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Improved LVRT Grid Code under Islanding Condition

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***Abstract*—The grid code Low Voltage Ride Through (LVRT) requires Renewable Energy Sources (RESs) to remain connected to the grid following the voltage sags resulting from disturbances. The LVRT pattern is based on voltage sag magnitude and its duration at Point of Common Coupling (PCC) and only voltage reflects the internal dynamics of RES. Therefore, making decision on RES connectivity to the grid just relying on one variable, i.e. voltage, may not be the best decision for wide range of possible combinational and cascading events leading to islanding. This paper proposes a novel LVRT characteristic in which all of applicable and determinant variables of RES are considered. If the RES safely and securely operates inside continuous operating range of rotor speed and current, the grid voltage and current, the RES interruption is diffidently avoided to keep supporting of power system.**

***Index Terms*—Wind turbine, low voltage ride through, grid code, voltage sag, reactive power support, permanent magnet synchronous machine (PMSG).**

I. Introduction

Rapid development of energy demand and abundant public concerns regarding global warming phenomena steers the energy production toward RESs, particularly the wind power, which is recently in the center of attention in terms of growth [1–3]. The wind energy is the most popular and affordable source of energy comparing to the other sources. As the share of RESs in the grid is increased, its consequences, i.e. the impacts on operation and control of power system may not be neglected anymore. The stochastic behavior and intermittent nature of RESs applies the uncertainty to the availability of sources, which diminishes the reliability of power system [4], [5].

Widespread development of RESs enforces the utility operators to codify a set of regulations and technical standards called *grid codes*, which should be respected by RESs during their connection status to the grid. The grid codes include of a full range of ancillary services similar to conventional synchronous machines to support the network during the disturbance/s [6], [7]. The grid code requirements for new generation of RESs are strictly legislated or revised to achieve an efficient and comprehensive grid code for different operating states of RESs and power system [8], [9].

Both static and dynamic requirements are encompassed by technical description of grid code. The static requirement dealing with the operation of RES in its steady state e.g. power flow at PCC, while the dynamic requirement i.e. the most important part, addresses the performance of RES during the transient state resulting from disturbance and/or fault conditions. The dynamic requirements basically covers many features and ancillary services such as voltage, frequency and power factor regulation and/or Fault Ride Through (FRT) capability.

The FRT feature is a widespread and general capability, which also covers LVRT and over speed ride through in RESs. The LVRT constitutes the principal requirement of FRT grid code and determines the connectivity of RES to the grid during short-term and transient voltage dips at its PCC, which may happen due to temporary decline of wind speed. In fact, the LVRT is dealing with how the RES can handle a significant reduction in the input energy, e.g. wind and solar plants. The LVRT grid code compels the RESs to stay connected to the grid for a specified time period, although the PCC voltage becomes zero or close to it due to the voltage sag/plunges.

The Permanent Magnet Synchronous Generator (PMSG) type of Wind Turbine (WT) is gradually going to be dominant comparing to the other WT types particularly in the offshore applications due to the underneath advantages:

- Full range of wind speed
- Self excitation (No power converter for field)
- Independent control of reactive and active power
- Gearboxless
- Low noise
- Brushless (low maintenance)

The PMSG type of WT is indirectly connected to the grid via power electronic converters, as indicated in Fig. 2. The LVRT behavior of PMSG during event/s is mainly determined by grid side converter, as electrical and mechanical dynamics of generator are fully decoupled from the grid by employed converters [10], [11].

The majority of converter control loops are executed using conventional PI controllers, which are basically adjusted for steady state operation rather than transient state. Generally, the PI controllers may not be efficient at all operation conditions, i.e. severe transient dynamics of voltage sags resulting from short circuits. The inrush current of grid side converter may not be properly limited even with the controlled DC link voltage inside the permissible boundary, which may harm the grid side converter of PMSG and rotor side converter of Doubly Fed Induction Generator (DFIG) [10], [12].

