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An Advanced Investigation on LVRT Requirement in Wind Integrated Power Systems

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***Abstract*— The increasing proportion of wind energy in the past decade has led to modifications in the grid code to account for, and mitigate the impacts it will have on power system stability. Low Voltage Ride Through (LVRT) is one of the critical requirement for grid connection of wind power plants (WPPs) required by grid code regulation. The paper identifies the factors affecting LVRT requirements across countries and traces the evolution of LVRT curves over time. It also investigates the conflicting LVRT schemes with regards to active and reactive power provision. Active power priority results in higher active current injection and is used for primary frequency support during low voltage event in islanded power systems while reactive power priority results in improved voltage recovery due to higher reactive current injection. Case studies have demonstrated that the popular perception of active power priority always resulting in higher active power injection and better frequency response during LVRT period, is not always true. In such cases, prioritizing reactive current during LVRT period resulted in higher active power injection, even at a lesser value of active current, as compared to active power priority LVRT case. It was found that reactive power priority can inject 15-25 % (of rated power of WPP) more active power during voltage recovery period compared to active power priority case, thus improving the frequency nadir by up to 100 mHz.**

Keywords- Wind; grid code; LVRT; DFIG; reactive power priority; active power priority; PowerFactory

I. INTRODUCTION

The looming threat of climate change, rapidly increasing energy requirements per capita and the need to ensure long-term energy security has led to a sustained push by the international community to incorporate more of renewable energy sources into the generation mix. As a result, renewable energy resources, particularly wind energy have seen significant technological break-throughs in past few decades which have made them economical and robust enough for use in large capacities. The massive deployment of such resources however introduces various technical challenges for secure and stable operation of power system, owing to their reduced inertia, intermittency and unpredictability [1]. To safeguard the system against these challenges, Transmission System Operators (TSOs) have over the years incorporated stringent regulations with regards to connection of Wind Turbine Generators (WTGs), particularly large WPPs in grid code regulations [2]. Such strict regulations for grid connection were not there earlier as most of these plants were present on distribution level and their penetration was very low in comparison to the conventional generation systems.

LVRT is one of the most crucial requirement mandated in the grid code regulation with regards to connection of WPPs. The requirement dictates that in the event of short-circuit fault, the WPP should not only remain connected to the grid for a pre-determined duration pertaining to the voltage dip, but also support voltage recovery during the low voltage event. Conforming to LVRT requirements is quite challenging, particularly in type III WTG as the stator of the generator is directly connected to the grid. Consequently, voltage disturbances in the grid are directly transferred to stator and hence to the rotor because of the magnetic coupling. High voltages on the rotor side can damage the power electronic converters and the dc-link. Significant number of studies are available in literature that address technologies to assist grid code compliance of WTGs with LVRT requirements [3]–[5]. While majority of the countries adopt reactive current injection priority from WTGs during LVRT period, some countries such as Ireland require active power injection in proportion to the retained voltage into the grid during LVRT period. The main purpose of active power priority is to minimise the impact on frequency stability, which is of more concern in such countries which include small islanded systems. Therefore, the main focus of this paper is to analyse the conflicting LVRT schemes i.e. active power and reactive power priority during LVRT period, and to demonstrate cases where rigid adherence to the former may not always result in the most optimal fault ride through behaviour in terms of frequency nadir and recovery. The paper also traces the evolution of LVRT curves, succinctly examines the factors leading to differing LVRT requirements across grid code regulations/countries.

The work presented in this paper centers around type III WTGs as currently such WTGs have maximum market penetration among all the WTG technologies available in the market. The main advantage of these WTGs compared to type IV WTGs (full-scale converter) is that they allow for decoupled control of active and reactive power with the power electronic converters handling just 20 to 30 percent of the total power of system [6], thus leading to lower costs and higher efficiency(due to reduced power losses). The study presented in this paper was performed in DigSilent PowerFactory platform with type III WT model based on IEC 61400-27-1 standards.

The rest of this paper is organized as follows. Section-II describes the factors affecting LVRT requirements as well as the varied LVRT requirements in countries over time. It also delves in detail about LVRT active and reactive power priority schemes. Section III first showcases the conventional scenario wherein active power priority injects more active power than reactive power priority and then provides counter-examples where the said phenomenon was found to be invalid. Finally, conclusion is presented, which analyzes scenarios in which such cases may occur.

