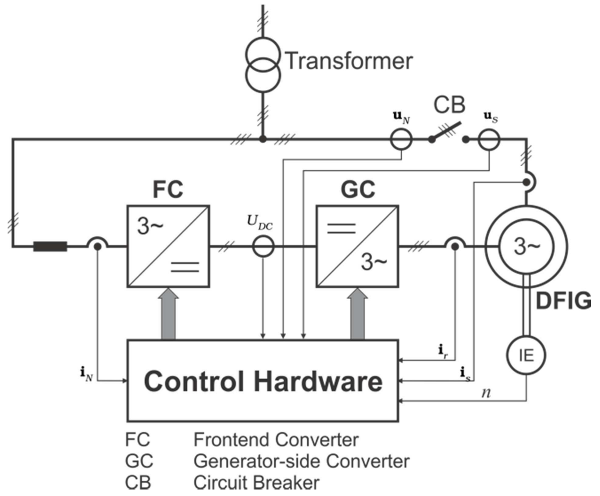


Figure 9: Control hardware for WPP using DFIG [5]

The two dimensional current controller (Figure 10) can be design with dead-beat behavior which will result in fast dynamics and accuracy. The design ensures good decoupling between the components i_{rd} and i_{rq}, and therefore between active power P and reactive power Q or power factor cosϕ.

However, it must be said, for a less fast (and thus less noise sensitive) behaviour, designs with finite adjustment times or PI-type designs may be applicable as well.

The linear control structure has been extremely successful and very often implemented in commercial systems. However, since the *grid code* has been introduced, it should also be recognized that compliance with this requirement presents problems for the linear approach, because that such compliance is a nonlinear operation equivalent.

5.2. Nonlinear control

In recent years many nonlinear control approaches ([11–15]) for DFIG have been investigated. The results have shown that only two concepts could be proved as applicable for the practice.

5.2.1. Control using exact linearization

The basic idea of the *exact linearization* ([16, 17]) can be shortly summarized as follows: If the nonlinear MIMO system in the form (7):

$$\begin{cases} \dfrac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x}) + \mathbf{H}(\mathbf{x})\,\mathbf{u} \\ \mathbf{y} = \mathbf{g}(\mathbf{x}) \end{cases} \tag{7}$$

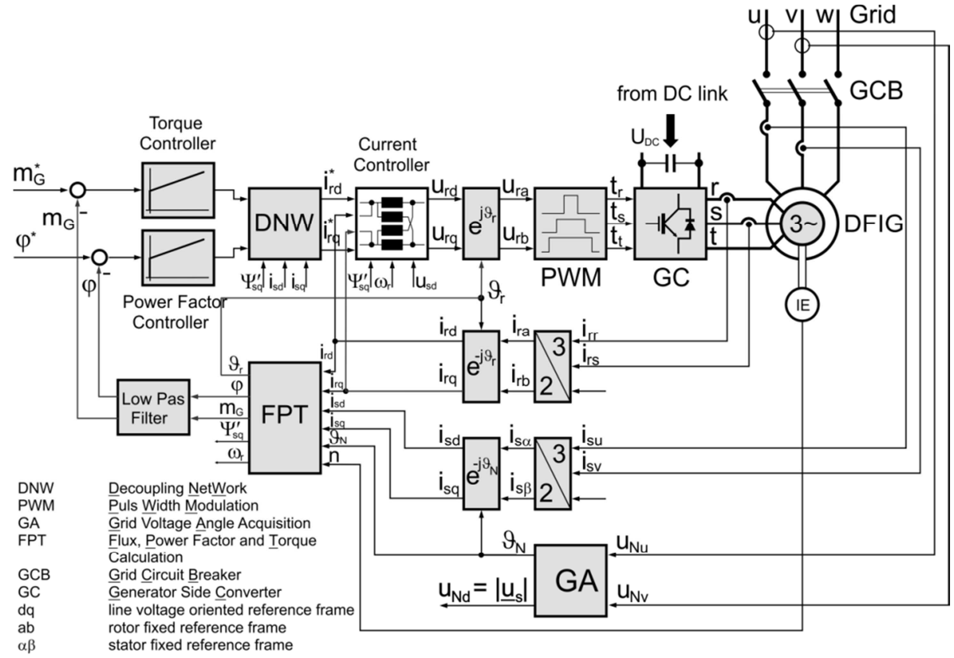


Figure 10: Generator-side linear control structure of WPP using DFIG ([5–7])

