Analysing Frequency Support from DFIG-based Wind Turbines - Impact of Parameters and Initial Conditions

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***Abstract*—Enabling the type-III and type-IV wind turbine generators to participate in grid frequency control couples them to the electromechanical modes of the grid. In this paper we have investigated how initial wind speed, rotor-side controller parameters, PLL parameters and pitch angle controller parameters influence the virtual inertial response and primary frequency response of the total power controlled DFIG-based wind turbine generator. Preliminary analysis shows that although there is some influence of these parameters, most of them are not significant. However, further and more in depth research is needed. Furthermore, we discuss the results with respect to other research related to this topic.**

***Index Terms*—wind energy integration, power system dynamics, power system simulation, power system modelling, power generation control**

I. Introduction

A high rate of penetration of renewable energy sources (RES) in the last decade has brought along certain problems for the power systems of today as well as for power systems of tomorrow. Variable and stochastic RES, of which wind energy and solar photovoltaic (PV) energy are the most prolific representatives, are connected to the grid via power electronic interface which ensures power production at the rated grid frequency. Connection of this converter-connected generation and decommissioning of large synchronous units has a couple of consequences:

1) grid inertia is reduced since power electronics decouple the rotating mass from grid frequency (in the case of PVs there is no rotating mass)
2) these RES usually do not contribute to primary frequency control[1]

That is why a lot of attention has been given to developing auxiliary control algorithms for Type-III and Type-IV wind turbine generators (WTGs) which enable the utilisation of their decoupled kinetic energy to respond to frequency disturbances, usually named *virtual or synthetic inertia* [1]. Furthermore, these wind turbines can be operated according to some sub-optimal power curve which ensures a certain amount of power reserves during normal operation [2]. Then, a droop control can be added so WTGs can contribute to primary frequency response during frequency drops. However, WTGs are complex electromechanical systems and there were no comprehensive studies on how exactly do different parameters and initial conditions influence the inertial response and droop control capabilities of a Type-III or Type-IV WTG. Kayikçy and Milanović [3] have thoroughly investigated the impact of model order of DFIG-based wind turbines on transient response (short-circuit) and have concluded the following: constant wind power or constant mechanical torque assumptions are not realistic; simplification of the converter and machine models does not significantly influence the transient response of the DFIG; DC voltage can be assumed constant. In [4], the same authors have analysed the impacts of the following aspects on system frequency response: control strategy (power or torque), maximum-power-point-tracking (MPPT) characteristic, initial loading and auxiliary inertial controller parameters. They have concluded that torque control is more stable than power control, MPPT curve provides a self-stabilising mechanism, initial loading has a significant impact of inertial response provision due to the converter limits and that various power and frequency responses could be obtained depending on the design of the inertial controller. Recently, research has shown [5], [6] that there is a link between the virtual inertial response (VIR) and phase-locked loop (PLL) which can affect both the small-signal stability of the power system and the strength of the VIR. Arani and Mohamed [7] have analysed the impacts of droop control in DFIGs on microgrid and weak grid stability and have also concluded that torque control is more stable than power control. They have also shown that pitch angle controller does not have a significant impact on droop control. Impact of some parameters has been studied in [8]–[10], but there a simplified small-signal modelling was used not

[1]In a sense that they usually operate at a maximum power and do not ensure some amount of spinning reserve for when grid frequency drops below rated. Although, they may have over-frequency power reduction capabilities implemented. On the other hand, some systems (e.g. Irish one) require that wind power plants operate with some reserve power at rated grid frequency.

taking into account rotor-side control system nor the generator dynamics.

However, the surveyed papers have not investigated the influence of DFIG parameters and initial conditions (initial wind speed/generator speed) on the system frequency response [both virtual inertial response (VIR) and droop control for primary frequency control/response (PFC/PFR)]. These parameters include: rotor-side (RSC) and grid-side (GSC) controller parameters, PLL parameters, pitch angle controller parameters, mechanical parameters). Some of those will be investigated in this paper. The rest of the paper is organised as follows: In section II, the test system used for simulations and methodology are shown. In section III, simulations are conducted and the results are shown. Discussion on the results is given in Section IV. Section V concludes the paper.