II. LOW VOLTAGE RIDE THROUGH

A. Evolution of LVRT

In the past, where wind penetration level was of low level, the grid code regulation for WTGs permitted the wind turbines (mainly old technology wind turbines) to disconnect from the grid during voltage dips as the main emphasis was on WTG safety, and not on the impact the WTGs disconnection will have on power system stability. The increased penetration of WTGs in power systems, however, led to disconnection of a significant proportion of wind generation following a fault, thus resulting in shortfall of generation as has been experienced in a few countries and more recently in China [7]. Denmark and Germany were amongst the first countries to have defined LVRT requirements for interconnection of WTGs to the high voltage network. To a large extent, these countries have influenced LVRT requirements in grid code regulations across the world.

The shape of the LVRT curve is representative of worst-case realistic voltage recovery profile that may occur in the power system, once it recovers from the lowest voltage point [8]. These regulations have evolved with time across TSOs owing to factors such as:

- Current and anticipated wind penetration levels
- Strength of grid
- Type of load in the system (predominance of induction motor load leads to poor voltage recovery)
- Islanding of system
- Dynamic voltage support devices in the system and plant reactive power headroom

B. LVRT active and reactive power provision schemes

The WTG may prioritize either active current or reactive current during fault, thus limiting the other within the remaining margin of the capability limit. While majority of the countries follow reactive current priority based LVRT requirement, some countries require active current priority during an LVRT event.

1) Reactive Power Priority: Reactive current (i_q) proportional to the magnitude of dip is injected into the grid till a threshold beyond which it is set at 1 p.u. The remaining margin i.e. $\sqrt{(i^2_{max,dip} - i^2_q)}$ (where $i_{max,dip}$ represents WTG current overload limit and is typically set at 1.2 p.u.) is set as the upper limit for active current (i_d) injection. It results in improved voltage recovery due to higher reactive current injection. The inadequate active power during this period due to delayed active current recovery however may result in frequency excursion, which may get further aggravated in systems with delayed voltage recovery. Countries such as Denmark, Germany, Australia and Spain [9] follow this priority. The reactive current provision curve of Denmark [10] can be seen in Fig. 1(a).

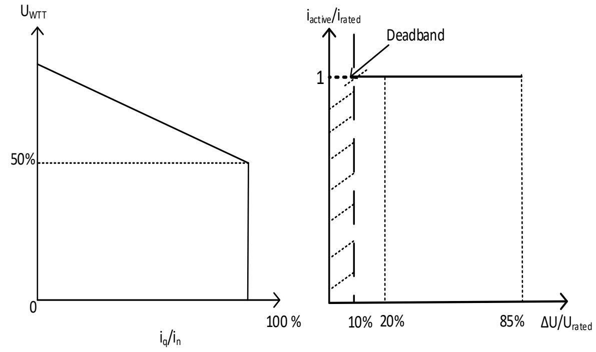


Figure 1. LVRT ride through schemes (a) Reactive power priority (Energinet.dk, Denmark) (b) Active power priority (EirGrid, Ireland)

2) Active Power Priority: Active power provided by the wind power plant is supplied in proportion to the retained voltage i.e. active current (i_d) is maintained at its pre-fault value (typically 1 p.u.), restricting reactive current to a maximum value of $\sqrt{(i^2_{max,dip} - 1^2)}$ as seen in Fig. 1(b). It is used to minimize the impact of generation shortfall during LVRT period and is preferred in weakly interconnected and islanded systems. For a given fault impedance, the voltage recovery is adversely affected, however the frequency response is improved significantly. Ireland [11] and Alberta [9] are amongst the few regions which follow this priority.

C. LVRT requirements

1) Germany: The grid code for WTGs in Germany came into effect in 2003. As can be seen in Fig. 2 ,the LVRT curve was modified as per a DENA study (2005) to also account for zero-voltage ride through (ZVRT) [12], [13]. The reason for this may be attributed to the anticipated higher penetration of WTGs and the resultant poor transient stability of system in case of deep voltage dips if ZVRT was not included. The total installed capacity of wind has increased from 16.63 GW in 2004 to 44.94 GW in 2015[14], [15]. Germany met 14.7% of its annual electricity demand by wind energy in 2015 [15]. The total time duration of low voltage period has also been reduced to 1.5s. The poor voltage recovery scenario earlier can be attributed to the presence of large number of old WTGs (type I and type II) which became extremely inductive at lower voltage, thus hindering the voltage recovery [16].

