

Fault Ride Through for Solar Photovoltaic and Wind-Turbine Integrated Distribution Network: A Systematic Review

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Abstract— The purpose of this paper is to provide a systemic review on fault ride through (FRT) capabilities. As there are multiple types of power system faults, where each type has different effect on the power quality, faults types along with their effects on the power quality are firstly highlighted for better understanding of the FRT capabilities. The FRT techniques along with its types are then introduced. Furthermore, the most common renewable energy sources where FRT techniques are implemented are discussed. Recent Improvement methods for FRT are highlighted and summarized. The protection devices used to detect and isolate faults are lastly introduced, where the paper is then concluded.

Keywords—Power System Faults, fault ride through, fault detection, solar photovoltaic systems, wind turbines

I. INTRODUCTION

An electric power system is a multifaceted power network referred to as a grid and consists of generation plants, transmission lines, and distribution networks that are spread over a large geographical area. The design configuration and the operation characteristics of an electric power system is what determine the complexity of the system. A fault in such a complex power system is a disturbance of the normal power flow from the source to the load. Faults mostly occur within the transmission lines causing an insulation failure of the electrical components due to the damage caused by mechanical issues or environmental reasons such as lightning or a fall of a tree on the transmission line [1], [2]. The insulation damage exposes generators, transformers, transmission lines, cables, etc. to extreme heating, which can eventually lead to fire or explosion. The power system; as a result, can completely shut down due to the disruptive effect of power system stability.

The increasing demand for energy in the modern-day world, in presence of restricted use of conventional energy, shifted us towards renewable energy (REN). As a result, the integration of REN sources has significantly grown which led to the facilitation of different operational aspects such as protection, stability, reliability and power quality [3]. The 2030 REN target for the selected countries is given in Table I.

Based on the connection complexity of power generating units (such as solar photovoltaic (PV) systems, wind turbines (WTs), diesel generators, etc.), the transmission system operators (TSOs) establish a set of operative regulations called the grid code in order to coordinate the integration of these generation units to the grid. Grid codes are developed based on

international standards such as the American National Standards Institute (ANSI) and the International Electrotechnical Commission (IEC). However, grid codes may be modified by TSOs based on the local network requirements. The aim of the grid code is to maintain the stability of the grid by regulating the voltage and frequency. As a result, the grid model during design stage may be subject to changes due to grid codes requirements [4].

TABLE I. Renewable energy target for selected countries

Country	Target Percentage of REN Generation	Target year
New Zealand	90% of energy production is from REN	2025
Saudi Arabia	80% of energy production is from REN	2030
France	32% of energy production is from REN	2030
Turkey	30% of energy production is from REN	2030
Japan	22-24% of energy production is from REN	2030
South Korea	11% of energy production is from REN	2030
South Africa	10% of energy production is from REN	2030

Fault ride through (FRT) is a key component of the grid code, and its properties have an impact on the performance and rating of power system equipment. FRT specifies the capabilities required for a generation unit to ride through a voltage or frequency disturbance in order to prevent the loss of that generation unit during and in post-fault conditions. In order to set the FRT's requirements, the fault type shall be determined as each type of fault has a different effect on the voltage and frequency of the system [5].

In [6], faults in a three-phase system are introduced where a unified fault matrix method is used for calculating open and short circuit faults which shows a complete duality between open and short circuit faults. [7]–[9] give a comprehensive analysis about the FRT techniques, including LVRT, ZVRT and HVRT, and controllers which already have been implemented in the grid code of 38 countries for renewable energy sources. [10] discusses current injection methods related to FRT techniques for GCPV systems, while [11] reviewed the state-of-the-art FRT enhancement methods for GCPV systems.

Hitherto, many methods are invented to detect faults within different parts of the power system. In [12], [13] a survey on various practices for fault classification in transmission lines is

provided. The survey introduces old as well as newly developed approaches in fault classification. In [14] proposes another technique to detect faults during power swing. However, it comprises the signals of both voltages and currents as one quantity. Since the proposed fault detector works with fixed thresholds, it is claimed to be setting-free, meaning revising from one system to another system is not needed. The study in [15] proposes an intelligent protection scheme, which eliminates the need to install costly limiters of current fault. This protection scheme utilizes communication capabilities specified in IEC 61850 to design intelligent cascading switching actions to isolate the defective part of the system. The research in [16], [17] proposes intelligent artificial methods (include fuzzy logic, artificial neural network (ANN), genetic algorithm (GA), support vector machine (SVM) and matching approach) that are based on wavelet theory to detect faults within a distribution network. This method is intended to provide a mean of islanding detection, which refers to the situation in which a main power source forms microgrids if it is disconnected without stopping the distributed renewable sources.

