Increasing the Share of Wind Power by Sensitivity Analysis based Transient Stability Assessment

N. Farrokhseresht[1], A.A. van der Meer[1], J. R. Torres[1], M.A.M.M. van der Meijden[1,2] and P. Palensky[1]
[1] Department of Electrical Sustainable Energy, Delft University of Technology (TUD), Delft, Netherlands
[2]TenneT TSO B.V, Arnhem, Netherlands
Email:n.farrokhseresht@tudelft.nl

***Abstract*—This paper presents a study based on sensitivity analysis to investigate the impact of wind power plants (WPP) based on full converter wind turbine generators (FCWTG) on the transient stability of the interconnected power system. A combination of different fault ride through (FRT) capability and voltage support mechanisms for FCWTGs such as "low voltage ride through", "voltage-dependent reactive power injection" and "current limitation strategy during grid faults" are considered for the sensitivity analysis. The Critical clearing Time (CCT) is used as a transient stability indicator in this work. The implementation of the wind turbine models according to IEC 61400-27-1 and the time domain simulations are developed in DIgSILENT PowerFactory. The results on the IEEE 9-bus system show that by more effective use of the existing controllers of wind turbines, the share of wind power plants can be increased substantially.**

***Index Terms*—full converter wind turbine generator, fault ride through, sensitivity analysis, transient stability**

I. INTRODUCTION

The significant penetration of wind generations in power grids brings new challenges in the operational and planning decisions of power systems [1]. Particularly, their influences on power system dynamics in the transient stability time-frame needs to be studied [1], [2].

Large disturbance rotor angle stability known as transient stability refers to the ability of synchronous generators to remain in synchronism after being subjected to a severe grid fault [3]. When such a significant disturbance occurs, the electro-mechanical power imbalance is generated, which causes some oscillations in speed deviations (and corresponding angle deviations) of generators in the system. If these oscillations cannot be diminished, transient instability occurs.

Within the different type of wind turbines, full converter wind turbine generator (FCWTG) is more superior in terms of flexibility in operation and control, the capability of providing ancillary service, and easy maintenance [4]. FCWTG contains power converters that decouple the wind power generators from the grid. This decoupling reduces the inertial response and short circuit power of the grid and consequently reduces the transient stability margin [5]. Moreover, unlike synchronous generators, FCWTGs cannot contribute to voltage support during a fault. Thus, the lack of voltage support creates an extra electro-mechanical power imbalance at the synchronous generator's terminal bus and jeopardizes the transient stability [6]. Therefore, Transmission System Operators (TSOs) devise grid connection requirements for Wind Power Plants (WPPs) to remain connected for any contingency and provide ancillary services during and immediately after a grid fault [7]. The Fault Ride-Through (FRT) and the voltage support are example of grid codes to ensure transient stability and grid security.

Transient stability enhancement methods of a power system, including FCWTGs, can be based on: (i) addition of hardware components (e.g. crowbar, FACTS devices, fault current limiter); (ii) modification or addition of control systems on the power electronic converters that interface the wind generator with the electrical power system.

Additional hardware-based methods [8][9] may involve substantial capital investments, which may not necessarily entail effectiveness. Therefore the modification or addition of control systems of wind generator's converters is the preferred approach in this paper.

Research efforts so far have been devoted to either modify the way current limitation occurs in the grid side converter or to alter the way active and reactive power injection is performed, by considering signals taken from the connection point of the wind generator with the power system. In [10] active current reduction method is applied by adding a compensation torque signal depended on DC link current. A coordinated control scheme for active and reactive power injection is proposed in [11] for a wind power plant with fully decoupled wind generators, connected to the power system by an AC cable. An alternative vector current control is proposed in [12]. A decoupled and gain-scheduling controller is implemented in the outer loop of the grid side converter to tackle possible interactions between the active power and voltage control when a FCWTG should operate close to the nominal power and is connected to a weak transmission system.

In the last 20 years, significant research effort has been devoted to the tuning of existing wind generator controllers for transient stability enhancement, by using special techniques like sliding mode control [13], model predictive control [14], and artificial intelligence [15]. These methods show great potential to adjust the settings of wind generator controllers in a near real-time context. Nevertheless, sensitivity to changes

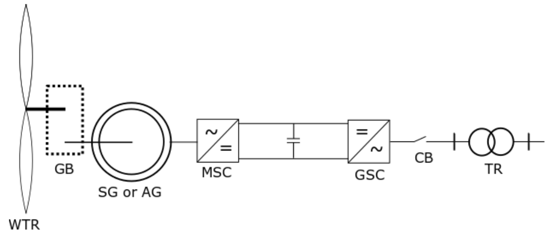

Fig. 1: Main components of full convert wind turbine [17]

in operating conditions, network topology, and disturbances not considered in the training or application of the methods mentioned above, remains as an open research gap.