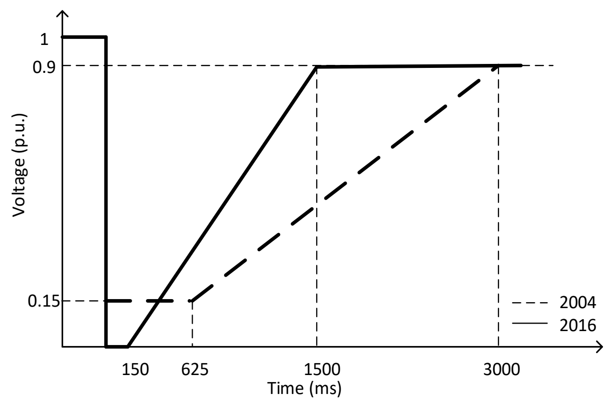


Figure 2. LVRT curve followed in Germany

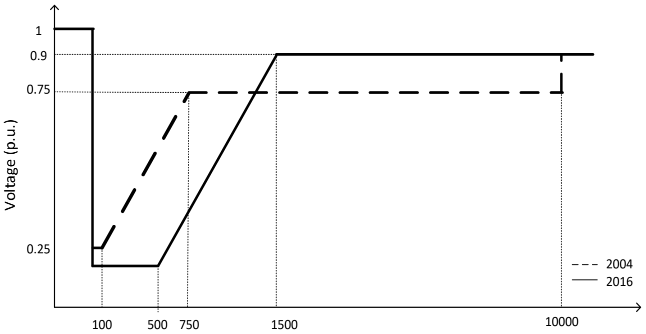


Figure 3. LVRT curve in Denmark

2) Denmark: Over the years, the Danish grid code has become more stringent in terms of lowest voltage to withstand, as well as the time duration of low voltage as can be seen in Fig. 3 [10], [17], [18]. A reason for this may be the extremely high levels of wind penetration which in 2015 stood at 42% compared to 18% in 2005 [14], [15]. The maximum instantaneous penetration of wind power even stood well above 100%. Despite higher levels of penetration in Denmark, the requirements for deep sags are much less onerous than German grid code. This can be explained by the fact the Danish power system (≈ 14 GW) is much smaller than the latter's power system (≈ 200 GW) [19], and its electricity interconnection level (defined as transmission capacity by production capacity) with its neighbours Norway, Sweden and Germany stands at 44% as compared to Germany which is 10% [20].

3) Ireland and India: Ireland follows the same LVRT curve as was followed in Germany in 2004 as shown in Fig. 4 [11]. The stringent voltage recovery profile can be linked to the fact that Ireland, being a synchronously isolated system with limited HVDC interconnections [21] with Great Britain, follows active power priority which results in poor voltage recovery. The poor voltage recovery is also aggravated by the large penetration which can be gauged by the fact that in 2015 WTGs contributed to 24% of Ireland's annual electricity usage [15]. Lack of ZVRT may be attributed to the fact that Ireland has a reserve margin of about 53% which may be enough to supply dynamic reactive power during deep voltage dips [22]. India follows the same LVRT regulations as that of Ireland, the only difference lies in the varying fault clearing times which are dependent on the nominal system voltage as seen in Table I [23] and Fig. 4.

