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An analytical evaluation of losses impact on initial condition calculation for wind generating units

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Abstract: This paper proposes a detailed analysis of wind turbine equipped with direct drive permanent magnet synchronous generator with particular attention to the problem of the initialisation of fundamental frequency dynamic simulations in presence of active power losses. It is a common procedure to neglect power system losses when the dynamic system model is considered but these aspects can lead to a steady state that differs from the one of a model including losses.
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Key-Words: Wind power, power system modelling, renewable power generation.

1 Introduction

The evolution of the electricity production scenario changed the operating conditions of the electricity system itself providing, on one side, benefits relating to distributed generation from renewables [1]-[2] but, on the other, issues in terms of quality, security and reliability of power generation and delivery related to the stochastic behavior of the prime energy source [3]-[5].The strong presence of power electronic devices in Renewable Energy Sources (RES) like photovoltaic or wind power plants makes them suitable and flexible enough to act as supporters for the electricity system operation [6]-[7], as they can provide some of the ancillary services that in the past needed the installation of dedicated devices ([8]-[9]). As a consequence, both the increasing number of RES installations integrated into large-scale electrical power systems and the necessity of enhancing the performances in order to meet the standards requirements, claim for the development of adequate modelling of such units and effective control systems.

In particular, the wind turbine electrical generating systems are much more demanding, due to the presence of many different devices (turbine, gearbox, shaft, electrical machine, power electronic converters, controllers and so on) and configurations. The two most important currently applied wind turbine concepts are the Doubly Fed Induction Generator (DFIG) [10]-[11] and the Direct Drive Synchronous Generator (DDSG) [12]-[15] consisting of either a permanent magnet synchronous machine or an electrically excited one. The present paper deals with DDSG with permanent magnets and focuses its attention on the modeling aspect.

As far as wind power models are concerned, they have to be incorporated in software packages in which the fundamental frequency simulation approach is applied, in order to allow the investigation of the impact of high wind power penetrations on electrical power systems. To reach this goal, many different papers have been published in literature specifying the assumptions that have to be made in order to make such models effective with respect to the results one wants to obtain and consistent with the modelling of the remaining part of the power system (see [16]-[17] for details). To this extent, one problem to be solved is related to the definition of the dynamic system initial conditions for a dynamic simulation coherent with the load flow results. This aspect has been addressed in [18], under the hypothesis of lossless system, but, to the best of our knowledge, is still unsolved if one wants to account for active power losses.

The aim of the present article is that of fully detailing the procedure to solve the initialization problem of a wind turbine generator provided with DDSG accounting for power system losses. As it will be shown the presence of power losses increases the complexity of the system that can anyway solved in a systematic way.

The paper is organized as follows: in Section 2, the power system model is reviewed while Section 3 is dedicated to the definition and solution of the initialization problem. Section 4 proposes an analytical application of the proposed method compared with the traditional (lossless) one. Finally, Section 7 provides some conclusive remarks.

2 Power System Model

One of the two most employed strategies to integrate the power coming from a wind plant into the electric system is to use a permanent magnet Direct Drive Synchronous Generator (DDSG) connected to the grid by means of two power electronic converters (see Fig. 1) [16]-[17].

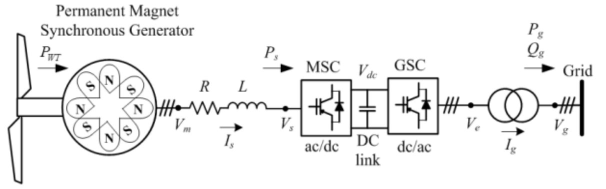

Fig. 1: DDSG wind turbine layout.

The first one (from now on Machine Side Converter, MSC) is typically adopted in order to extract the maximum power from the wind turbine and to control the voltage (V_m) at the machine terminals. The second one (from now on Grid Side Converter, GSC) controls the voltage on the DC (v_{DC}) link and the reactive power Q_g delivered to the main network.

In order to find out a suitable control architecture to follow the above-mentioned goals, first a mathematical model of the system to be controlled has to be derived.

