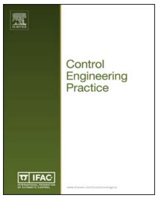
Control Engineering Practice 61 (2017) 124–133

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac



# Impact of voltage dip induced delayed active power recovery on wind integrated power systems

Z.H. Rather[a,b], D. Flynn[a]

[a] Electricity Research Centre, University College Dublin, Belfield, Dublin 4, Ireland
[b] Indian Institute of Technology Bombay, Mumbai 400076, India

## ARTICLE INFO

*Keywords:*
Power system dynamics
Wind power generation
Wind generator modelling

## ABSTRACT

Installed wind power capacity is increasing rapidly in many power systems around the world, with challenging penetration targets set at national, and/or regional level. Wind power, particularly at higher penetration levels, introduces various grid issues, with frequency and voltage stability being particularly critical concerns. Voltage dip induced frequency stability following a network fault in such systems is one potential risk that has so far received limited attention by the research community. With state of the art modelling, the potential impact of a delayed active power recovery from wind generation following a network fault induced voltage dip is investigated. The subsequent voltage oscillations introduced by wind turbines, exacerbating frequency stability, are also examined. Analysis is carried out for a wide range of wind penetration levels and system scenarios, with the results demonstrated on the New England benchmark system.

## 1. Introduction

The last decade has witnessed a significant increase in wind power integration, with ambitious goals set at regional and national level. Currently, global installed wind power capacity has reached 433 GW, with 63 GW added in 2015 alone (GWEC, 2016). The trend of increasing wind power integration is likely to continue into the future, underscoring the need to investigate and understand the impact that wind power has on the secure and reliable operation of such systems. Due to its time-varying nature, limited predictability and controllability, wind generation integration poses a wide spectrum of challenges (Flynn, Rather, & Ardal, 2016), ranging from short-term frequency deviations (Ilic, Makarov & Hawkins, 2007), dynamic voltage stability (Rather et al., 2014), small signal stability (Mendonca & Lopes, 2005), inertial and rate of change of frequency (RoCoF) issues (O'Sullivan, Rogers, Flynn & Smith, 2014; Ruttledge, Miller, O'Sullivan & Flynn, 2012), voltage control challenges (Rather, Chen, & Thogersen, 2013) to long-term generation-load balancing (Aigner, Jaehnert, Doorman & Gjengedal, 2012), steady-state voltage control and stability issues (Ma, Liu, & Zhao, 2010). Further, the impact of such issues of concern for a particular system will depend on system size, wind penetration level, system network configuration, along with the unit commitment / economic dispatch (UC/ED) schedule. Typically, such impacts will be more evident during the night valley/seasonal low-demand periods when instantaneous wind penetration may be significantly high (Fox et al., 2014). Higher penetration levels leading to the displacement of conventional generation, is likely to result in reduced governor response and lower synchronous inertia (Dangelmaier, 2011; Pelletier, Phaethon, & Nutt, 2012; Ruttledge & Flynn, 2015; Sharma, Huang, & Sarma, 2011), which is in turn likely to reduce frequency stability (Ela et al., 2013; Miller, Shao, & Venkataraman, 2011). Furthermore, with older wind turbine technology (type 1 and type 2) their reactive power consumption is related to their real power output, particularly during voltage dips when reactive power absorption by such wind turbines increases sharply, affecting the system dynamics. Transpower (New Zealand) observed that such old technology (fixed speed) wind turbines can reduce the transient stability of the system and generally do not comply with voltage ride through grid code regulations (Transpower, 2008).

Renewable-driven displacement of conventional power plant is leading to diminishing sources of online flexibility/ancillary services, required to maintain secure and stable system operation. Therefore, in order to accommodate higher wind targets, transmission system operators (TSOs), government agencies and other associated regulatory authorities are endeavouring to tackle such issues through updated/more stringent grid codes (Mohseni & Islam, 2012) and/or by considering alternative sources of flexibility/ancillary services, procured either through electricity market arrangements or by installing their own infrastructure (Rather, Chen, & Thogersen, 2013; Abildgaard & Qin et al., 2015). More stringent grid codes have, in

---

*E-mail addresses:* zakir.rather@iitb.ac.in (Z.H. Rather), damian.flynn@ucd.ie (D. Flynn).

http://dx.doi.org/10.1016/j.conengprac.2017.01.003
Received 30 June 2016; Received in revised form 6 January 2017; Accepted 7 January 2017

**Nomenclature**

| | |
|---|---|
| CHP | Combined heat and power plant |
| PCC | Point of common coupling |
| RoCoF | Rate of change of frequency |
| TSO | Transmission system operator |
| LVRT | Low voltage ride-through |
| WF | Wind farm |
| WT | Wind turbine |
| WTT | WT terminal |
| $F_{UVRT}$ | Under voltage ride-through flag |
| $T_{ufiltq}$ | Voltage measurement filter time constant |
| $T_{pfiltq}$ | Power measurement filter time constant |
| $K_{Pq}$ | Reactive power PI controller proportional gain |
| $K_{iq}$ | Reactive power PI controller integrator gain |
| $K_{Pu}$ | Voltage PI controller proportional gain |
| $K_{iu}$ | Voltage PI controller integrator gain |
| $u_{db1}$ | Voltage deadband lower limit |
| $u_{db2}$ | Voltage deadband upper limit |
| $K_{qv}$ | Voltage scaling factor for LVRT current |
| $u_{max}$ | Maximum voltage for voltage PI controller integral term |
| $u_{min}$ | Minimum voltage for voltage PI controller integral term |
| $u_{ref0}$ | User defined bias in voltage reference |
| $u_{qdip}$ | Voltage threshold for LVRT detection in q control |
| $T_{qord}$ | Time constant for reactive power order lag |
| $T_{post}$ | Time duration when post-fault reactive power is injected |
| $i_{pmax}$ | Maximum active current injection |
| $i_{qmax}$ | Maximum reactive current injection |
| $i_{qmin}$ | Minimum reactive current injection |
| $i_{qh1}$ | Maximum reactive current injection during dip |
| $i_{qpost}$ | Post-fault reactive current injection |
| $i_{pcmd}$ | Active current command to generator system |
| $i_{qcmd}$ | Reactive current command to generator system |
| $p_{WT}$ | WTT active power generation |
| $q_{WT}$ | WTT reactive power generation |
| $q_{WTmax}$ | Maximum WTT reactive power |
| $q_{WTmin}$ | Minimum WTT reactive power |
| $u_{WT}$ | WTT voltage |
| $x_{WTref}$ | WTT reactive power reference, or delta voltage reference, depending on WT control mode |