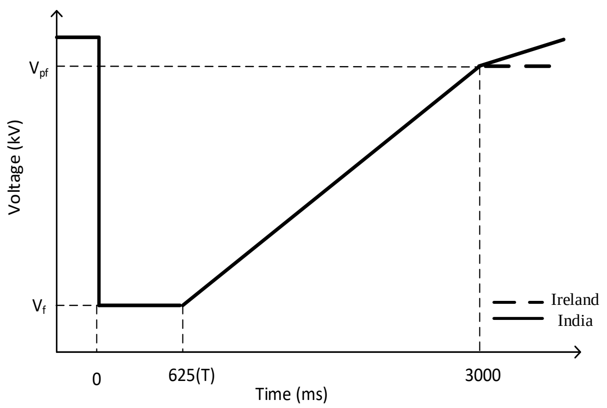


Figure 4. LVRT curve in Ireland and India

TABLE I: VOLTAGE LIMITS AND CLEARING TIME (IWGC)

Nominal Voltage(kV)	Clearing Time (T)	V_{pf} (kV)	V_f (kV)
400	100	360	60
220	160	200	33
132	160	120	19.8
110	160	96.25	16.5
66	300	60	9.9

III. CASE STUDIES

Different test case systems were considered to examine if voltage improvement under reactive power priority during the low voltage event may be adequate enough to overcome the higher active current in active power priority, consequently leading to higher active power injection for reactive current priority based LVRT, compared to that in active power priority. The two test cases demonstrated here, under certain conditions validated the above stated claim. The Test system I consists of WPP connected with synchronous generator through a long transmission line while the Test system II is a modified New England 39 bus system. The WTG is operated under voltage control mode and the current overload limit in both these test systems is taken as 1.2 p.u. ($i_{max,\,f}$). The limits on active (i_d) and reactive current(i_q) during fault are decided based on the ride through scheme being followed. In reactive current priority, reactive current is supplied as per Fig. 1(a) and remaining margin is utilized for active current injection. In active power priority, active current is injected as per Fig. 1(b) and the remaining margin serves as an upper limit for injection as per Fig. 1(a).

A. Test System I

The test system is shown in Fig. 5 and consists of two synchronous machines of 300 MVA rating each, connected to a WPP through a long transmission line. The WPP has been represented as an aggregate model i.e. as a single machine. The load connected to Bus 1, which is near to the WPP, is composed of induction motor(IM) load and constant power load (250 MW, 50 Mvar). Capacitor bank C1 is also connected at bus 1. Load 'L6' is also a constant power load with power consumption of 250 MW and 50 Mvar. The loads operate in constant power mode under the voltage limits 0.8 p.u. to 1.2 p.u. and shift to constant impedance mode outside these limits. A three phase short-circuit fault is introduced at Bus 2 at 0.7s for a duration of 150 milliseconds.

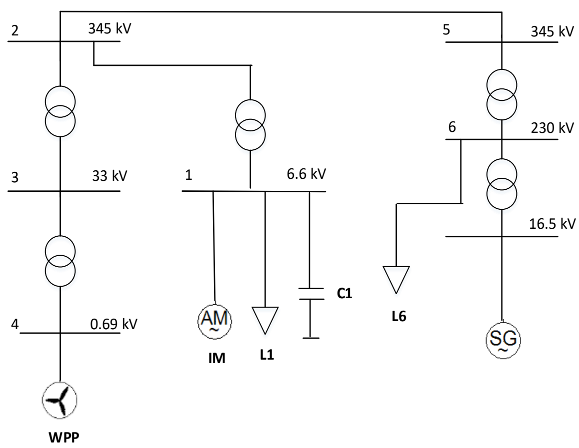
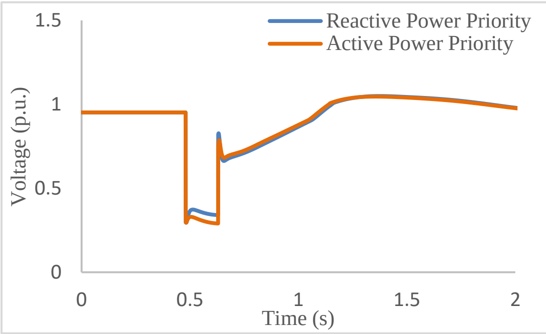
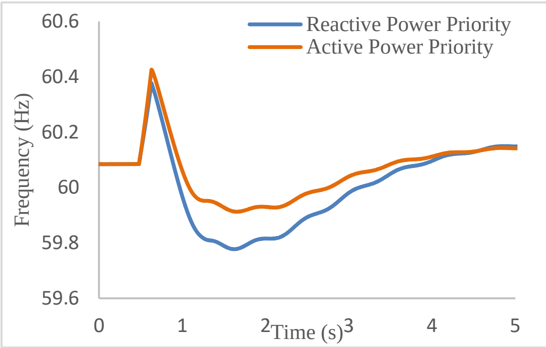