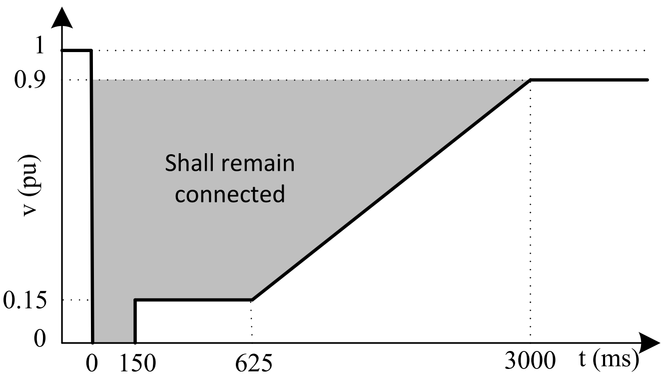

Fig. 1: Typical LVRT requirement [10]

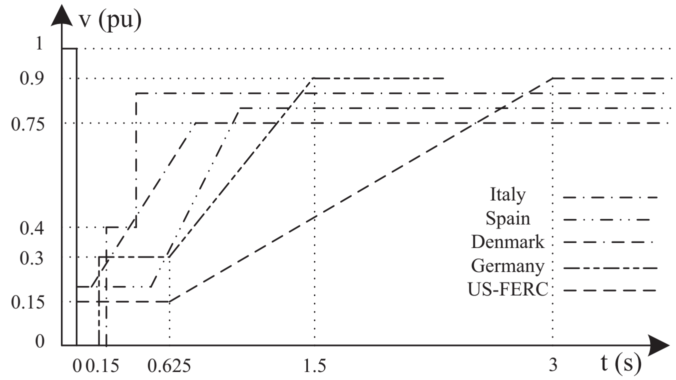

Fig. 2: The LVRT of different countries [13]

II. LVRT Grid Code Requirements

A more reliable interconnection of high share of wind power with power system may be achieved if the WTs are equipped with LVRT capability. The LVRT compels the WTs to stay connected to the grid and support the network stability, similar to conventional synchronous machines during the voltage dip/sags resulting from various faults [6], [8]. The WTs should continuously contribute in active and/or reactive power support of the network following the grid faults in order to able to participate in load-frequency control and/or voltage regulation. The connectivity of WT to the grid is determined based on a specific voltage-time characteristic pattern, which depends on both voltage sag magnitude and its time duration measured at PCC. As can be seen from Fig. 1, the LVRT grid code is basically specified by a voltage versus time characteristic, stating the minimum required safety of WT regarding the grid voltage sags. The WT can be decoupled from the grid in case of any of following conditions [10], [12]. The PCC voltage is:

- equal to zero and is lasting for more than 150 ms
- less than 0.15 pu for more than 475 ms
- crossing the ramp line at any time between 625 ms and 3000 ms
- less than 0.9 pu for more than 3000 ms

As the WTs normally operate at Maximum Power Point Tracking (MPPT) condition with maximum efficiency or a nearby point to procure some spinning reserve, they are adjusted on a point close to their full capacity and therefore sufficient spinning reserve is not available to be used in case of more demand of active/reactive power [5], [9]. According to LVRT grid code, under the fault conditions, the active power set point of WT is intentionally declined to a lower value to provide some capacity for reactive power support and hence voltage regulation. The priority of grid support is assigned to the voltage regulation instead of load-frequency control and/or MPPT operation point in case of voltage magnitude less than 0.9 pu [6], [12].

III. Control Strategy of Inverter

The control strategy of inverters typically consists of two cascaded loops [13]. The first loop is the inner current control loop, responsible power quality issues and current protection of the inverter, which is out of scope of current paper. The second loop, which is not as fast as the inner loop and is addressed in this paper, is an outer loop established to prepare desired voltage or power reference signals for the inner control loop. The new proposed method is implemented in the outer control loop to shape both transient and steady state operation condition of inverter, especially in the LVRT operation mode, which active and reactive power support of grid is determinant and essential.

A. Voltage Regulation by Reactive Power Support

The grid code Low Voltage Ride Through (LVRT) requires that optimal performance of renewable energy sources, i.e. Maximum Power Point Tracking (MPPT) or Load-Frequency Control (LFC), should be temporarily disabled during the disturbances leading to voltage sags by reducing the active power set point and assigning the released capacity to reactive power compensation/voltage regulation [10]. The required active power can be provided globally, whereas the reactive power has to be procured locally, since the reactive power cannot be transmitted to the long distances [5].