The structure of this paper is as follows. In section II, types of power system faults and their effects on power quality are discussed. In section III, FRT capabilities along with their types are introduced. Section IV represents the most common REN systems that FRT techniques are used with while section V highlights improvement approaches for FRT. Section VI represents the protection devices used to detect and isolate faults. Section VII concludes this paper.

II. TYPE OF FAULTS

Faults in power systems are divided into open circuit (also called series) faults and short circuit (also called shunt) faults. Faults shall stimulate the switching of the protection devices. Therefore, faults occur at the terminals of either active or passive electrical equipment. Active electrical equipments include synchronous and asynchronous machines or grid equivalents. Passive electrical equipment include transformers, transmission lines, or loads

A. Open Circuit Faults

Open circuit faults are characterized by an increase in voltage and frequency and a decrease in current in the faulted phase. Therefore, they can be detected by monitoring the voltage of each phase. If the voltage value rises, it means that an open-circuit fault happened. Open circuit faults cause cessation of current flow and they rarely occurs.

B. Short Circuit Faults

Whenever there is a short circuit fault, the voltage and frequency will decrease while the current will increase in the faulted phase. Accordingly, they can be detected by the observation of the current of each phase. If there is an increase in the current value, it highlights the initialization of a short circuit fault.

Short circuit faults are the most hazardous as the current is increased to a lot more (e.g. 10 times more) than the nominal current of the instrumentation. Short circuit fault may take an

arc form on overhead transmission lines causing the conductor to burn and break if not timely cleared. Short circuit faults may also turn the faulted phase into loads in interconnected systems and that is because of the large decrease in voltage and frequency in those faulted phases. Accordingly, induction and synchronous motors may feed the fault during a short circuit fault which worsens the situation even more. Shorts are commonly occurring and there are two main types of short circuit faults, namely: symmetrical faults and unsymmetrical faults.

1) *Symmetrical Faults*: A symmetrical fault is balanced and it affects all phases equally as shown in Fig. 1, meaning the voltage drops of all the three-phase is equal and has the same magnitude, which is proportional to the severity of the faults. A symmetrical fault is the most severe because it involves all three phases and roughly 5 % of faults involved in a three-phase system are symmetrical.

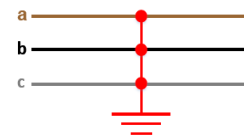


Fig. 1: Scheme of symmetrical fault

2) *Asymmetrical Faults*: An asymmetrical fault is unbalanced and it affects each phase separately, meaning the voltage drop of each phase is uneven and has different magnitude depending on the nature of the fault. An asymmetrical fault can occur as a line-to-ground (L-G) fault, line-to-line (L-L) fault, or double-line-to-ground (L-L-G) fault. Asymmetrical faults are difficult to analyze and almost 95% of faults involved in a three-phase system are asymmetrical. The subsections below will provide additional details about the types of asymmetrical faults:

a) *Line-to-ground Fault*: A line-to-ground (L-G) fault is caused by a conductor making contact with a grounded structure and it is the most common. 70% of the entire faults are found to be L-G faults. The L-G faults depicted in Fig. 2 causes $I_b = 0$, $I_c = 0$ and $V_a = 0$

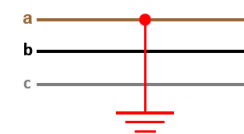


Fig. 2: Scheme of L-G fault

b) *Line-to-line fault*: If one phase touches another phase, it causes a line-to-line (L-L) fault. About 15% of all faults are found in L-L faults. The L-L fault depicted in Fig. 3 causes $I_b = 0$, $I_c = 0$, $V_b = 0$ and $V_c = 0$.

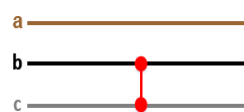


Fig. 3: Scheme of L-L fault

c) *Double-Line-to-Ground Fault*: When two phases come in contact with a ground, it leads to a double-line-to-ground (L-L-G) fault. 10% of all faults fall under this type. The L-L-G fault that is depicted in Fig. 4 causes $I_a = 0$, $V_b = 0$ and $V_c = 0$.

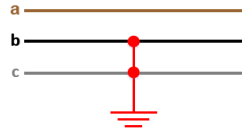


Fig. 4: Scheme of L-L-G fault

III. FAULT RIDE THROUGH

Continuity of electric power supply is essential; therefore, issues that might cause a loss of a generation unit are unsolicited. The purpose of preventing a generation unit loss using FRT techniques is as much as economically important as it is technically. A voltage-time or frequency-time diagram called the FRT diagram is used to demonstrate the essential requirements a generation unit shall meet to ride through a voltage or frequency disturbance. The FRT diagram may be different among countries as the grid codes differ.