This paper presents a study based on sensitivity analysis to investigate the impact of a full converter wind turbine generator on the overall transient stability of the interconnected power system considering the grid code requirements. A sensitivity analysis is performing to determine key parameters of controllers in wind turbines to tune them properly for the FRT capability and voltage support during a large disturbance.

The paper is organized as follows: first, full converter wind turbine modeling with its overall control scheme is introduced. Then, in section III, the methodology for sensitivity analysis is explained. In Section IV, a case study of the IEEE 9-bus system is described, and the simulation results for different FRT parameters are presented. Finally, Section V summarizes the main conclusions.

II. FULL CONVERTER WIND TURBINE MODELLING

Fig. 1 shows the main components of investigated FCWTG which is developed based on [16]. The Machine Side converter (MSC) regulates the stator currents and thus controls the rotation speed of generator to regulate the extracted mechanical power. On the other hand, Line Side Converter (LSC) is responsible to regulate the active power and reactive power injected to the grid.

Fig.2 illustrates the overall structure of the wind turbine control [18]. The main features of the model are described as follows:

- In the measurement part of this model, the blocks Frequency, Power, and Voltage Measurement are connected directly to the terminals of the wind turbine and put out the corresponding measurement data.
- The Generator Block contains the PowerFactory element ”Static Generator,” and works as a current source.
- The mechanical part is represented by the Aerodynamic block, which calculates the mechanical power on the turbine, and the Mechanical block, which contains a two-mass oscillator.
- Input part: the block Wind speed gives the wind speed.
- The control part consists of the block P control for active power control, the Pitch angle control, inertia emulation block, Q control for reactive power control, current limitation block and finally the grid protection block that includes protection feature against over and under voltage, and against over and under frequency.

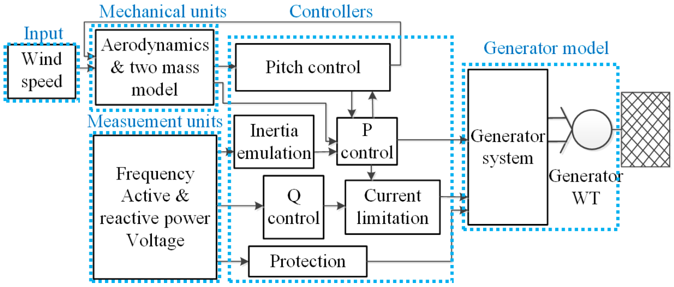

Fig. 2: Control structure of the wind turbine [18]

III. SENSITIVITY BASED APPROACH FOR TRANSIENT STABILITY ENHANCEMENT

Fig. 3 shows the proposed approach for sensitivity analysis. The procedure starts with the model preparation. The input is a given power system with several WPPs associated with a given penetration level and an initial set of control parameters. After the preparation of the model, the second step is to find a critical wind turbine for further investigation. Every synchronous generator in the system is replaced with the same installed capacity of FCWTG, one by one, and then a selected disturbance (e.g. a 3-phase short circuit on a Bus) is applied. The Critical Clearing Time (CCT) is used as a transient stability indicator in this work. The CCT is the maximum time it may take to clear the fault without the system going out of synchronism. An iterative process (implemented via Python script) is performed to calculate CCT, as shown in Fig. 4. The critical wind turbine is selected as the one that gives a minimum amount of the CCT. After that, sensitivity to different FRT parameters is conducted for the selected WPP. Five different control parameters are investigated separately including: ”reactive current boosting gain”, ”dead-band threshold”, ”active or reactive power priority during grid faults”, ”maximum allowable current of the wind turbine” and finally ”inertia emulation capability”. Afterward, by identifying the most effective parameters on the transient stability and their optimum values, the penetration level of the wind power generation is increased.

The assumptions made for the study of wind power plants consist of FCWTGs are:

- The load will not change in different scenarios,
- One aggregated wind turbine is used to represent all wind turbines inside a wind farm,
- The wind speed remains constant during the simulations,
- Synchronous generator controls (speed and voltage) are not modified.