Under the normal operation condition, in order to achieve maximum possible efficiency and desired operation of generation unit, the active power reference is typically adjusted on MPPT with zero reactive power injection to the grid (i.e. unity power factor):

$$P_{ref} = P_{MPPT} \tag{1}$$

$$Q_{ref} = 0 \tag{2}$$

When a voltage sag is recognized at Point of Common Coupling (PCC), the operating status is transited from steady state condition to the LVRT mode, in which not only withstanding the voltage sags are required by grid codes according to the LVRT characteristic, voltage regulation by injection of reactive power to the grid is mandatory. According to the LVRT grid code requirements depicted in Fig. 3, the reactive power deviation of outer control loop (ΔQ) following the voltage sag can be defined as below:

$$\Delta Q = \begin{cases} 1 & 0 \leq v \leq 0.5 \\ k \cdot (v_n - v) & 0.5 \leq v \end{cases} \tag{3}$$

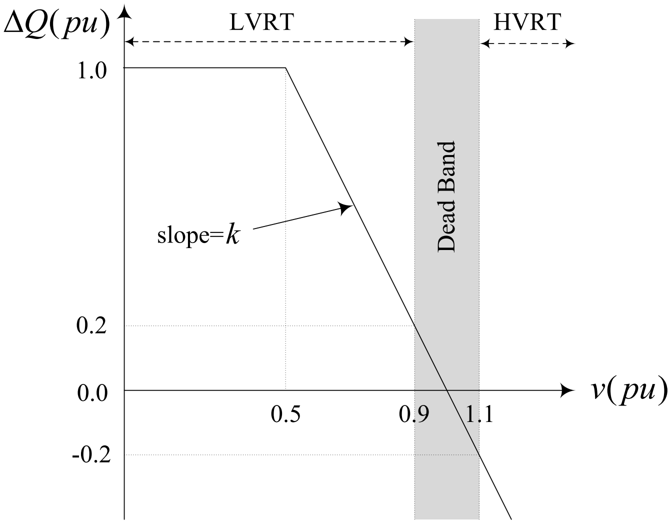

Fig. 3: Grid code reactive power support requirement [14], [15]

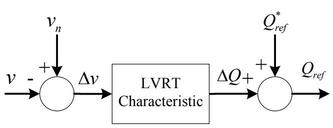

Fig. 4: Reactive power support

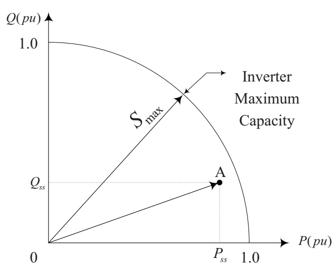

Fig. 5: Inverter thermal limit

The injected reactive power is proportional to the voltage sag magnitude in the range of 0.5 to 0.9 pu, as it can be seen in (3) and Fig. 3. k stands for the slope of line in the aforementioned range and is typically chosen at least equal to 2 pu, which means that more than 2 percent of full scale reactive power capacity is injected to the grid per each percent of voltage drop. Therefore, according to the (3), the maximum possible reactive power is achieved at half of nominal voltage [6], [13]. The voltage drop (Δv) as the voltage deviation from its nominal value (v_n=1) can be determined as below:

$$\Delta v = v_n - v \tag{4}$$

The reactive power reference can be calculated using summation of desired set point of reactive power at steady state mode (Q^*_{ref}) and the reactive power deviation of outer control loop (ΔQ) following the voltage sag as follow:

$$Q_{ref} = Q^*_{ref} + \Delta Q \tag{5}$$

IV. Malfunction Operation of LVRT in Case of Islanding

A rigid and non flexible LVRT pattern, in which disconnection of RES from the grid is determined independent of availability of standby spinning reserve inside the RES, may not be an efficient grid code to deal with widespread range of combinational and cascading contingencies. Early and undesired trip of RES, which is rejection of an advantageous grid support provided, not only may not improve the stability, but also may deteriorate the situation by increasing the existing active and/or reactive power imbalance between load and generation, triggering more initiating events, which may lead to blackout.