2.1 Wind Turbine Model

As well known, in power system simulations where the electrical behaviour of the wind system is the main point of interest, a simplified way of modelling the wind turbine rotor is normally used. Such model consists of the following algebraic relation between wind speed and mechanical power extracted:

$$P_{WT}(\omega,v_w,\theta)=\frac{1}{2S_b}\rho A c_p\left[\lambda(\omega,v_w),\theta\right]v_w^3 \tag{1}$$

where P_{WT} is the power extracted from the wind in p.u. on the electric machine base S_b; ρ is the air density [kg/m^3]; A is the area covered by the rotor [m^2], θ is the pitch angle of rotor blades [deg], v_w is the wind speed at hub height upstream the rotor [m/s] and ω is the turbine angular speed in p.u. on the rated machine speed ω_n. Moreover, c_p is the performance coefficient or power coefficient depending on the pitch angle and on the tip speed ratio $\lambda=v_t/v_w$ i.e. the ratio between the blade tip speed v_t [m/s] (proportional to the turbine angular speed) and the wind speed. Examining the performance coefficient behaviour, it is clear that for an assigned value of the pitch angle, there exists only one value of the tip speed ratio that maximizes the performance coefficient. As a consequence, for any wind speed, there exists only one turbine angular speed ω^* that allows extracting the maximum power P_{WT}^* from the wind. So, to maximize the unit power production, the following control curve (MPPT curve) can be defined [19]:

$$P_{WT}^*=\begin{cases}0 & \omega<\omega_{\min}\\ g\left(\omega^*\right) & \omega_{\min}\le\omega<\omega_{\max}\\ P_{\max} & \omega\ge\omega_{\max}\end{cases} \tag{2}$$

where the g function maps the locus of the maximum values of the function P_{WT} defined in (1) in correspondence of the possible values of the wind speed and with pitch angle equal to zero, i.e.:

$$g(\omega)=\max_\omega P_{WT}(\omega,v_w,0) \tag{3}$$

Moreover, increasing the pitch angle will result in a reduction of the power extracted from the wind. As a consequence, this feature is typically used to avoid over synchronous speeds and is implemented in the so-called pitch angle controller (see [16]-[17] for details). The working principle of such controller is the following: when the electric machine angular speed exceeds a specified threshold, the controller changes the value of the pitch angle in order to reduce the power extracted from the wind. Since the pitch control works only for over synchronous speeds, an anti-wind up limiter locks the pitch angle to 0 for sub synchronous speeds.

The machine stator voltage amplitude, $V_{m,}$ is set according to the desired machine speed in the so-called “constant V/f” regulation mode. In other words, the per unit stator voltage amplitude is equal to the per unit machine speed until its rated value, that is to say:

$$V_m{}^*=\min\left\{\omega^*,1\right\} \tag{4}$$

So, given the wind speed, also the machine angular speed, the power extracted from the primary source and the machine voltage amplitude result uniquely determined by (2) (3) and (4).

2.2 Electric Machine (DDSG) model

Describing the machine in the Park domain with the user convention from the mechanic point of view and the generator convention from the electric one, one has that the stator electric equations (in p.u. on the machine basis) are given by[3]:

$$\begin{cases}v_{md}=-R_s i_{sd}-\dfrac{1}{\omega_n}\dfrac{d\phi_{sd}}{dt}-\omega\phi_{sq}\\ v_{mq}=-R_s i_{sq}-\dfrac{1}{\omega_n}\dfrac{d\phi_{sq}}{dt}+\omega\phi_{sd}\end{cases} \tag{5}$$

being R_s the stator resistance, $v_{md(q)}$ the direct (quadrature) axis component of the machine voltage, $i_{sd(q)}$ the direct (quadrature) axis component of current outgoing from the machine (see Fig. 1) and $\phi_{md(q)}$ the direct (quadrature) axis component of the machine linkage. The magnetic stator equations are the following:

$$\begin{cases}\phi_{sd}=x_d i_{sd}+\psi\\ \phi_{sq}=x_q i_{sq}\end{cases}\tag{6}$$

having indicated with x_d, x_q and ψ the stator direct and quadrature axis reactances at rated frequency and the permanent magnet flux respectively. Finally, the electromagnetic torque is given by:

$$T_e=-i_{sd}\phi_{sq}+i_{sq}\phi_{sd}=\left(x_d-x_q\right)i_{sd}i_{sq}+\psi i_{sq}\tag{7}$$

and the motion equation states that:

$$\frac{P_{WT}}{\omega}-T_e=2H\frac{d\omega}{dt}\tag{8}$$

being H the machine inertia constant.