IV. RESULTS AND DISCUSSIONS

In this section, the procedure defined in Section III is applied to a modified version of the IEEE 9-bus system [19]. The single line diagram of the system is shown in Fig. 5 that includes three WPPs, to create different penetration levels. After a fault screening, a three-phase short circuit on Bus number 1 is considered as the type of fault. The total demand

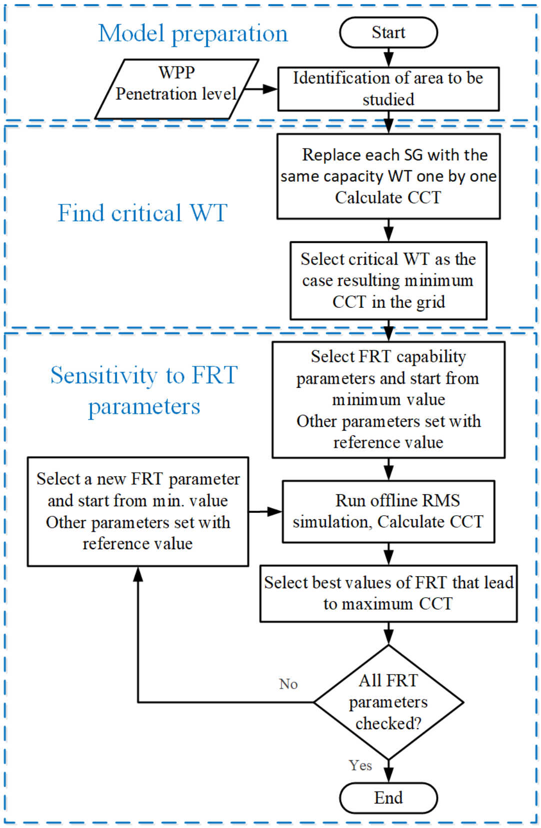

Fig. 3: Procedure for sensitivity analysis

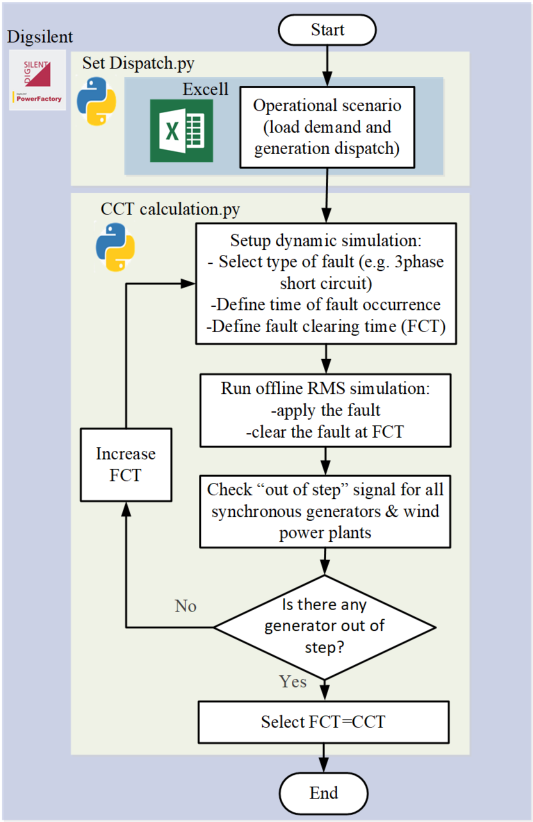

Fig. 4: Procedure for calculation of CCT

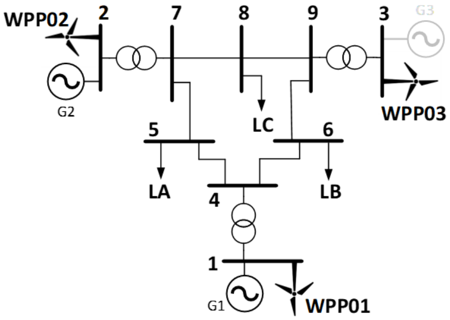

Fig. 5: Modified IEEE 9-bus system single line diagram

for the system is 315 MW and it is fixed for all scenarios. Table I shows initial conditions of synchronous generators and WPPs in the "original case" and the "base case study with WPPs". The share of WPPs is defined as ratio between total wind power generation and the total demand. It is calculated as 57% for the base case study.