fact, become one of the major drivers for the development of wind generation technology (Tsili & Papathanassiou, 2009). However, wind turbine technology has considerable implications for system dynamics, primarily due to the decoupling of the rotating mass of variable speed wind turbines (type-3 and type-4) from the electrical grid (Lalor, Mullane, & O'Malley, 2005; Morren, de Haan, & Ferreira, 2006). Diminishing online rotational inertia due to displaced conventional power plant, coupled with power electronic interfaced wind turbine technology, has a negative impact on system frequency stability, with implications being more prominent in smaller and isolated grids. Due to diminished inertia, the resulting high rate of change of frequency may result in anti-islanding RoCoF (rate of change of frequency) protection to mal-operate, which may result in further frequency variation (Beddoes, Thomas, & Gosden, 2005).

Wind-driven displacement of conventional power plant, particularly at higher penetration levels is also likely to reduce the net system dynamic reactive power and short-circuit power capacity, required to maintain adequate voltage stability (EirGrid, 2015; Rather, Chen, & Thogersen, 2012). A study on the New Zealand system reported that wind generation, particularly when connected at distribution system has resulted in reduced voltage stability by 10–34% (Transpower, 2007). A similar case study carried out on the projected 2030 Danish power system concluded that at higher penetration levels with conventional power plant displaced by grid code compliant wind turbines, and without considering any new reactive power compensating devices (synchronous condensers, SVCs, etc.), that system stability would be significantly compromised (Rather, Chen, Thogersen & Lund, 2015). The study reported that old technology fixed speed wind turbines deteriorated system stability due to under voltage protection during the LVRT period.

In addition to prominent and widely documented issues associated with wind integration, one particular limitation of wind turbine technology is their delayed active power recovery following significant voltage dips, unlike that seen for a conventional power plant where the active power recovery is relatively fast, in the order of milliseconds. The extent of the active power recovery delay from a wind turbine will depend on the severity and location of the fault (Tsili & Papathanassiou, 2009; Asmine et al., 2011; Bech, 2014), with the impact potentially critical for both frequency and dynamic voltage stability. A severe short circuit fault, resulting in a widespread voltage dip in a region hosting substantial wind capacity, may result in a temporary reduction in active power output, which in some cases may exceed the size of the largest infeed, and hence the allocated primary reserve (Rather & Flynn, 2015). Subsequently, the resulting frequency nadir (minimum frequency observed following a disturbance) may breach acceptable limits, leading to underfrequency load shedding, possible outage of wind generators (especially fixed speed wind turbines experiencing a delayed voltage recovery) and, in the worst case, may lead to cascading events resulting in system collapse.

In contrast to the above concerns, the LVRT capability of wind turbine technology has remained a major focus of grid code regulations, ensuring that wind generators not only successfully ride through a fault, but also support the grid during the course of the event (Mohseni & Islam, 2012). However, it is important to observe that due to technology limitations, LVRT capability, as required by grid code regulations, is not equivalent to conventional synchronous generators that can inject short circuit currents as high as 5–7 times rated values. Therefore, following a short circuit fault, and depending on the (local) voltage recovery profile while adhering to the grid code, the delayed active power recovery, due to physical limitations on the mechanical side of the turbine, may be exacerbated due to a delayed voltage recovery in the fault affected region.

Furthermore, wind turbines are susceptible to eigenswings, particularly due to torsional swings in the shaft (Akhmatov, Knudsen, & Nielsen, 2000), and these eigenswings are reflected in the terminal voltage and power output. Therefore, fault-induced torsional oscillations introduced in the electrical power output, with a frequency close to the power oscillations (≈1 Hz), may consequently impact system stability further. In such cases, especially at higher wind penetration levels, a short circuit fault, followed by a delayed active power recovery, could lead to severe power and voltage oscillations.

Due to the above limitation of a delayed active power recovery in wind turbines, wind integration potentially introduces a new complex coupling between voltage and frequency dynamics in wind integrated systems. A limited number of studies investigating such issues have been reported in the literature: EirGrid is planning to introduce a new ancillary service product ‘fast post-fault active power recovery service’ to mitigate the impact of such an issue, whereby participating units are rewarded for providing a fast responding service (EirGrid, 2014). Rather and Flynn (2015) examined the impact of a delayed voltage recovery from wind turbines, although, in this study, all the wind farms were based on type-3 wind turbines, while limiting wind penetration to 50%. The main contributions of this paper are i) a detailed study of the emerging challenge of ‘voltage dip induced delayed active power recovery’ and its impact on frequency stability in wind integrated systems, while considering both (type-3 and type-4) variable speed