2.3 Machine Side Converter Model

The machine side converter can be considered as a voltage source V_s, whose axis components v_{sd} and v_{sq} can be adjusted acting on the PWM inverter parameters. Such voltage is related to the machine one according to the following relationships:

$$\begin{cases}v_{sd}=v_{md}-Ri_{sd}-(\frac{L}{\omega_n})\frac{di_{sd}}{dt}-\omega Li_{sq}\\ v_{sq}=v_{mq}-Ri_{sq}-(\frac{L}{\omega_n})\frac{di_{sq}}{dt}+\omega Li_{sd}\end{cases}\tag{9}$$

being R and L the connection cable resistance and inductance.

Finally, the PWM modulating index m_a and phase angle δ can be obtained as follows:

$$\begin{cases}v_{sd}=m_a\frac{V_{DC}}{2}\cos\delta\\ v_{sq}=-m_a\frac{V_{DC}}{2}\sin\delta\end{cases}\tag{10}$$

being V_{DC} the DC link voltage.

2.4 Grid Side Converter Model

Assuming that the GSC can be modelled as an ideal voltage source (i.e. with no delays and no switching and no-state losses) and the connection between the converter and the main network can be represented as a R-L series impedance (accounting for cables, transformer and the series section of the filters), then, the system portion between the GSC and the network can be represented with the equivalent circuit of Fig. 2.

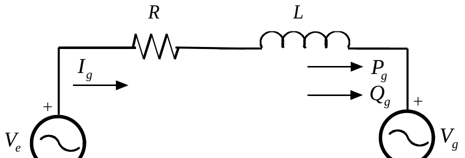

Fig. 2: Equivalent circuit of the grid side converter, the connection system and the main network

Describing the system in a Park reference frame rotating at the network angular frequency ω_e (expressed in p.u. on the rated angular frequency ω_g), The KVL applied to the mesh depicted in Fig. 2 states that:

$$\begin{cases}v_{gd}=v_{ed}-R_T i_{gd}-\frac{L_T}{\omega_g}\frac{d}{dt}i_{gd}-\omega_e L_T i_{gq},\\ v_{gq}=v_{eq}-R_T i_{gq}-\frac{L_T}{\omega_g}\frac{d}{dt}i_{gq}+\omega_e L_T i_{gd},\end{cases}\tag{11}$$

being:

- R_T and L_T the connection resistance and the inductance respectively,
- $v_{ed(q)}$ the direct (quadrature) axis components of the voltage at the AC terminals of the GSC
- $v_{gd(q)}$ the direct (quadrature) axis components of the grid voltage
- $i_{gd(q)}$ the direct (quadrature) axis components of the current flowing in the connection.

All in p.u. on the machine basis.

3. Initialization of fundamental frequency simulations starting from load-flow calculation

All the fundamental frequency simulations start from an equilibrium point deriving from a load flow calculation. As a consequence, it is necessary to derive a procedure that allows finding out the system equilibria starting from the load flow output, i.e. to initialize the variables of a wind power plant. Such procedure has been studied in [18].

When calculating the initial conditions of a dynamic model from load flow data, the model quantities are evaluated from the output to the input. The initial values of the output are determined in the load flow case and the initial values of the state variables and other values have to be calculated from these load flow data. Therefore, the description and modelling of the components of the wind power plant have to start from the grid connection point. Moreover, when calculating the initial conditions, the system is assumed to be at steady state. Therefore, the equations presented in the previous sections will be used zeroing all the time derivatives. However, the procedure derived in [18] assumes that the system losses (i.e. electrical machine, transformer, cables and so on) are negligible. This means that if one applies such algorithm to a system where such losses are different from zero, the initial load flow solution will not result in an equilibrium point from which to start the simulation.

In the present section, a modification of the initialization procedure will be presented accounting also for the system losses.