TABLE I: Initial conditions of original and base case

	Original case	Base case with WPPs
G1 (MVA)	247,5	247,5
G2 (MVA)	192	100
G3 (MVA)	128	—
WPP01 (MVA)	—	72
WPP02 (MVA)	—	36
WPP03 (MVA)	—	72
CCT (ms)	180	120

In the next part, as already explained, the five identified control parameters that affect transient stability are investigated. After replacing synchronous generators by WPPs, one by one, it is found that the CCT reduces the most if synchronous generator G3 is decommissioned and replaced by WPP03. Therefore, WPP03 is selected as the critical generator for the following analysis.

A. *Reactive power boosting gain (k-factor)*

Wind power plants shall provide reactive power support during grid faults dependent on voltage deviations [7]. The additional reactive current injection is given by the following equation:

$$\triangle i_Q = k.(u_{db,low} - u_{WT}) \tag{1}$$

Here k is a proportional gain that is called K-factor [20], u_{WT} is the grid connection point voltage and $u_{db,low}$ is the lower limit of the voltage dead-band threshold. The k-factor could vary between 0 and 10 for wind power generation units [20]. A larger k-factor, means that wind turbines will supply the larger reactive current during grid fault which is helpful to restore faster the post disturbance voltage and thereby improve transient stability. This control parameter is accessible through Q control block . Fig. 6 shows how CCT increases when larger K factor are being used. The response of WPP03 terminal voltage for k-factor of 1 and 10 during a 3-phase short circuit at Bus1 is shown in Fig. 7. A comparison of different k-factor shows a significant decrease in voltage support and as a result larger voltage excursions during grid disturbances if lower k-factor is used.

It can be seen that higher K-factor will result in less voltage drop during the fault. This significant positive effect of increasing K-factor can be seen also in Fig. 8 that shows by increasing K-factor, more reactive power can be injected during the fault.

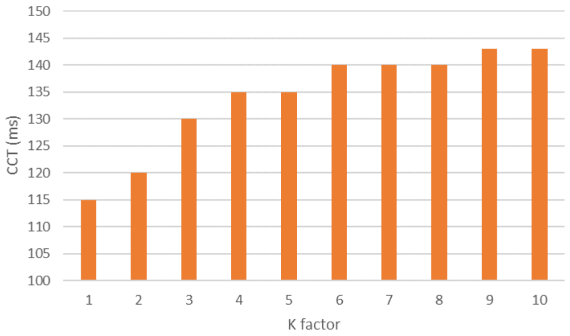

Fig. 6: CCT corresponding to different reactive power boosting gain

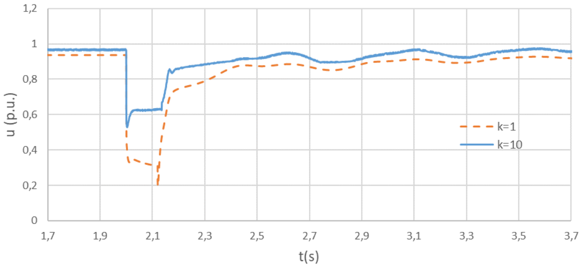

Fig. 7: Terminal voltage of the WPP03 with k=1 and k=10

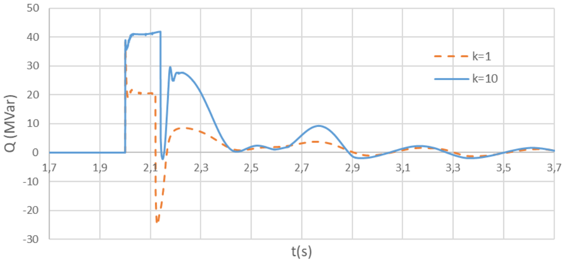

Fig. 8: Reactive power injection of the WPP03 with k=1 and k=10

B. The dead-band threshold effect

Next, the choice of the dead-band $u_{db,low}$ in eq.1 for the provision of fast reactive current is investigated. Fig. 9 show reactive power injection of WPP03 when a dead-band of 10% is applied compared to a case without any dead-band. From the presented figures it can be observed that the deactivation of $u_{db,low}$ results to a better fault response due to the fact that without dead-band, WT activated immediately to inject additional reactive power.