During a fault, the grid code require the generation unit to stay connected to the grid within a certain range of voltage and frequency. Accordingly, the setting of the protection devices strongly relies on FRT requirements, which may require the generation units to generate maximum reactive power without violating the transient rating limits. The parameters involved in defining the FRT requirements include the follow:

- Network design
- Generator type
- Fault type and amplitude (commonly short circuit faults)
- Fault occurrence impedance
- Fault clearance period
- Power control procedure

The effects of the symmetrical and asymmetrical short circuit faults on the three-phase voltage magnitudes vary. Consequently, they affect requirement of the FRT differently. Furthermore, the location of the generation units and other components is crucial in the application of the FRT.

A. Voltage Ride Through

During a fault, changes will occur to the system's voltage, current, and frequency which can lead to the disconnection of some generation units from the grid. This reduces the reliability of the power system. Therefore, TSOs, in presence of high integration of REN sources, require generation units to have LVRT capabilities or even ZVRT capabilities. In some cases, TSOs will require HVRT capability as well.

A LVRT capability curve is displayed in Fig. 5. The voltage of a generation unit operating in normal condition (V_n) is as demonstrated in area A. During a symmetrical fault or an asymmetrical L-L or L-L-G fault, which occurs at the time interval (t_0), the generating unit experiences a voltage sag (V_l). The LVRT allows the generating unit to remain connected to

the grid by withstanding the voltage drop for a certain time (represented in area B). When the voltage level reaches at area C, the generating unit should disconnect from the power system. The voltage is regulated back to (V_r) when the fault is cleared after (t_2). This LVRT capability ensures fast post-fault recovery and stability for the system.

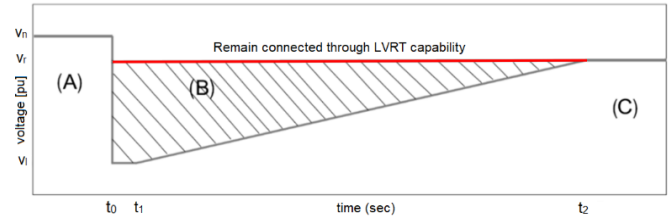


Fig. 5: Low-voltage ride through (LVRT) curve

Furthermore, the occurrence of asymmetrical L-G fault causes a voltage swell. When a voltage swell occurs, the generating withstands this condition through a HVRT capability. A HVRT capability curve is displayed in Fig. 6.

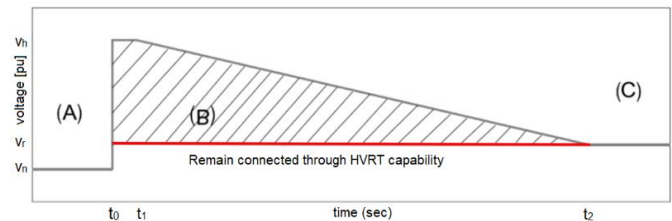


Fig. 6: High-voltage ride through (HVRT) curve

B. Frequency Ride Through

Frequency ride through (FrRT) capability is another type of FRT. This type ensures that the operation of generation plants are governed by strict guidelines. Hence, the generation operations are not disturbed by sudden frequency-changing conditions.

The instantaneous balance of load and generation determines the grid interconnection frequency. Therefore, a loss of a transmission line, or a generation unit or load disturbs the frequency. Such a loss can unbalance between the load and generation causing under-frequency or over-frequency conditions.

A loss of generation causes an under-frequency condition while a loss of load cases a high-frequency condition. TSOs; therefore, require utilities to apply load-shedding policies that automatically respond to under-frequency events. On the other hand, TSOs also require that bulk generators to have under-frequency ride-through (UFRt) capabilities that extends beyond the lowest frequency of these load-shedding policies as well as high-frequency ride-through (HFRt) capabilities that extends beyond the highest frequency of these load-shedding policies.

IV. FRT FOR RENEWABLE INTEGRATION

Increased integration of REN sources makes TSOs more conscious towards them during faults as they have significant effects on the stability of the power system [18]–[20]. Because

of the large integration of REN sources; for example, FRT-related grid codes in the United Kingdom, Japan, Germany, and most recently in the unified European Network of Transmission System Operators for Electricity (ENTSOE) network contain multistage and complex rules with many specifications. Consequently, the FRT technical requirements in the grid codes should consider the integration percentage of REN sources.