II. Test system modelling and methodology

The test system used in simulation is shown in Fig. 1. It is a simple 20 kV network (developed in DIgSILENT PowerFactory) of one 2 MW DFIG-based WTG, one synchronous generator, a couple of overhead lines and a DFIG step-up transformer. Local load is 3 MW with a power factor of 0.9. The synchronous generator is equipped with a *IEEET1* automatic voltage regulator (AVR) and TGOV1 turbine-governor model. To test the VIR/PFC action from the DFIG, a step increase in load of 0.5 MW is applied at the load bus at $t = 1$ s. Default parameters of the DFIG, step-up transformer and the synchronous generator are given in the Appendix. It is important to note that the DFIG generator is total power controlled, instead of stator power or torque controlled which is just a design choice in this case.

DFIG is equipped with an auxiliary controller which enables the virtual inertial response (VIR) and primary frequency control (PFC) capabilities. The generator vs. rotor speed curve and the auxiliary controller are given in the Appendix (Fig. 3 and Fig. 4, respectively). DFIG is 10% deloaded to ensure a spinning reserve, but detailed description of the implemented PFC algorithm is beyond the scope of this paper.

In this paper, we will test how certain parameters influence the VIR and PFC capabilities of the DFIG. These parameters are:

- initial conditions (initial wind speed, that is generator speed).
- RSC controller parameters
- PLL parameters
- Pitch angle controller parameters

III. Simulation and results

A. Case I: Impact of initial wind speed

Fig. 2a and Fig. 2b show the impact of initial wind speed on VIR and PFC, respectively. Generally, it can be seen that the higher the initial wind speed the lower the apex of VIR when the wind speed is increased until rated speed (11.7 m/s). Above the rated wind speed, pitch angle control becomes active and the apex is the lowest resulting in weakest inertial response, but it's value doesn't vary with wind anymore. This behaviour may be explained by the smaller gain of the small-signal model at higher wind speeds [11]. Similar behaviour can be observed for PFC, however, once the pitch angle becomes active (at 10.8 m/s due to the deloading by overspeed), the peak is slightly higher as well as the steady state value due to the interaction between rotor control and pitch control [10], [11].

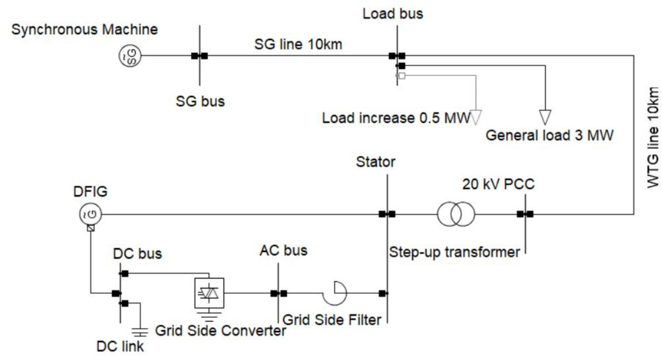


Fig. 1. Test system

B. Case II: Impact of RSC parameters

RSC consists of an slower, outer loop tracking the active and reactive power references, and fast, inner control loop that tracks the rotor currents. The RSC is tuned in order to achieve a stable operation of the WTG with satisfactory setpoint tracking performance, but its impact on VIR and PFC provision is relatively unexplored. The following behaviour is observed: Proportional gain of the outer loop does not have a significant impact on VIR nor on PFC, but too large gains will introduce oscillations in the output power (Fig. 2c, Fig. 2e). Meanwhile, larger outer loop integrator gain will result in a slightly lower apex of the VIR and PFC active power injection (Fig. 2d, Fig. 2f). Slightly different behaviour can be observed for inner loop parameters: too small proportional gain will introduce significant oscillations in DFIG power during VIR (Fig. 2g), while bigger gain will introduce oscillations in PFC (2i). Inner loop integral gains do not have a significant impact on the VIR nor on the PFC (Fig. 2h, Fig. 2j). In summary, the outer and inner loop do not have a significant impact on the provision of VIR and PFC. If improperly tuned, they will affect the initial transient behaviour and the strength and duration of the fast power oscillations. Outer loop integrator gain K_i is shown to have the most significant impact on the strength of VIR/PFC.