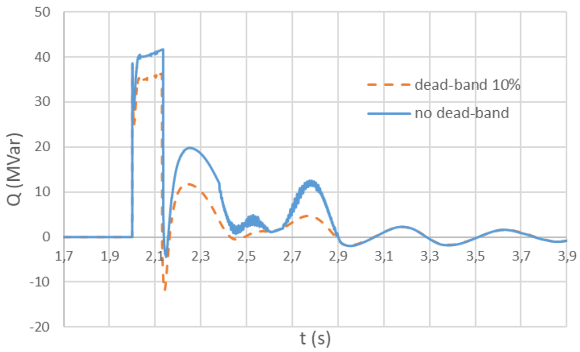

Fig. 9: Reactive power injection of the WPP03 with 10% dead-band and deactivation of the dead-band

C. Active or reactive power priority during grid faults

In this part, current limitation strategy is assessed during the grid fault. Typically during the fault condition, reactive current is given priority and therefore active power limitation is applied according to the following equation:

$$i_{P,max} = \sqrt{{I_{max}}^2 - {i_{Q,ref}}^2} \tag{2}$$

Where I_{max} is the maximum allowed current of wind turbine and $I_{Q,ref}$ is the reactive current reference value from the turbine controller. The reactive current is limited by the maximum allowed reactive current:

$$i_{Q,ref} = I_{Q,max,ref} \tag{3}$$

However, in some countries such as the republic of Ireland that they have frequency stability concern, active power limitation is not allowed and wind turbine shall provide active power in proportion to the retained voltage during fault [21].

The result of the applied current limitation strategy (active power versus reactive power priority) during a grid fault is shown in Fig. 10. It shows a slightly better reactive power support during the fault when reactive power priority is chosen.

D. Maximum allowable current of the wind turbine

The maximum current injection of a FCWTG during network fault is limited to the maximum fault current capacity shown as I_{max} in eq. 2. In this study, FCWTGs have default value of 1.6 p.u. as the maximum allowed current during a grid fault. In order to analysis the affect of I_{max} on transient stability, the value is decreased $I_{max} = 1.3$ p.u. The response of WPP03 for two different I_{max} is presented in Fig. 11 and 12. It can be seen that the higher value of I_{max} results in lower voltage drop.

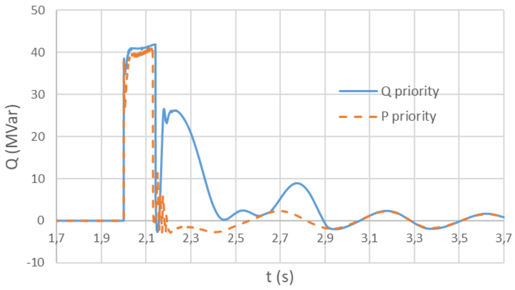

Fig. 10: Reactive power injection of the WPP03 with different current limitation strategy

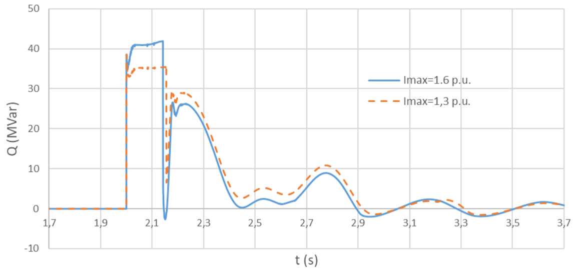

Fig. 11: Reactive power injection of the WPP03 with $I_{max} = 1.6$ p.u. and $I_{max} = 1.3$ p.u.

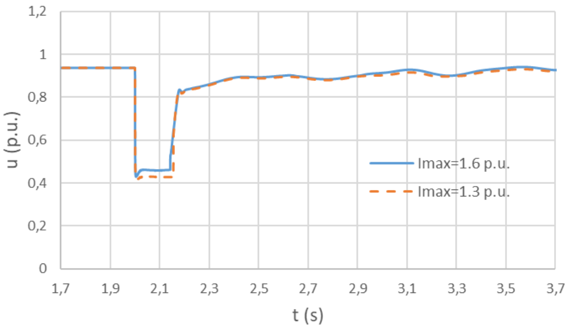

Fig. 12: Terminal voltage of the WPP03 with $I_{max} = 1.6$ p.u. and $I_{max} = 1.3$ p.u.