Solar PV systems and WTs are the most REN sources exposed to grid faults as they are the most common integrated into a conventional grid; hence, they play a big role in developing the grid codes. One of the major challenges in maintaining solar PVs and WTs connected to the grid during faults is the lack of necessary requirements such as the automated voltage regulator (AVR).

A. FRT for Solar Photovoltaic Systems

GCPV systems typically operate in balanced conditions, with ideal load voltages and currents that are within the inverter's operational limits. The occurrence of a grid fault interrupts the current flow of the inverter for a few milliseconds, resulting in low impedance and short circuit faults (categorized by current increase, and voltage and frequency decrease in the faulted phases). This makes the GCPV systems in an unbalanced condition. The FRT enables the PV system to remain connected to the grid when the voltage reduces through LVRT capabilities. Even if the voltage is reduced to zero, the PV system should remain connected to the grid through ZVRT capabilities. During a fault condition, the PV system generates reactive power (analogous to the excitation increase in conventional generators) in order to increase the grid's voltage. When a disturbance is cleared, PV systems must promptly generate pre-fault active power. A common configuration of a GCPV system that has a FRT capability is shown in Fig. 7.

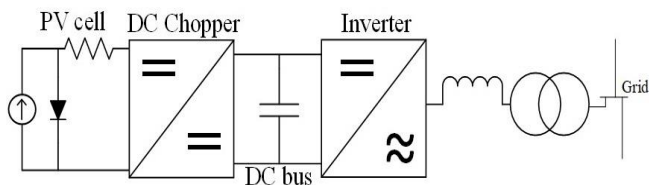


Fig. 7: Configuration of grid-connected photovoltaic system

Every GCPV system is composed of three primary components that are: PV array, DC-to-DC converter, and DC-to-AC inverter. The inverter is critical to GCPVs since it controls the voltage as well as the active and reactive powers in accordance with grid requirements. The proposed control scheme forces the inverter to remain connected to the grid during 50% and 100% voltage sag by separating the grid voltage's sequences. The positive sequence is fed to a phase-locked loop (PLL) where a feed-forward loop (FFL) and current limiters are augmented in order to maintain stability [21]. The control scheme accordingly supports the inverter to ride through the fault; however, the swinging of the reactive

and reactive powers is increased as they are dependent on the direct-axis (d-axis) and quadrature-axis (q-axis) algorithm. Therefore, the current and voltage are initially measured and used to calculate the d-axis and q-axis voltages (V_d and V_q) and currents (I_d and I_q) from which the reference d-axis and q-axis currents (I_d^* and I_q^*) voltages (V_d^* and V_q^*) are determined in order to satisfy the LVRT requirements as shown in Equation 1 and 2.

$$V_d^*(t) = \left(\frac{K_p + K_i}{S} \right) [I_d(t) - I_d^*(t)] \quad (1)$$

$$V_q^*(t) = \left(\frac{K_p + K_i}{S} \right) [I_q^*(t) - I_q(t)] \quad (2)$$

Where $\left(\frac{K_p + K_i}{S} \right)$ is the application of a PI transfer function on the error signal e and K_p and K_i are PI controller parameters. The reference voltages in Equation 1 and 2 then fed to the inverter's control gate circuit to operate the LVFRT or ZVRT capabilities. Similar approach is followed for the negative, positive and the zero sequence.

B. FRT for Wind Turbines

WTs operate in balanced conditions, similar to PV systems, with ideal load voltages and currents that are within the inverter's operational limits. When a fault occurs, the WTs are required to remain connected to the grid through LVTR capabilities. The LVRT capabilities for WTs are established based on the topology and control strategy of the WT's circuit. The LVRT capabilities for WTs normally reduce reactive drawl and even generate reactive power during a faulty condition. When the fault is cleared, the WTs promptly produce active power when possible. A common configuration of a WT that has a FRT capability is shown in Figure 4.2.

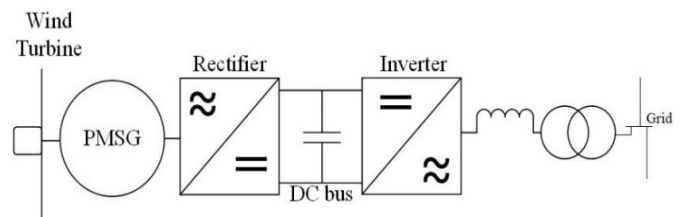


Figure IV.1 – Configuration of wind turbine (WT)