belongs to the class of processes with a vector of *relative difference orders*, the condition for exact linearization, then the system (7) can be transformed using the coordinate transformation (8):

$$\mathbf{z} = \begin{pmatrix} z_1 \\ \vdots \\ z_n \end{pmatrix} = \mathbf{m}(\mathbf{x}) = \begin{pmatrix} m_1^1(\mathbf{x}) \\ \vdots \\ m_{r_1}^1(\mathbf{x}) \\ \vdots \\ m_1^m(\mathbf{x}) \\ \vdots \\ m_{r_m}^m(\mathbf{x}) \end{pmatrix} = \begin{pmatrix} g_1(\mathbf{x}) \\ \vdots \\ L_f^{r_1-1} g_1(\mathbf{x}) \\ \vdots \\ g_m(\mathbf{x}) \\ \vdots \\ L_f^{r_m-1} g_m(\mathbf{x}) \end{pmatrix} \tag{8}$$

into the following linear MIMO system:

$$\begin{cases} \dfrac{d\mathbf{z}}{dt} = \mathbf{A}\mathbf{z} + \mathbf{B}\mathbf{w} \\ \mathbf{y} = \mathbf{C}\mathbf{z} \end{cases} \tag{9}$$

The original input $\mathbf{u}$ is then controlled by the coordinate transformation law:

$$\mathbf{u} = \mathbf{a}(\mathbf{x}) + \mathbf{L}^{-1}(\mathbf{x})\,\mathbf{w} \tag{10}$$

The vector $\mathbf{a}(\mathbf{x})$ and the matrix $\mathbf{L}^{-1}(\mathbf{x})$ in (10) look as follows:

$$\mathbf{L}\left(\mathbf{x}\right)=\begin{pmatrix} L_{h_1}L_f^{r_1-1}g_1\left(\mathbf{x}\right) & \cdots & L_{h_m}L_f^{r_1-1}g_1\left(\mathbf{x}\right) \\ \vdots & \ddots & \vdots \\ L_{h_1}L_f^{r_m-1}g_m\left(\mathbf{x}\right) & \cdots & L_{h_m}L_f^{r_m-1}g_m\left(\mathbf{x}\right) \end{pmatrix};\ \mathbf{a}\left(\mathbf{x}\right)=-\mathbf{L}^{-1}\left(\mathbf{x}\right)\begin{pmatrix} L_f^{r_1}g_1\left(\mathbf{x}\right) \\ \vdots \\ L_f^{r_m}g_m\left(\mathbf{x}\right) \end{pmatrix} \tag{11}$$

Formula (11) also requires the ability, with respect to the coordinate transformation or to the exact linearization, to invert the matrix $\mathbf{L}(\mathbf{x})$. In equations (8) and (11), the term:

$$L_f g\left(\mathbf{x}\right)=\frac{\partial g\left(\mathbf{x}\right)}{\partial \mathbf{x}}\mathbf{f}\left(\mathbf{x}\right) \tag{12}$$

notifies the Lie derivation of the function $g(\mathbf{x})$ along the trajectory $\mathbf{f}(\mathbf{x})$. Following the equation (9) the process is now linear in the new state space $\mathbf{z}$ so that only linear controller must be designed. Besides the exact linearization, the *input-output decoupling* (decoupling between both axes *dq*) *relations are totally guaranteed.* The so called concept with *direct decoupling* is dynamically effective for the complete state space.

Starting from equation (3) it can be easily recognized that also DFIG can be exactly linearized. Using the coordinate transformation (8), the new generator-side control scheme can be derived as in the Figure 11. The investigation results from this control approach show that the new direct decoupling concept clearly outperforms the linear control in both aspects:

- Smaller oscillation amplitudes of stator and rotor currents occur in the first milliseconds after the fault instant while the rotor current controllers work in limitation mode. This means practically, that the system may cope with more serious fault events without triggering hardware protection functions.
- The system control functionality is regained very fast after the controllers return to linear operation, resulting in short recovery time from disturbances and continuation of defined control behaviour.