E. Inertia emulation (IE) capability

The droop based fast active power injection controller as inertia emulation (IE) capability for wind turbine is implemented based on modified version of [22]. Although IE helps to damp speed oscillation of synchronous generator G1 as shown in Fig. 13 but it isn't beneficial for the transient stability. Fig. 14 demonstrates the reactive power injection of WPP03 with and without IE capability. It can be seen that without IE capability, amount of reactive current injection is slightly increased.

F. Increasing share of WPPs

The last part of the study is increase the share of WPPs by considering the relevant parameters found in mentioned analysis. The k-factor equal to 10 is considered with the deactivation of the dead-band. The reactive power priority is chosen for current limitation strategy and maximum allowed current of $I_{max} = 1.6$ p.u. are selected. Also the inertia emulation block is disabled. A fault of 3-phase short circuit at Bus 1 is considered and cleared after 140ms. The result shows that share of FCWTGs can be increased from 57% to 78% without jeopardizing transient stability.

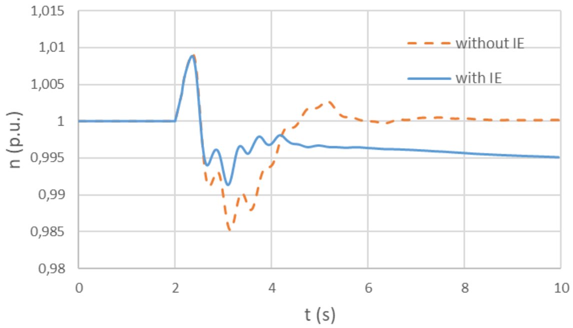

Fig. 13: Speed of synchronous generator G1 corresponding to different inertia emulation capability

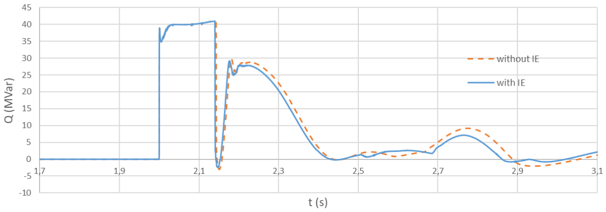

Fig. 14: Reactive power injection of WPP03 corresponding to different inertia emulation capability

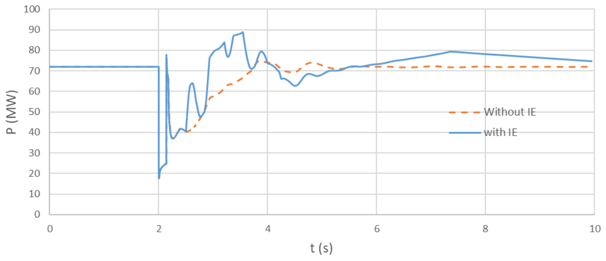

Fig. 15: Active power injection of WPP03 corresponding to different inertia emulation capability

V. CONCLUSIONS

The increasing share of wind generation is changing the dynamic behaviour of power systems. This paper investigates the effect of full converter wind turbines on transient stability. It proposed a sensitivity based method to tune wind turbine controllers as a mitigation measure to increase the penetration level of wind generation.

The results show how the influence of wind turbines on transient stability depends on different parameters of FRT capability. The deactivation the dead-band and increasing maximum allowed current of the wind turbine can enhance transient stability; however, reactive current boosting gain k-factor is the most effective factor.

Also, by setting "Q priority" during the fault, transient stability can be improved. However, in some grid codes, this feature is not possible. Although the "inertia emulation" option has a positive effect on the damping of oscillation of synchronous generators, it cannot be beneficial in transient stability. During faulted conditions both active and reactive power interact very closely and their relationship becomes very complex. Therefore, the effect of a high penetration of wind generation on frequency and transient stability should be comprehensively studies.

Finally, the results show that by more effective use of the existing controllers of the wind turbine, the share of wind power plants can be increased substantially.

ACKNOWLEDGEMENT

This project has received the funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691800. This paper reflects only the authors' views and the European Commission is not responsible for any use that may be made of the information it contains.

REFERENCES

[1] D. Flynn *et al.*, "Technical impacts of high penetration levels of wind power on power system stability," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 6, no. 2, pp. 1–19, 2017.

[2] A. A. van der Meer, M. Ndreko, M. Gibescu, and M. A. M. M. van der Meijden, "The Effect of FRT Behavior of VSC-HVDC-Connected Offshore Wind Power Plants on AC/DC System Dynamics," *IEEE Transactions on Power Delivery*, vol. 31, pp. 878–887, April 2016.