C. Case III: Impact of PLL parameters

PLL is used to synchronise the WTG to the grid and also to measure the grid frequency for VIR and PFC provision. The following behaviour is observed: The smaller the K_p parameter is, the higher is the apex of both VIR and PFC (Fig. 2k, Fig. 2m). However, the tracking of the grid frequency is weaker and the power oscillations of the WTG are higher and the DFIG power oscillations are translated into synchronous generator power oscillations (not shown). On the other hand, increasing K_i increases the active power injection apex up until some value (not determined in this paper). After that value, further increase of K_i decreases the apex (Fig. 2l, Fig. 2n). Absolutely speaking, PLL parameters did not have a significant influence on the strength of both VIR and PFC. However, one must note that simultaneous increase of decrease of parameters has a much more significant impact on the response than changing them one at a time, especially when the parameter held constant exhibits a strong tracking behaviour.

D. Case IV: Impact of pitch angle controller parameters

Pitch control is usually only active during above rated wind speeds in normal operation. Impact of pitch PI controller parameters K_p, K_i and the time constant of the pitch servomechanism T_s is shown in Fig. 2o–Fig. 2t. The following behaviour is observed: Bigger K_p will result in stronger inertial response (Fig. 2o) and negligibly weaker primary frequency response (Fig. 2r). Too low value of K_p will cause an oscillatory behaviour of the DFIG active power (Fig. 2o). Bigger K_i will result in slightly bigger VIR, although too large of a value can also cause oscillatory behaviour (Fig. 2p). K_i doesn't have a significant influence on PFC (Fig. 2s). Faster pitch mechanism (smaller T_s) will result in slightly stronger VIR (Fig. 2q) while it doesn't have a significant influence on PFC (Fig. 2t). However, one should be careful in drawing a general conclusion that the pitch controller doesn't have an impact on the DFIG output power oscillations: in this paper, the DFIG output power is the sum of stator power and rotor power and both of those show significant oscillations for a weaker pitch controller (Fig. 2u). It's just that those oscillations to a large extent destructively interfere with each other so their sum doesn't show oscillatory behaviour.

IV. Discussion on the results

In this paper, the influence of various parameters on VIR and PFC from DFIG based WTG has been investigated. The DFIG in question is total power controlled and uses a normal MPPT and deloaded characteristic that generates the power set-point based on actual rotor speed. However, a WTG is a complex electromechanical system that may use different modelling approaches and different control designs (e.g. torque control with inverse MPPT characteristic or stator power control, different implementations of VIR and PFC, etc.) so the results obtained in this paper should not be generalized to all possible cases because more analysis is needed on different types of models and with multidimensional parameter analysis.

First, the impact of wind speed was analysed (Fig. 2a–Fig. 2b). The simulations show that higher initial wind (but up to rated wind speed) will result in weaker VIR which agrees with the results from [11], [12]. The same conclusion is valid for PFC up to maximum generator speed (when pitch angle control kicks in). This, however, does not agree with the results obtained in [13] who used simplified torque control model with natural inertial response where stronger response is reported under higher wind speed conditions. We do not offer a clear explanation for these differences except that the results strongly depend on the model and VIR/PFC implementation and more thorough analysis is needed. Furthermore, both [11], [12] simulate with both VIR and PFC active, while in this paper we test them individually so that may or may not have an influence on the results. Continuing, once the pitch control becomes active VIR is weaker and the PFC is slightly stronger.