5.2.2. Flatness-based control

The concept of flat systems was introduced by Fliess, Lvine, Martin and Rouchon in the years 1992-1999 ([8–10]). The application of the idea of flat systems can be re-iterated shortly as follows.

Given is the following nonlinear system:

$$\frac{d\mathbf{x}}{dt}=f\left(\mathbf{x},\mathbf{u}\right) \tag{13}$$

with $\dim\mathbf{x}=n,\ \dim\mathbf{u}=m<n$ and $\operatorname{rank}\left(\partial f/\partial\mathbf{u}\right)=m$. The system (13) is differentially flat, or shortly flat, if the two following conditions are fulfilled:

- *Condition* 1: There exists an output vector $\mathbf{y}$ and finite integers l and r such that:

$$\mathbf{y}=\begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix}=F\left(\mathbf{x},\mathbf{u},\frac{d\mathrm{u}}{dt},...,\frac{d^l\mathbf{u}}{dt^l}\right) \tag{14}$$

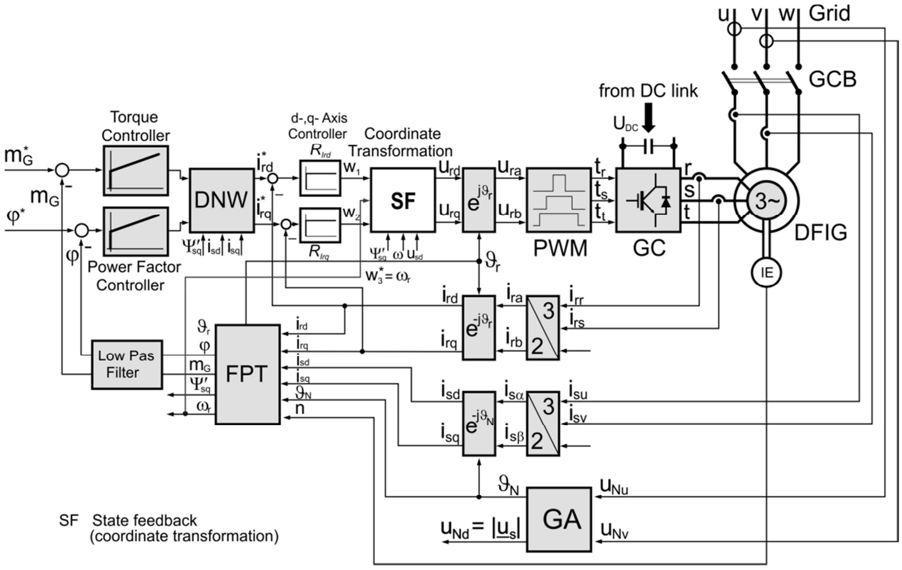


Figure 11: Generator-side control scheme using exact linearization by state coordinate transformation and two separate axis controllers to impress current components ([7, 25])

- *Condition* 2: Both input vector $\mathbf{u}$ and state vector $\mathbf{x}$ can be expressed in function of $\mathbf{y}$ and its successive derivatives in finite number:

$$\mathbf{x} = P\left(\mathbf{y}, \frac{d\mathbf{y}}{dt}, ..., \frac{d^r\mathbf{y}}{dt^r}\right);\ \mathbf{u} = Q\left(\mathbf{y}, \frac{d\mathbf{y}}{dt}, ..., \frac{d^{(r+1)}\mathbf{y}}{dt^{(r+1)}}\right) \tag{15}$$

with $dP/dt = f\left(P,\, Q\right)$. The output vector $\mathbf{y}$ is called a flat output. The 2^{nd} equation in (15) is also called the "inverse" process model of the system (13) with the output (14). According to (14) and (15) it can be concluded that to every output trajectory $t\ \mapsto\ \mathbf{y}\left(t\right)$ being enough differentiable, there corresponds a state and input trajectory:

$$t\ \mapsto\ \left(\mathbf{x}\left(t\right),\ \mathbf{u}\left(t\right)\right) = \left(P\left(\mathbf{y}, \frac{d\mathbf{y}}{dt}, ..., \frac{d^r\mathbf{y}}{dt^r}\right);\ Q\left(\mathbf{y}, \frac{d\mathbf{y}}{dt}, ..., \frac{d^{(r+1)}\mathbf{y}}{dt^{(r+1)}}\right)\right) \tag{16}$$

that identically satisfies the system equations. Conversely, to every state and input trajectory $t\ \mapsto$ $\left(\mathbf{x}\left(t\right),\ \mathbf{u}\left(t\right)\right)$ being enough differentiable and satisfying the system equations, a trajectory:

$$t\ \mapsto\ \mathbf{y}\left(t\right) = F\left(\mathbf{x}, \mathrm{u}, \frac{d\mathbf{u}}{dt}, ..., \frac{d^l\mathbf{u}}{dt^l}\right) \tag{17}$$

should correspond. In the case that both conditions (14), (15) are fulfilled, and the system (13) and its output vector (14) are flat, we can figure out a general control structure as in the Figure 12 which is engineer-friendly and easier to understand as the original nonlinear system.

The operation of the concept in Figure 12 can be summarized as follows:

- If the process satisfies the conditions of the flatness, the inverse model of the process may be used as a feed forward component of a tracking control concept.

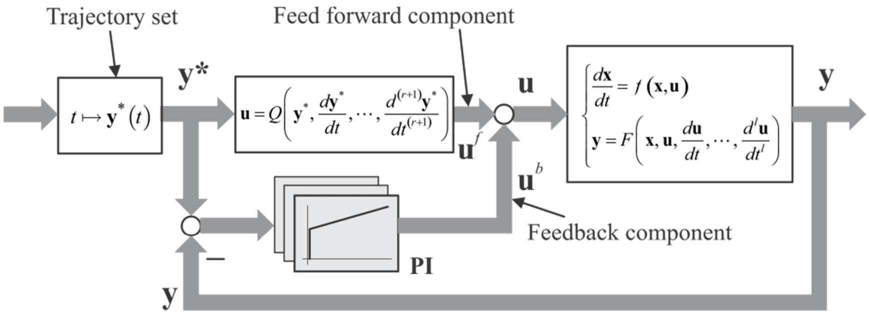


Figure 12: The general flatness-based control structure ([7])

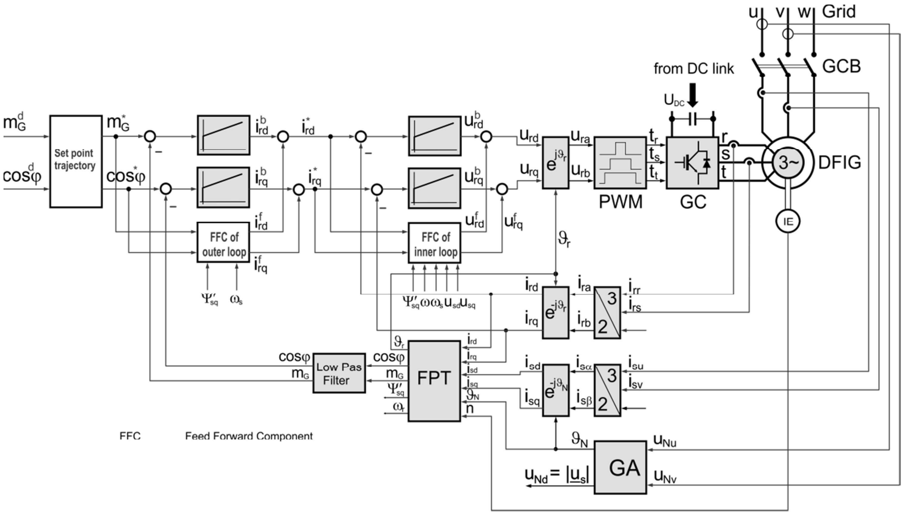


Figure 13: Flatness-based control structure for GC in WPPs using DFIG: Each control loop contains beside the two feed forward and feedback components also a set point trajectory ([7])