Relatively low voltage drop resulting from islanding situation typically requires less reactive power support comparing to the short circuit fault, which cause large voltage sags with a magnitude close to 1 pu. Hence, voltage drop resulting from islanding is essentially different from the voltage decay of short circuit fault regarding reactive power deficit. The conventional LVRT grid code cannot differentiate between islanding and short circuit situations.

As dispersed generation especially renewable energy sources are gradually going to become dominant in the power system, in order to achieve more flexible and efficient LVRT grid code in the presence of high penetration of dispersed generation, the existing grid codes need to be revised under all possible contingencies and not just short circuit faults. Malfunction operation of LVRT in case of events with low voltage drop, e.g. islanding situations should be precisely investigated, which causes early and improper interrupt of generation units despite of their ability to safely support the grid following disturbances.

V. The proposed LVRT Grid Code

All of key and determinant variables available inside the dispersed generation unit are involved in the suggested algorithm, to achieve a comprehensive, versatile and practical scheme. The current of grid and rotor side converter, grid voltage, rotor current and speed, DC link voltage, etc. are among significant variables, which may applicable to all or some of dispersed generation units. Violation from their normal and/or permissible range are considered as a trigger criterion of new LVRT grid code. The flowchart of proposed general LVRT grid code is depicted in Fig. 6, in which the applicable variables to the PMSG wind turbine are grid voltage and current and rotor speed. Instead of decision making for disconnection of RES only based on voltage sag at PCC and its duration, more variables are involved in the proposed LVRT and as long as the RES operates at a safe region of all aforementioned variables, its interruption is definitely avoided.

In the first checkpoint of flowchart, exceeding the rotor and grid side converter current from their maximum value is examined, which may cause immediately trip of RES without any delay. In the second checkpoint, two different level of rotor speed with distinct time delays are considered. It means that higher speeds of rotor behind its normal range causes sooner disconnection of RES.

Although, the reactive power support to regulate the PCC voltage is one of mandatory tasks to be done by RES during abnormal conditions, two level of grid voltage above nominal