Figure 5. Test system I

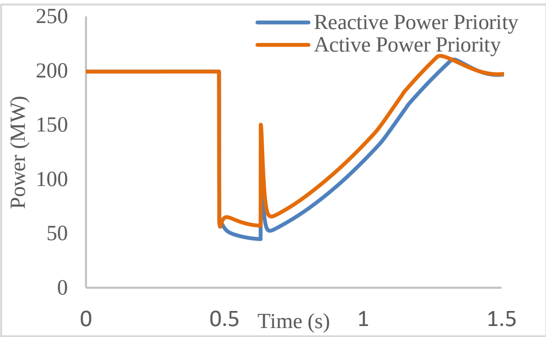
Fig. 6 shows the dynamic characteristics (terminal voltage, grid frequency, active power, active current and reactive current) for the WTG in a conventional scenario in Test System I albeit with a smaller WPP (200 MVA) and lower IM load (20 MW, 8 Mvar). The voltage profile during fault duration is shown in Fig. 6(a). The higher active current injection in active power priority, leads to higher active power injection as compared to reactive power priority as shown in Fig. 6(c) and Fig. 6(d) leading to an improved frequency response as shown in Fig. 6(b).



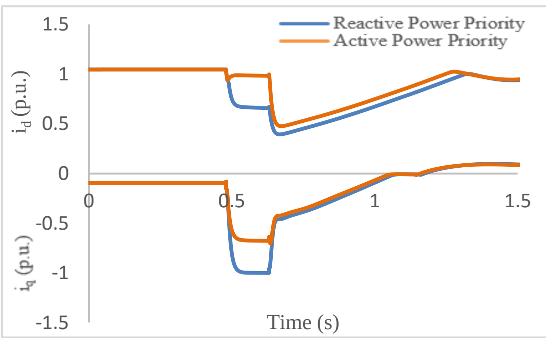
(a) Voltage at bus 4 (WPP terminal)



(b) Grid frequency



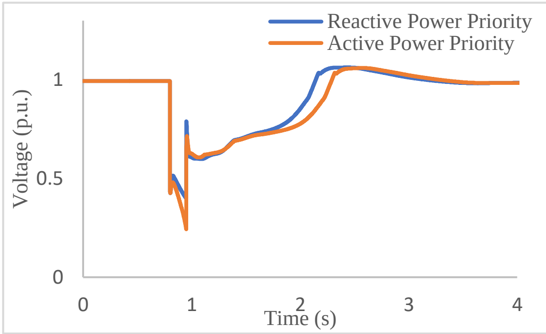
(c) Active power injection



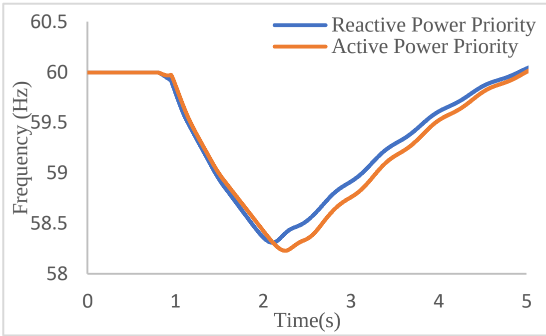
(d) Active (i_d) and reactive(i_q) current injection

Figure 6. Dynamic profiles for test system I under shunt fault at bus 2 (in conventional scenario)

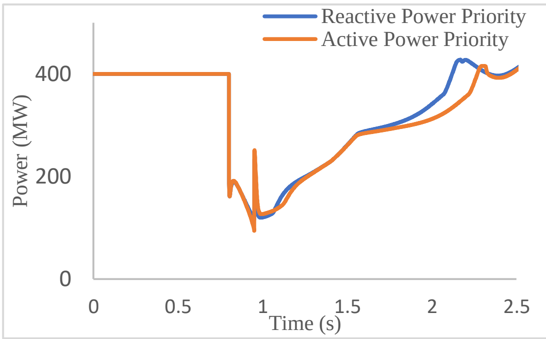
However, with a larger WPP (400 MVA) and higher IM load (110 MW, 50 Mvar), the results provide interesting insights as is seen in the dynamic characteristics in Fig. 7. It can be observed from Fig. 7 (d), that in active power priority, reactive current gets curbed at value of 0.66 p.u. while in reactive power priority, it keeps increasing till it reaches the upper limit of 1 p.u. In the latter case, this extended margin for reactive current helps in curtailing voltage drop during fault period as observed in Fig. 7(a). The better voltage ride through thus leads to higher active power injection in reactive power