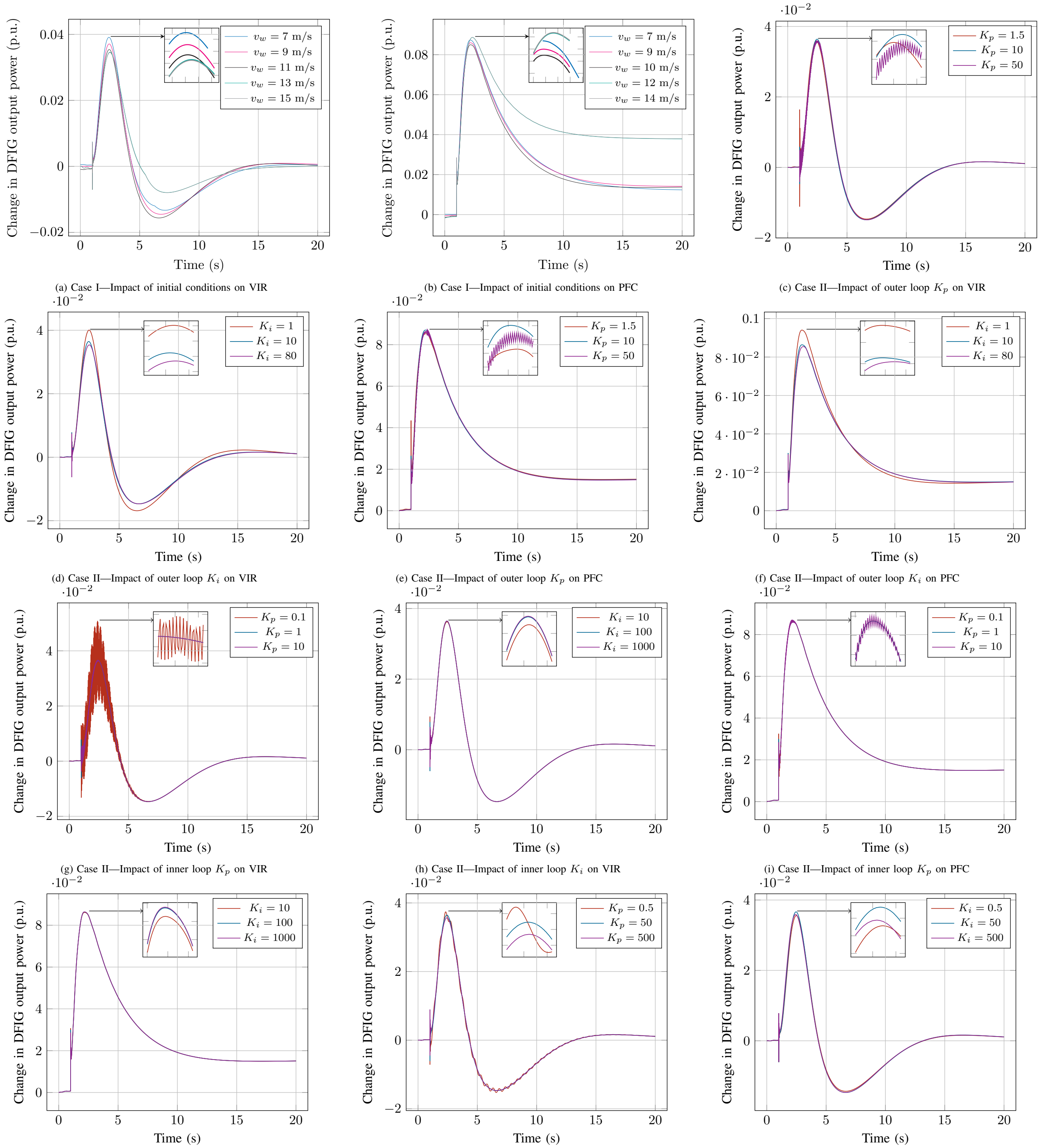
Then, the impact of inner and outer loop RSC PI parameters has been investigated (Fig. 2c–Fig. 2j). We have shown that these parameters basically do not contribute to the strength of VIR and PFC except the integral gain K_i of the outer loop where a weaker gain will results in stronger VIR and PFC. Hu et al. [13] arrive to a similar conclusion although their model is somewhat different. They report that bigger gains of torque control loop (both K_p, K_i) will result in a weaker inertial response because a faster speed tracking will restrain the overproduction power. However, more thorough analysis with smaller gains is needed as the values tested in this paper provide strong tracking and good damping. As we've said, other parameters do not have a significant impact on the VIR and PFC, but a bad choice of parameters may cause power oscillations. However, this will probably never happen in a real case scenario since those parameters are well tuned to ensure WTG stability.