[3] P. Kundur *et al.*, "Definition and classification of power system stability ieee/cigre joint task force on stability terms and definitions," *IEEE Transactions on Power Systems*, vol. 19, pp. 1387–1401, Aug 2004.

[4] P. Pourbeik, *WECC Type 4 Wind Turbine Generator Model*, 2013. https://www.wecc.biz/Reliability/WECC-Type-4-Wind-Turbine-Generator-Model-Phase-II- 012313.pdf.

[5] MIGRATE Work Package 1, responsible partner: TenneT, "MIGRATE Deliverable 1.1: Report on Systemic issues," tech. rep., MIGRATE consortium, 2016.

[6] K. Amarasekara, L. G. Meegahapola, A. P. Agalgaonkar, and S. Perera, "Characterisation of long-term voltage stability with variable-speed wind power generation," *IET Generation, Transmission Distribution*, vol. 11, no. 7, pp. 1848–1855, 2017.

[7] "Network code for requirements for grid connection applicable to all generators - requirements in the context of present practices," tech. rep., European Network of Transmission System Operators for Electricity (ENTSO-E), 2012. https://www.entsoe.eu/. [Accessed: 4 November 2016].

[8] S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura, "Integration of an energy capacitor system with a variable-speed wind generator," *IEEE Transactions on Energy Conversion*, vol. 24, pp. 740–749, Sep. 2009.

[9] L. Wang and D. Truong, "Dynamic stability improvement of four parallel-operated pmsg-based offshore wind turbine generators fed to a power system using a statcom," *IEEE Transactions on Power Delivery*, vol. 28, pp. 111–119, Jan 2013.

[10] H. Geng and D. Xu, "Stability analysis and improvements for variable-speed multipole permanent magnet synchronous generator-based wind energy conversion system," *IEEE Transactions on Sustainable Energy*, vol. 2, pp. 459–467, Oct 2011.

[11] M. Arags Pealba, O. Gomis-Bellmunt, and M. Martins, "Coordinated control for an offshore wind power plant to provide fault ride through capability," *IEEE Transactions on Sustainable Energy*, vol. 5, pp. 1253–1261, Oct 2014.

[12] A. Egea-Alvarez, S. Fekriasl, F. Hassan, and O. Gomis-Bellmunt, "Advanced vector control for voltage source converters connected to weak grids," *IEEE Transactions on Power Systems*, vol. 30, pp. 3072–3081, Nov 2015.

[13] A. Mohanty, M. Viswavandya, and P. K. Ray, "An adaptive fuzzy sliding mode controller for reactive power amp; transient stability management," in *2016 IEEE Region 10 Conference (TENCON)*, pp. 3195–3199, Nov 2016.

[14] V. Yaramasu and B. Wu, "Predictive control of a three-level boost converter and an npc inverter for high-power pmsg-based medium voltage wind energy conversion systems," *IEEE Transactions on Power Electronics*, vol. 29, pp. 5308–5322, Oct 2014.

[15] M. A. Soliman, H. M. Hasanien, H. Z. Azazi, E. E. El-kholy, and S. A. Mahmoud, "Hybrid anfis-ga-based control scheme for performance enhancement of a grid-connected wind generator," *IET Renewable Power Generation*, vol. 12, no. 7, pp. 832–843, 2018.

[16] *IEC standard 61400-27-1, Wind turbines Part 27-1: Electrical simulation models - Wind turbines*, 2017.

[17] J. Fortmann, *Modeling of Wind Turbines with Doubly Fed Generator System*. PhD thesis, University Duisburg-Essen, 2014.

[18] Energynautics, *MIGRATE Project, Type-3 and Type-4 EMT - Model Documentation*, 2017.

[19] P. Anderson and A. Fouad, *Power System Control and Stability*. The Iowa State University Press, Ames, Iowa, 1977.

[20] B. Weise, "Impact of k-factor and active current reduction during fault-ride-through of generating units connected via voltage-sourced converters on power system stability," *IET Renewable Power Generation*, vol. 9, no. 1, pp. 25–36, 2015.

[21] "The grid code, Issue 5, Revision 6," tech. rep., National Grid Electricity Transmission plc, UK, 2013.

[22] S. Engelken, A. Mendonca, and M. Fischer, "Inertial response with improved variable recovery behaviour provided by type 4 wts," *IET Renewable Power Generation*, vol. 11, no. 3, pp. 195–201, 2017.