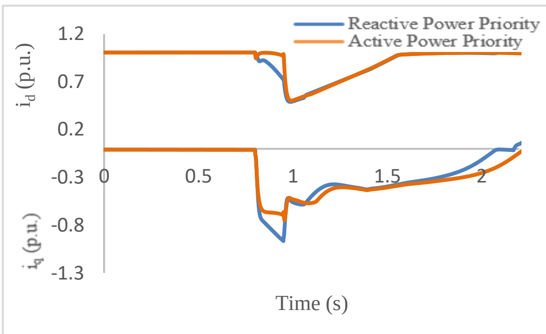
(a) Voltage at bus 4 (WPP terminal)



(b) Grid frequency



(c) Active power injection



(d) Active (i_d) and reactive (i_q) current injection

Figure 7. Dynamic profiles for test system I under shunt fault at bus 2

priority during the voltage recovery period. Maximum difference in active power injection among the two LVRT strategies occur during the recovery period with reactive power priority supplying around 80 MWs (20% of the rated capacity of WPP) more active power than active power priority, as shown in Fig. 7 (c). Consequently, frequency nadir is improved relatively in reactive power priority case by about 100 mHz as shown in Fig. 7 (b).

B. *Test System II*

Test system II is taken as modified New England 39 bus system as shown in Fig. 8. Three wind power plants WPP1, WPP2 and WPP3 (represented as aggregate models) of ratings 500 MVA each respectively are added in lieu of generators G3, G6 and G7. Generators G1 and G4 are shut down along with an equivalent amount of load at bus 39 and bus 20. The total wind penetration in system stands at 36%. Induction motors IM1, IM2 and IM3 are used to replace the load at bus 23, 21 and 27. The consumption of load at bus 15 is reduced (from 320 MW and 173 Mvar to 160 MW and 70 Mvars) to accommodate IM4. Each induction motor in steady state operation consumes 158 MW and 68 Mvar and the motor load is 15% of the total load of the system. The nature of loads at bus 15, 16 and 24 is changed to constant power between the voltage limits 0.7 p.u. to 1.2 p.u., outside of which they behave as constant impedance.

1) Fault at bus 36: Three phase shunt fault of duration 160 ms is simulated at Bus 36 (near WPP1) at 0.5s. Fig. 9 compares the dynamic behavior of the power system at terminal of WPP1 for the two fault ride-through schemes. As voltage retained at WPP1 terminal is lower than 0.5 p.u., the reactive current shoots to 1 p.u. in reactive power priority and is curbed at 0.66 p.u. in active power priority as shown in Fig. 9 (d). Consequently, higher reactive power is injected in the former case throughout the voltage recovery period, leading to improved voltage response and hence higher active power injection as is observed in Fig. 9 (a). The maximum difference in active power injection between reactive and active power priority cases is seen to be 80 MWs more in the former case, which is 15% of rated capacity of WPP1, as shown in Fig 9 (c). Consequently, the grid frequency nadir is improved by 50 mHz, Fig. 9 (b).