Ma et al. [5] report that lower gains of the PLL will results in a weaker VIR. On the other hand, our results (Fig. 2k–Fig. 2n) show no strong influence of PLL parameters on the strength of VIR and PFC. We have shown that lower proportional gain of the PLL will results in stronger power oscillations. However, Ma et al. have used one set of small values of K_p, K_i and one set of big values while we changed the parameters individually which will have an influence on the results. Therefore, no general conclusion can be drawn at this point, only that a change of one PLL parameter while the other one was kept constant didn't have a strong influence on the strength of VIR and PFC. However, multidimensional analysis may reveal that sets of smaller and bigger gains really do have an influence on the strength on VIR and PFC as reported in [5].

Finally, the impact of pitch angle controller has been investigated (Fig. 2o–Fig. 2u). We have shown that bigger pitch controller gains (K_p, K_i) and a faster servomechanism (smaller T_s) will results in a stronger VIR (which agrees with results from [11]), while vice-versa is valid for PFC although the impact on PFC is negligible which agrees with conclusions of Arani et al. [7]. Although the sum of stator and rotor electrical power does not show any oscillations, both the stator and rotor power can swing significantly if the pitch angle controller is too weak.

V. Conclusion

In this paper, we have simulated the impact of initial conditions, RSC parameters, PLL parameters and pitch angle controller parameters on the virtual inertial response and primary frequency response of a total power controlled DFIG-based WTG in DIgSILENT PowerFactory tool. Once the