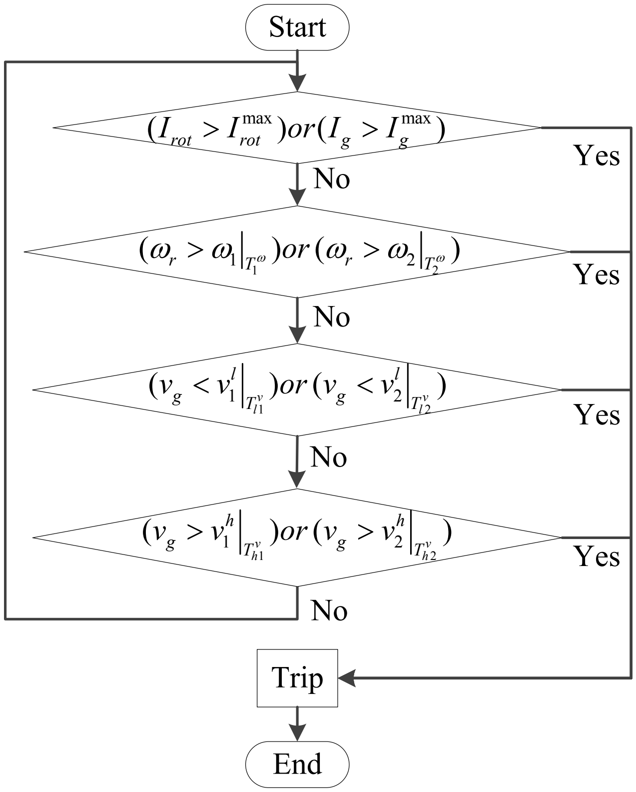

Fig. 6: Flowchart of proposed LVRT grid code

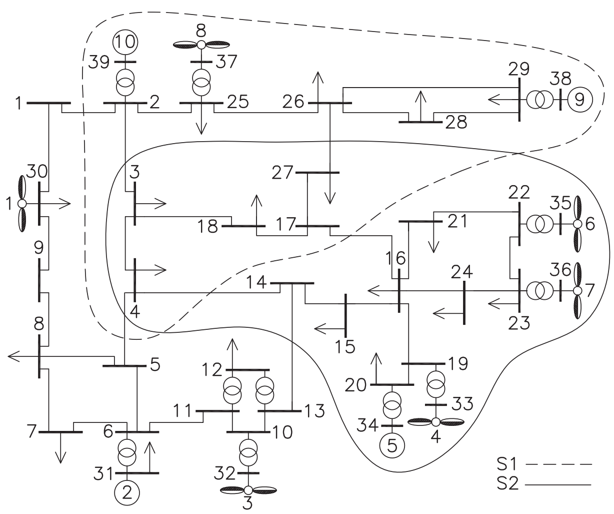

Fig. 7: Islands defined in 39 bus IEEE standard test system

range with different time delays are defined to protect the equipments of RES against over voltage in the checkpoint three. Similarly, same number of voltage thresholds are foreseen for the case of very low voltage conditions at PCC, i.e. short circuit faults. The low voltage levels and their time delay is same as the conventional LVRT grid code, in which the grid code of different countries are agreed on.

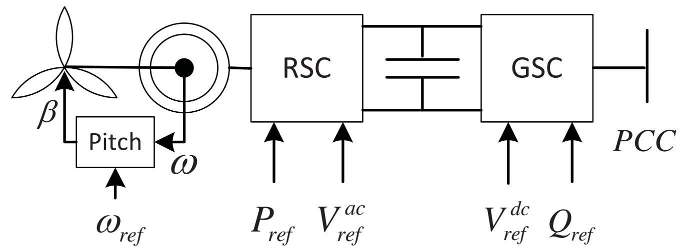

Fig. 8: Control structure of PMSG

VI. Simulation Setup

The 39 bus IEEE standard test system depicted in Fig. 7 is selected to study the behavior of LVRT in islanding condition [16], [17]. The 4th order mathematical model of synchronous machine, the IEEE standard governor IEESGO and Automatic Voltage Regulator (AVR) IEEEX1 are considered for all synchronous machines. The details of the system data can be accessed in [18]. The dependency of load's active and reactive power to the voltage and frequency in term of different type of loads are defined according to [19], [20]. Moreover, the relevant parameters and the Share (s) of different types of loads such as types i, c and p in the composite model of loads is given in Table. II of Appendix [21]. Some of existing synchronous machines are replaced with Permanent Magnet Synchronous Generator (PMSG) type of WT to achieve integration of wind power into the power system. Different scenarios indicated in Fig. 7 with various wind power penetration levels are defined to assess malfunction operation of LVRT grid code. The Federal Energy Regulatory Commission (FERC) LVRT pattern from Fig. 2 is employed in simulations.

VII. Simulation Results

Numerical simulations are conducted in DIgSILENT PowerFactory 15.1 software. Distinct scenarios consisting of islanding and/or cascading events are defined in different areas of power system (Fig. 7) to demonstrate the malfunction operation of WT LVRT in case of islanding.

A. Scenario 1:

In the scenario 1, outage of G10 at 2 s triggers some cascading events including loss of transmission lines 1-2 at 3 s, 4-5 at 4 s and both 16-17 & 4-14 at 5 s, which separates an island from the power system indicated in Fig. 7. By replacing G8 with a PMSG wind farm, 39% wind power penetration is achieved.

Figs. 9-10 show the PCC voltage and current of WT8 throughout 15 seconds of time simulation using proposed and conventional LVRT, respectively. The cascading events are started at 2 s and the islanding happens at 5 s. The grid voltage and current are suddenly decreased at 5 s. The WT inverter limitations are not exceeded at all and therefore its connection should not be interrupted. Fig. 10 demonstrates that the WT8 is disconnected by conventional LVRT at 8.5 s, while the proposed LVRT indicated in Fig. 9 keeps the