With reference to the notations of Fig. 2, the Load Flow calculation allows to know the initial values (indicated with the subscript “0”) of the active power P_{g0}, of the reactive power Q_{g0} and of the voltage phasor V_{g0} at the machine bus. Starting from these values, the initialization problem can be split into two parts regarding respectively the portion of the system between the AC terminals of the GSC and the external network connection (from now on network side portion) and the one between the wind turbine and the AC terminals of the MSC (from now on machine side portion).

3.1 Network side portion

For this portion, the initialization problem consists of finding the values of v_{gd0}, i_{gd0}, i_{gq0}, v_{ed0}, v_{eq0}.
Choosing the Park initial angle such that the network voltage V_g has only direct axis component, it follows that:

$$\begin{cases} v_{gd0} = V_{g0} \\ v_{gq0} = 0 \end{cases} \tag{12}$$

and

$$\begin{cases} P_{g0} = v_{gd0} i_{gd0} \\ Q_{g0} = v_{gd0} i_{gq0} \end{cases} \tag{13}$$

which allows finding the initial values of the current axis components, as:

$$\begin{cases} i_{gd0} = \dfrac{P_{g0}}{V_g} \\ i_{gq0} = \dfrac{Q_{g0}}{V_g} \end{cases} \tag{14}$$

inserting now (14) and (12) into (11) and nullifying the time derivatives, one can finally calculate the initial values of the axis components of the voltage at the AC terminals of the GSC.

3.2 Machine Side Portion

For this system portion, the initialization problem consists of finding the values of v_{sd0}, v_{sq0}, i_{sq0}, $i_{sd0,0}$, P_{WT0}, v_{w0}.
Neglecting the two converters losses, the active power P_{s0} delivered at the AC terminals of the MSC can be calculated as:

$$P_{s0} = [P_{g0} + R_T (i^2_{gd0} + i^2_{gq0})] \tag{15}$$

It should be observed that, if one wants to account also for the converter losses, an empirical correction to the resistances R and R_T can be done without affecting the procedure (see [20] for details).
The power P_{s0} can be expressed as:

$$P_{s0} = v_{sd0} i_{sd0} + v_{sq0} i_{sq0} \tag{16}$$

and, if one inserts (6) into (5) and (5) into (9), it is possible writing the following steady state equations:

$$\begin{cases} v_{sd0} = -\left(R_S + R\right) i_{sd0} - \omega_0 x_q i_{sq0} \\ v_{sq0} = -\left(R_S + R\right) i_{sq0} + \omega_0 x_d i_{sd0} + \omega_0 \psi \end{cases} . \tag{17}$$

Moreover, assuming that the initial point is characterized by a speed belonging to the range $[\omega_{\min}, \omega_{\max}]$, the MPPT curve belongs to the graph of function g defined in (3), so:

$$P_{WT0} = g\left(\omega_0\right) \tag{18}$$

At this point, the active power balance between the wind turbine and the AC terminals of the MSC allows writing:

$$g\left(\omega_0\right) - (R + R_S)(i^2_{sd0} + i^2_{sq0}) = P_{s0} \tag{19}$$

Finally, after some algebraic manipulations, requirement (4) becomes:

$$V^2_{m0} = v^2_{md0} + v^2_{mq0} =$$
$$(v_{sd0} + R i_{sd0} + \omega_0 L i_{sq0})^2 + (v_{sq0} + R i_{sq0} - \omega_0 L i_{sd0})^2 = \tag{20}$$
$$= \min\{\omega_0{}^2, 1\}$$

Equations (17), (16), (19) and (20) originate an algebraic nonlinear system of five equations in five unknowns that can be solved numerically.
Finally, the application of (18) provides the initial value of the wind turbine power, while wind speed can be defined by solving (1). If the initial value of the machine angular speed results to be out of the range $[\omega_{\min}, \omega_{\max}]$, then (18) is no longer valid; as a consequence, the procedure has to be modified as follows [18]:

- v_{w0} has to be assigned independently
- P_{WT} is set to P_{max}.

In this case, the set of equations that allow to find the problem solution is (17), (16), (19) and (20) simply by substituting the term g(ω_0) with P_{max}..