(a) Case I—Impact of initial conditions on VIR

(b) Case I—Impact of initial conditions on PFC

(c) Case II—Impact of outer loop K_p on VIR

(d) Case II—Impact of outer loop K_i on VIR

(e) Case II—Impact of outer loop K_p on PFC

(f) Case II—Impact of outer loop K_i on PFC

(g) Case II—Impact of inner loop K_p on VIR

(h) Case II—Impact of inner loop K_i on VIR

(i) Case II—Impact of inner loop K_p on PFC

(j) Case II—Impact of inner loop K_i on PFC

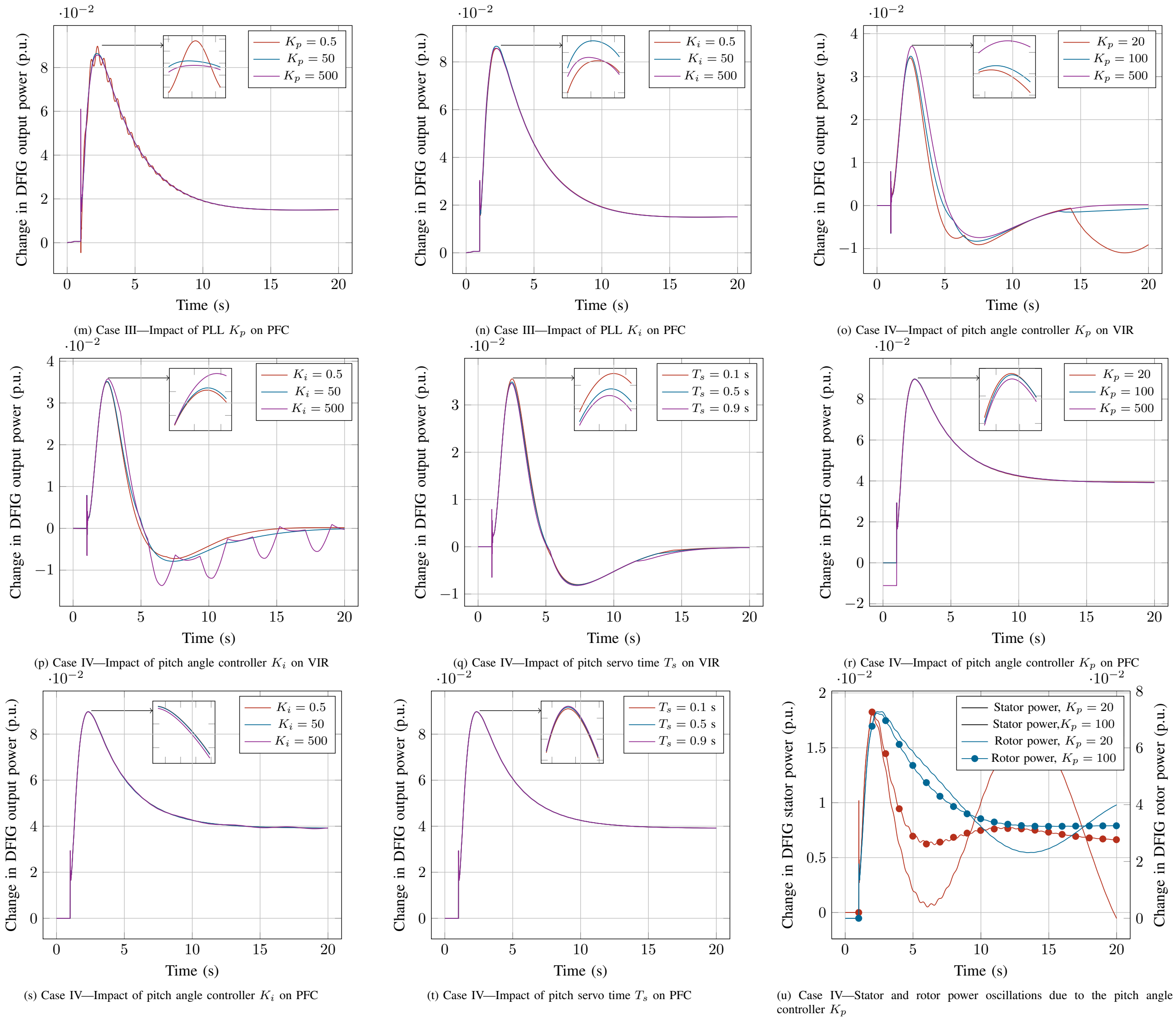
(k) Case III—Impact of PLL K_p on VIR

(l) Case III—Impact of PLL K_i on VIR

Fig. 2. Simulation results

DFIG is given the capability to participate in VIR and PFC it becomes coupled with the electromechanical oscillations of the grid. We have shown that all the parameters and initial conditions have some influence on the VIR and PFC, although most are negligible. Some of our results agree with previous literature while some disagree which suggests that the results strongly depend on the type of WTG model as well as VIR and PFC implementation, thus more detailed analysis is needed. Based on the results of this paper, we may conclude the following:

- initial conditions have a visible impact on VIR and on PFC;
- pitch angle control dynamics should be taken in to account at higher wind speeds because it will directly



(m) Case III—Impact of PLL K_p on PFC

(n) Case III—Impact of PLL K_i on PFC

(o) Case IV—Impact of pitch angle controller K_p on VIR

(p) Case IV—Impact of pitch angle controller K_i on VIR

(q) Case IV—Impact of pitch servo time T_s on VIR

(r) Case IV—Impact of pitch angle controller K_p on PFC

(s) Case IV—Impact of pitch angle controller K_i on PFC

(t) Case IV—Impact of pitch servo time T_s on PFC

(u) Case IV—Stator and rotor power oscillations due to the pitch angle controller K_p

Fig. 2. Simulation results (cont.)

impact the VIR and PFC. Although the impact on PFC is found to be negligible, it is necessary to coordinate it with the PFC algorithm in order to achieve a permanent active power increase;

- fast power converter can be neglected in power system stability studies which confirms the previous studies. However, the slower outer loop may have some impact on the VIR and PFC which also depends on the type of WTG model and parameter tuning;
- impact of PLL on VIR and PFC probably depends on the combination of the PLL parameters. More thorough analysis is needed, but it is possible that PLL dynamics should be taken into account since it couples the WTG to the grid and it is used to measure the grid frequency for VIR and PFC.

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APPENDIX

Wind turbine and shaft parameters: nominal/base power: 2 MVA; rotor radius: 37.5 m; gearbox ratio: 87; nominal wind speed: 12 m/s; turbine inertia constant: 4.33 s; shaft-stiffnes: 0.46 p.u./el. rad.; shaft-damping: 1 p.u.