The objective of the inverter is to balance the 3-phase power that is provided by the machine-side rectifier by shaping the output current. Failing to achieve this objective will cause the power to be unbalanced; thus, resulting in variation of the DC-link voltage. The current and voltage are then used to calculate the d-axis and q-axis voltages (V_d and V_q) and currents (I_d and I_q) from which the reference d-axis and q-axis currents (I_d^* and I_q^*) and voltages (V_d^* and V_q^*) are determined in order to satisfy the LVRT requirements as shown in Equation 3 and 4.

$$V_d^*(t) = V_d(t) + \left(\frac{K_p + K_i}{S}\right)[I_d^*(t) - I_d(t)] + \omega L_c \left(\frac{K_p + K_i}{S}\right)[I_d^*(t) - I_d(t)] \quad (3)$$

$$V_q^*(t) = V_q(t) + \left(\frac{K_p + K_i}{S}\right)[I_q^*(t) - I_q(t)] + \omega L_c \left(\frac{K_p + K_i}{S}\right)[I_q^*(t) - I_q(t)] \quad (4)$$

Where $(K_p + \frac{K_i}{S})$ is the application of a PI transfer function on the error signal e and K_p and K_i are PI controller parameters. The reference voltages in Equation 1 and 2 then fed to the inverter's control gate circuit to operate the LVFRT or ZVRT capabilities. Similar approach is followed for the negative, positive and the zero sequence.

V. FRT IMPROVEMENT METHODS

Many methods have been proposed to improve the FRT. These methods can be classified as passive or active methods as highlighted Table II. The implementation of passive methods depends on using auxiliary devices while active methods do not. All of these methods have been theoretically validated, and experimental findings show that they perform well.

TABLE II. Fault ride through improvement approaches

Approach	Advantages
Passive Methods	
Blade Pitch Angle Control	<ul style="list-style-type: none"> Allow power reduction Increases energy capture
Crowbar Method	<ul style="list-style-type: none"> Generator and converter fault protection Active-reactive power regulation Allows grid voltage regulation Cost-effective
Energy Capacitor System	<ul style="list-style-type: none"> Over-voltage protection Minimum impact on rotor current Improves energy saving
Energy Storage System	<ul style="list-style-type: none"> Generator and converter fault protection Energy market regulation
Active Methods	
Generator Side Converter Control	<ul style="list-style-type: none"> Generator and converter fault protection
AC Grid Side Converter Control	<ul style="list-style-type: none"> Allows grid voltage regulation

VI. FAULT DETECTION

The complexity in the configuration of an electric grid and the urgency of power supply make a fault unwanted even if there are FRT capabilities within the grid. Faults are expected in power systems; however, they have to be timely detected and clear. Transmission lines are the first line to ensure the integrity of the grid; thus, TSOs must always ensure the network's reliability and stability. When a fault occurs, the affected branch of the power network should be automatically isolated. For this purpose, many protection devices are used such as fuses, circuit breakers, relays, and instrument transformers to isolate faults. The function of these protection devices is as follows:

- **Fuse:** it is an electrical safety device that provides

overcurrent protection. It is essentially composed of a metal wire or strip that melts as excessive current flows through it; thereby it interrupts the current flow

- **Circuit breaker:** it is an electrical safety switch that is automatically operated to protect against overload or short circuit damage. It detects a faulty condition and interrupts the current flow by isolating the faulted branch in an electrical circuit
- **Relay:** it is an electrical safety switch that commands a circuit breaker to trip when it senses a fault, in order to isolate faulted branches of the electrical circuit
- **Instrument transformer:** it is an electrical measuring device (mainly coupled with a relay) that protects a power network substation against faults at high-level applications (e.g. high voltage or high current application). If a fault occurs, it transforms the voltage or current level down and isolates it

If protection devices timely and reliably operate, the detection of any deterioration in the system status will be easily identified. It will; accordingly, play a conclusive role to protect the operation of the grid. Otherwise, system crashes will be accelerated, hence, large-scale and long-time power blackout will occur. One of many serious events triggered by a grid fault is the large-scale blackout of the America-Canada power network that occurred on August 14, 2003. It was a result of an overload fault, which caused the removal of four connection lines between the cities of Cleveland and Akron in Ohio.

VII. CONCLUSION

A fault is a disturbance that affects the normal flow of current to the load. In this paper a systematic review of FRT capabilities is provided discussing FTR types and the most common REN system that FRT techniques are used with. For a better understanding of the FRT capabilities, types of power system faults along with their effects on power quality are introduced and discussed. The paper is finally concluded by introducing the protection devices used to detect faults.

Integration of REN sources into the grid to replace conventional generators has dramatically increased; as a result, the total inertia of the power system is reduced. This integration of REN sources makes the stability of the power system during faults a critical concern. In this regard, the FRT technical requirements will gain more attention among researchers in universities and industries

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