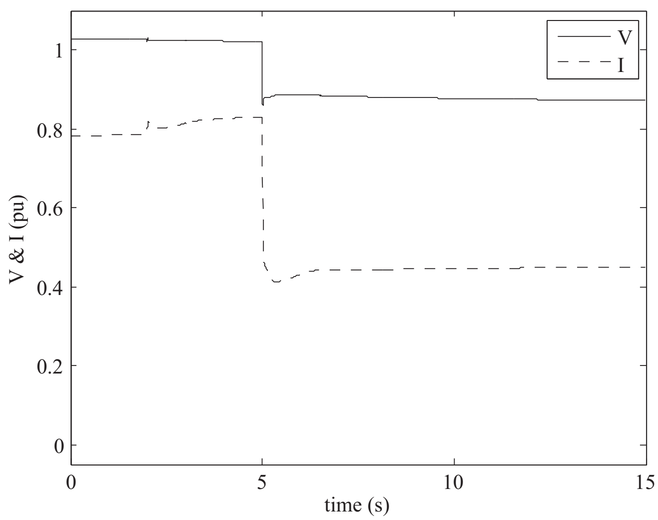

Fig. 9: S1: Voltage and current of WT8 (proposed LVRT)

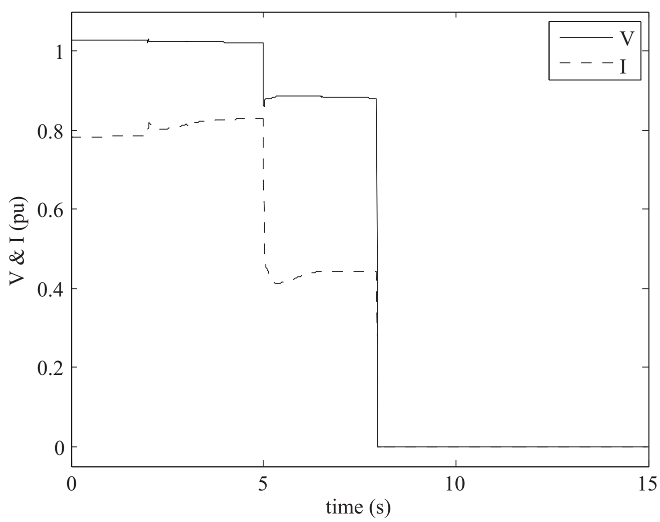

Fig. 10: S1: Voltage and current of WT8 (conventional LVRT)

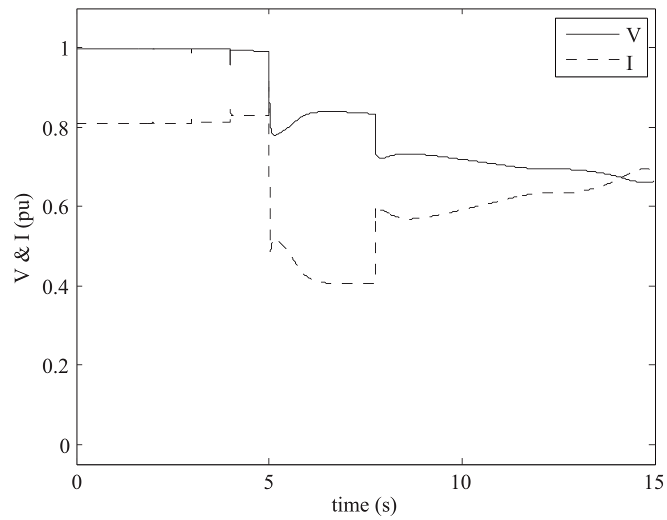

Fig. 11: S2: Voltage and current of WT4 (proposed LVRT)

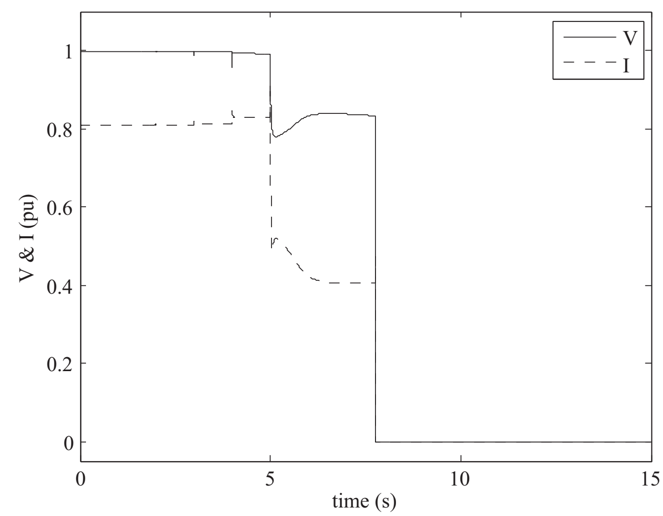

Fig. 12: S2: Voltage and current of WT4 (conventional LVRT)