4. Simulation and results

In order to provide a validation of the proposed methodology and to highlight the impact of power losses in the system equilibrium point, it is here proposed an initial condition calculation on a test case, 2 MW wind generating unit.
The electrical machine main parameters are reported in Table I [13]:

Table I: Permanent Magnet DDSG data

Rated Power	2 MVA
Rated voltage	690 V
Stator Resistance	0.042 p.u.
Direct axis reactance	1.05 p.u.
Quadrature axis reactance	0.75 p.u.
Permanent magnet flux	1.25 p.u.

With specific reference to the electric layout of Fig. 1 one can consider the following assumptions and data:

- the connection between the machine and the machine side converter is characterized by a 0.05 p.u. resistance (R=0.05 p.u.) and 0.05 p.u. inductance (L=0.05 p.u.) (both in per unit on machine basis)
- the connection between the grid side converter and the external network has an equivalent resistance R_t=0.005 p.u. and an equivalent inductance L_t=0.05 p.u. (both in per unit on machine basis).

The power system is assumed to be operated in a load flow condition characterized by unitary voltage magnitude on the grid side bus-bar, a power production equal to 1.6 MW (0.8 p.u. on machine power base) and reactive power production at the point of interconnection with the grid (i.e. V_g=1 p.u., P_g=0.8 p.u. and Q_g=0 p.u.).

With this set of parameters and data it is possible to feed the calculation procedure proposed in Section 3 calculating the direct and quadrature axis component of the machine and grid side converters in addition to the wind variables.

The results obtained by the proposed methodology are summarized in Table II.

Table II: Initialization results with losses

Grid Side Converter	
v_{gd0}	1 p.u.
i_{gd0}	0.796 p.u.
i_{gq0}	0 p.u.
v_{ed0}	1.03 p.u.
v_{eq0}	- 0.03 p.u.
Machine Side Converter	
v_{sd0}	- 0.58 p.u.
v_{sq0}	0.76 p.u.
i_{sq0}	0.68 p.u.
i_{sd0}	- 0.48 p.u.
Wind	
P_{wind0}	0.86 p.u.
v_{w0}	8.90 p.u.
ω_0	1.14 p.u.

In order to evaluate the difference with the simplified initial condition calculation (lossless) the approach proposed in [18] have been applied using the same parameters and data of Table I and following (neglecting the resistances). The results obtained are reported in Table III.

As one can see the effect of neglecting losses causes a different wind speed and power, thus meaning that the initial condition provided will not satisfy nor the maximum power characteristic nor the equilibrium for the detailed representation of the system.

Table III: Initialization results without losses

Grid Side Converter	
v_{gd0}	1 p.u.
i_{gd0}	0.8 p.u.
i_{gq0}	0 p.u.
v_{ed0}	1.0 p.u.
v_{eq0}	- 0.04 p.u.
Machine Side Converter	
v_{sd0}	- 0.57 p.u.
v_{sq0}	0.81 p.u.
i_{sq0}	0.64 p.u.
i_{sd0}	- 0.47 p.u.
Wind	
P_{wind0}	0.8 p.u.
v_{w0}	8.66 p.u.
ω_0	1.11 p.u.

As one can notice, the wind side quantities are affected by the losses impact. The error on the wind speed evaluation is around 3% while the error on the wind power is 6.9%. Also the converter quantities are different in the two cases.

5. Conclusions

The aim of the present study was that of providing an analytical procedure for the calculation of the initial condition of a wind generator unit provided with a permanent magnet direct drive synchronous generator accounting for power system losses. In literature the problem of the initialization of a wind generating unit is discussed and developed under the assumption of lossless system, since power losses increases the complexity of the resulting algebraic system. Nevertheless, power losses can have a sensible impact on the system initial condition and also in the design of an effective control strategy. In the paper a detailed model of the wind generator is proposed and the solution of the initial condition problem is fully described. The impact of power system losses on the results obtained are then evaluated in comparison with a traditional lossless approach.

Further development may regard the evaluation of the impact of system losses on the control strategy implemented to properly operate the wind turbine, since they may have an impact on the actual power point tracking and on the design of the power system regulator parameters.

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