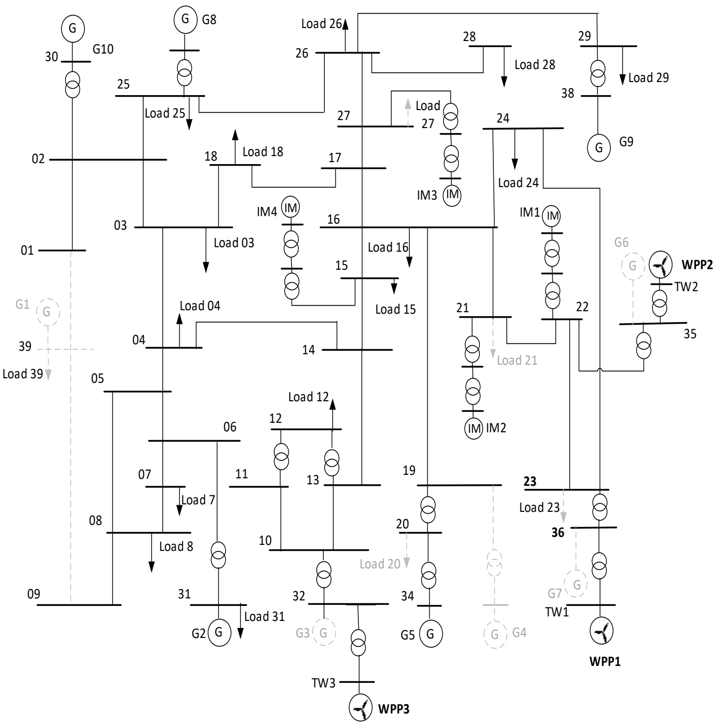
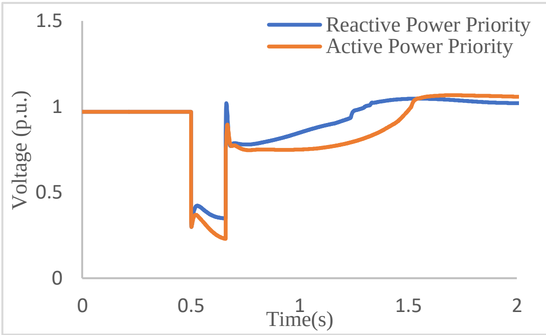
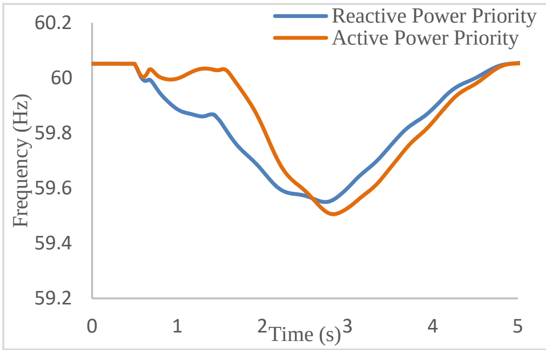


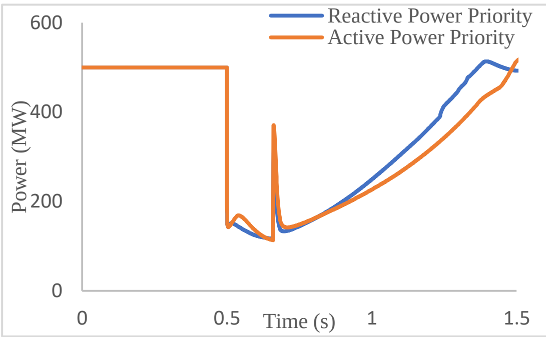
Figure 8. Test System II



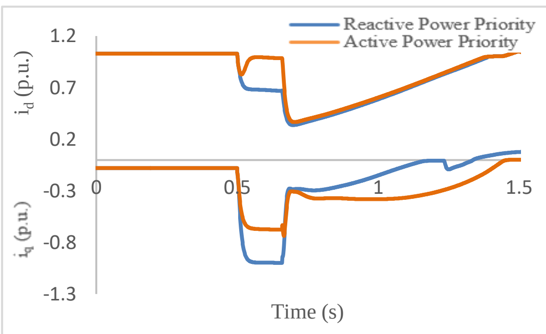
(a) Voltage at TW1 (near WPP1)