WT8 connected to the grid to serve and support the system stability. This case scenario shows that conventional LVRT, which acts based on voltage sag magnitude and its duration, is unable to differentiate between severe short circuit faults and the disturbances with a PCC voltage close to the normal range. Under such a circumstances, although there is plenty of standby capacity in the WT8 to support the grid without any difficulty, the WT8 is improperly disconnected by conventional LVRT at 8.5 s.

B. Scenario 2:

The performance of proposed LVRT is compared to the conventional one under a different scenario of combinational and cascading events, which covers a distinct part of power system. Fig. 7 shows the islanding scenario 2, which corresponds to an outage of tie-line 13-14 at 2 s, lines 4-5, 2-3 and 26-27 at 3 s, 4 s and 5 s, respectively. After islanding, the wind power share in the network reaches 78%, which is a relatively high level of wind power penetration.

Figs. 11-12 present the grid voltage and current of WT4. In this scenario, WT4, WT6 and WT7 are suddenly disconnected around 8 s following the islanding condition at 5 s, which causes a voltage drop slightly below the normal range at 5 s. Although, all WTs are undesirably disconnected despite of their ability to contribute in voltage and frequency regulation, the lost WTs in this scenario constitute the major part of total existing generation, which may lead the island to a much worse case or even blackout. Regardless of available spinning reserve in the WTs following the disturbance/s (observable in the current curve of WT4 in Fig. 12), the WTs are improperly disconnected from the island by the conventional LVRT without any stress on their converters, mechanical and/or electrical parts, which may not only be logic and affordable, but also may deteriorate the situation further. Contrary, the WTs are remained connected to the grid due to the appropriate decision made by the proposed LVRT in Fig. 11 using grid current of inverter, which is detected in range.

VIII. Conclusion

Although the LVRT pattern i.e. a voltage versus time characteristic curve is efficient for short circuit faults, which generally cause a deep voltage drop close to zero and therefore, are accompanied by a huge reactive power deficit, it may not operate properly in case of cascading events and islanding, in which the post-disturbance voltage is not faraway form the normal range and hence less reactive power support is expected from RESs. LVRT merely considers the voltage drop magnitude and its duration regardless of standby capacity available in the WT to support the grid for a longer time. This paper proposes a new LVRT grid code, in which the connectivity of RES is decided based on rotor speed and current, grid voltage and current, DC link voltage and thermal limit of inverter. Therefore, early interrupt of RESs despite of their available and standby spinning reserve to support the grid is avoided. As future works, the simulation results of remaining variables, i.e. DC link voltage, pitch angle and rotor speed are included in the paper.

Appendix A

TABLE I: Parameters of Proposed LVRT Grid Code

Protection	Parameters				
Current	Rotor	I_{rot} (pu)	I_{rot}^{max}		
			2.5		
	Grid	I_g (pu)	I_g^{max}		
			1		
Rotor Speed	ω_r (pu)	ω_2	ω_1		
		1.26	1.53		
	Time (s)	T_2^{ω}	T_1^{ω}		
		60	0		
Grid Voltage	V_g (pu)	v_1^l	v_2^l	v_2^h	v_1^h
		0	0.15	1.2	1.5
	Time (s)	T_{l1}^v	T_{l2}^v	T_{h2}^v	T_{h1}^v
		0.15	0.625	1	0.1

TABLE II: The Voltage & Frequency Dependency of Loads

Load type	Share (s)(%)	pv	pf	qv	qf
Light bulb (i)	10	1.6	0.0	0.0	0.1
Fluorescent bulb (c)	20	1.2	-1.0	3.0	-2.8
Asynchronous motor (p)	70	0.1	2.8	0.6	1.8

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