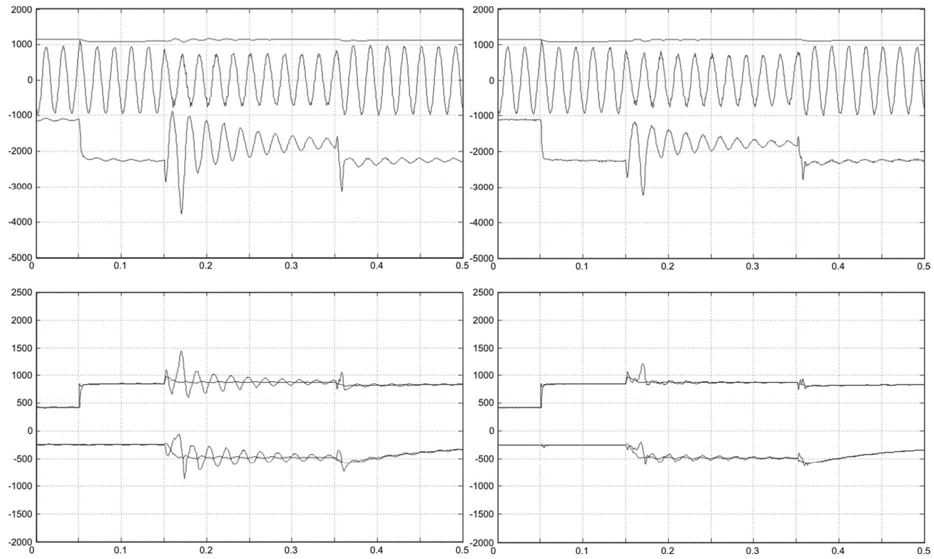
- The forward component is effective only when the input signal $\mathbf{y}^*$ is so often differentiable like the output signal $\mathbf{y}$ of the process. Therewith, the use of a trajectory set for $\mathbf{y}^*$ is absolutely necessary.
- Thus, the output signal $\mathbf{y}$ in the case of the perturbed system to the input signal $\mathbf{y}^*$ along the trajectory exactly follows and the steady-state error is eliminated in the new position of rest, a third component is still needed as feedback. In the case of electrical machines, PI controllers will be sufficient.

Based on the structure in Figure 12 the detailed flatness-based control structure for DFIGs can be developed as in the Figure 13.