DFIG parameters: stator voltage: 690 V (line-to-line, RMS); rated apparent power: 2.28 MVA; frequency: 50 Hz; number of pole-pairs: 2; stator resistance/reactance: 0.01/0.1 p.u.; rotor resistance/reactance (referred to stator): 0.01/0.1 p.u.; magnetising reactance: 3.5 p.u.; inertia constant: 0.6 s.

RSC parameters: outer control loop: $Kp = 4$, $Ki = 10$; inner control loop: $Kp = 1$, $Ki = 100$.

GSC parameters: DC voltage control loop: $Kp = 8$, $Ki = 40$; inner control loop: $Kp = 1$, $Ki = 100$.

PLL parameters: $K_p = 50$, $K_i = 150$.

Pitch angle controller parameters: $K_p = 150$, $K_i = 25$; servomechanism time constant: 0.3 s; max. rate-of-change-of-pitch: ±10 deg/s.

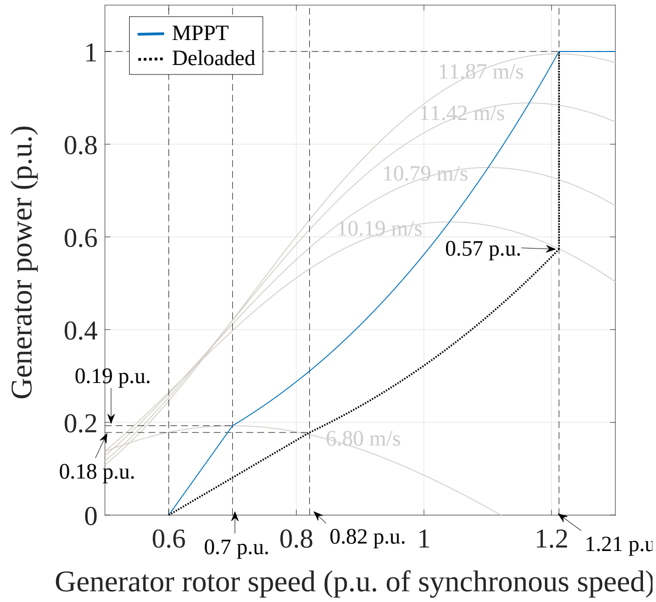

Fig. 3. Generator power vs. rotor speed curve

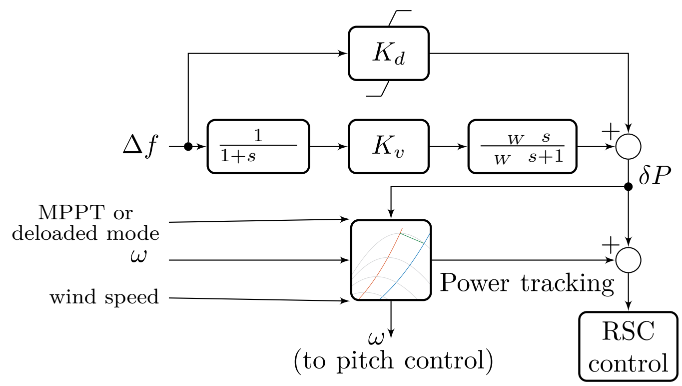

Fig. 4. VIR/PFC control structure

Auxilliary frequency controller parameters: $K_v = 10$; $T_{LP} = 1$ s; $T_{WF} = 1$; $K_d = 10$.

Synchronous generator parameters: Apparent power: 5 MVA; nominal voltage: 20 kV (line-to-line, RMS); Inertia constant: 3 s; stator resistance/reactance: 0.05/0.1 p.u.; synchronous reactance x_d/x_q: 1,5/0,75 p.u.; transient reactance: 0.256 p.u.

AVR parameters (IEEET1): default parameters in DIgSILENT PowerFactory.

Turbine-governor (TGOV1) parameters: high-pressure fraction: 0.3, reheat time constant: 8 s; droop: 5 %; governor time constant: 0.3 s

Step-up transformer parameters: nominal power: 3 MVA; LV/HV voltage ratio: 0.69/20 kV; short-circuit voltage: 10%; vector group: YNy0.

Overhead line parameters: resistance: 0.5 Ω/km; reactance: 0.25 Ω/km; length: 10 km