(b) Grid frequency



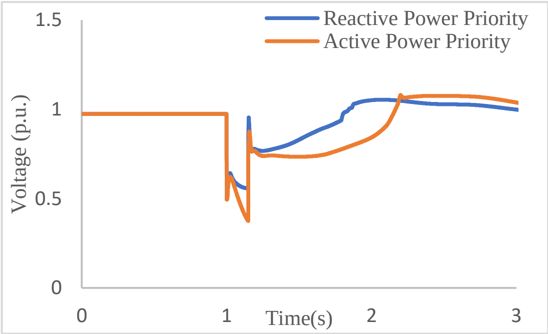
(c) Active power injection



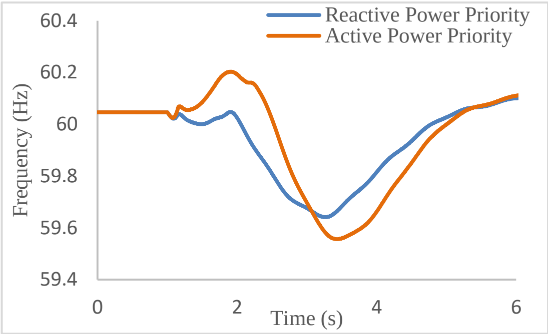
(d) Active (i_d) and reactive (i_q) current injection

Figure 9. Dynamic profiles for test system II under shunt fault at bus 36

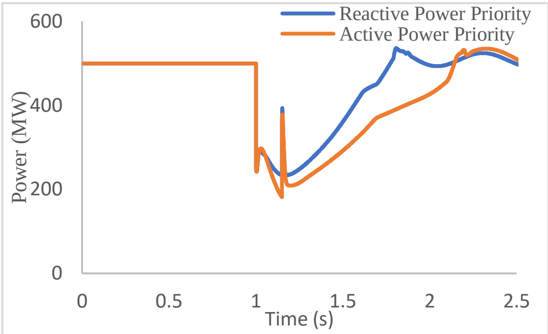
2) Fault at bus 23: Three phase shunt fault of 150 ms duration starting at t=1s is simulated at Bus 23. Fig. 10 compares the dynamic behavior of the power system at terminal of WPP1. In this case, active power injection is higher both during and post-fault in reactive power priority with maximum difference being observed at 140 MW (28 % of rated capacity of WPP1) leading to an improvement of 100 mHz in grid frequency over active power priority as shown in Fig. 10 (b) and Fig. 10(c). The improved voltage response, as shown in Fig. 10(a) in this case is aided by the higher active



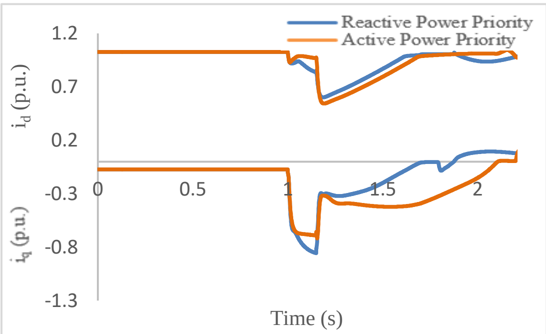
(a) Voltage at TW1(near WPP1)



(b) Grid Frequency



(c) Active power injection



(d) Active (i_d) and reactive (i_q) current injection

Figure 10. Dynamic profiles for test system II under shunt fault at bus 23

current post fault clearance in reactive power priority as seen in Fig. 10(d). This can be attributed to the active power ramp that is expected in WTGs due to technical constraints. The abrupt jump in voltage results in drop in active current to avert sudden change in active power. In this case, the jump in voltage after fault clearance in active power priority exceeds that in reactive power priority, and thus the corresponding drop in active current is higher in active power priority post-fault clearance. As the voltage seen by WPP terminal at the initiation of fault is 0.63 p.u., the reactive current in reactive power priority starts from 0.67 p.u. (instead of 1 p.u.) and increases till 0.85 p.u. to limit the voltage drop. Reactive current in active power priority however gets curbed at 0.66 p.u. Consequently, the voltage ride through and hence active power injection is higher in the former case.

IV. Conclusion

The paper traced the evolution of LVRT regulations and examined factors for differing LVRT regulations across grid codes. The dynamic behavior of WTGs for two fault-ride through schemes was compared. It is easy to surmise that for certain generator current over-load limit, the behavior of active and reactive power priorities is same for voltage dips lesser than a threshold value, beyond which active power priority is expected to inject more active power. However, as demonstrated, active power priority based LVRT requirement may in some cases deteriorate frequency stability instead of improving it during voltage dip. This reverse impact of LVRT has not been reported anywhere so far. It is observed that this phenomenon is more dominant in systems delayed voltage recovery post fault-clearance.

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