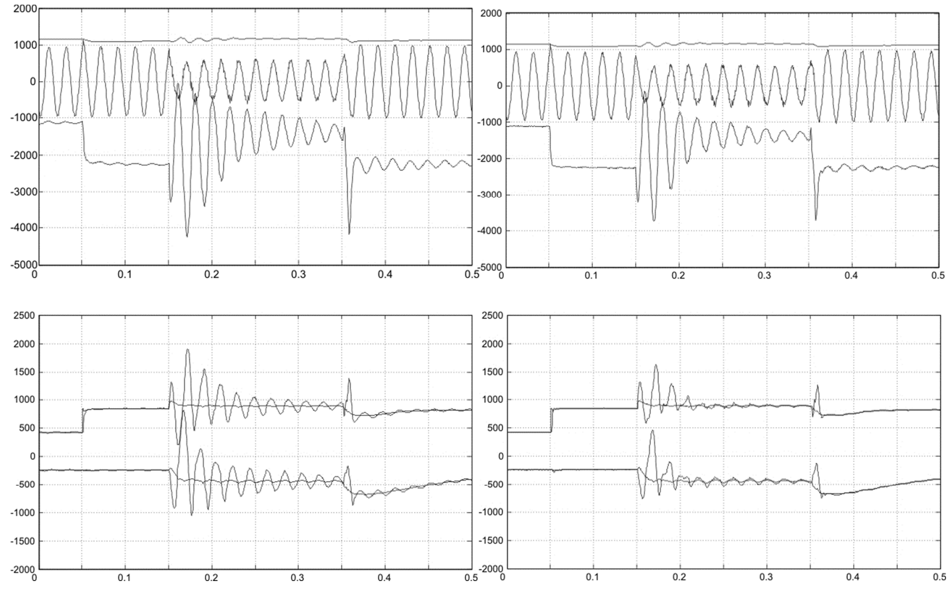
5.2.3. Simulation results

Some simulation results are now included to demonstrate the superiority of the nonlinear control strategies over the linear concept. In the simulations, the results for a linear control system according to Figure 10 and the nonlinear scheme outlined in Figure 11 are compared for 3 different voltage drops to 70%, 50% and 25% retained grid voltage (Figure 14). Both control schemes had been implemented into an otherwise identical converter-generator system of a 2500 kW WPP. For sole comparison of the control concept, hardware protection and FRT features had been excluded deliberately.

In all 3 cases, it can be stated that prolonged duration of the grid fault and especially in large voltage drop, the linear scheme threatens to lose the controllability. It is different for nonlinear control. In the figures on the right side with nonlinear control we can clearly see that after the beginning of the network fault controllability recovered quickly. The ability of the “*ride through*” has become in a nonlinear concept better so that compliance with the rule “*grid code*” is better guaranteed.



a)



b)

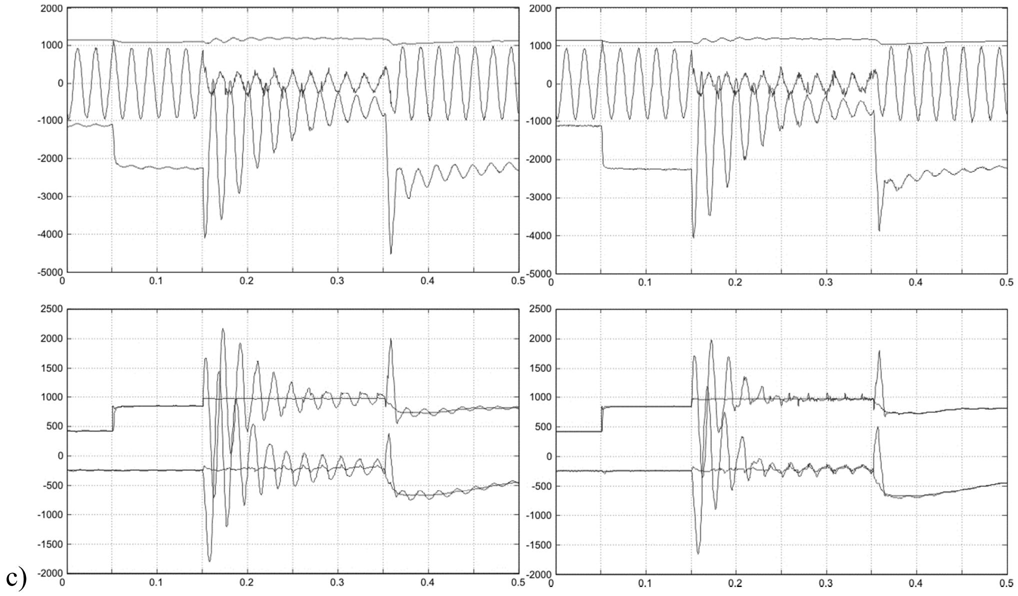


Figure 14: Grid voltage drop to (a) 70%, (b) 50% and (c) 25% retaining voltage 2500 kW converter-generator system: (**left**) linear control scheme, (**right**) nonlinear control scheme with exact linearization, (**top**) mechanical rotor peed [rpm], grid voltage [V], electric torque [10 Nm], (**bottom**) rotor current d (torque) [A], rotor current q (flux) [A]

6. CONCLUSION

The paper presents an overview of the control problems in WPPs using different types of generators, in order to give the readers a basic understanding of the following groups of problems:

- Operating modes and control hierarchy of a wind power plant using IG, DFIG or PMG.
- Control problems of the real-time level or of the generator control.
- Control problems during grid faults and the term of grid code.
- Linear and nonlinear control concepts for WPPs using DFIG.

The section "REFERENCES" introduces to the readers the abundant resource, derived from the investigation results of the control system of WPPs obtained at Hanoi University of Science and Technology for more than 15 past years [23–66].

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Received on December 18 - 2014
Revised on December 25 - 2014