



A REVIEW OF THE FAULT RIDE THROUGH REQUIREMENTS IN DIFFERENT GRID CODES CONCERNING PENETRATION OF PV SYSTEM TO THE ELECTRIC POWER NETWORK

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ABSTRACT

The growing of Photovoltaic (PV) power generation and integration into the electric power has started to touch on the stability and reliability of the network. As a result, standards have to be defined in guaranteeing a secure and reliable operation of the power system and one of the important topics is the capability of the PV system to ride through fault during the disturbance. This paper provides an overview and comparison study about Fault Ride-Through (FRT) capability requirements in the recent grid codes, which are enforced by transmission and distribution system operators in different Grid Codes (GCs) regarding the penetration of Photovoltaic Power Plant (PVPP) to medium and low voltage level of the network. This study compared the following common requirements such as FRT either Low Voltage Ride-Through (LVRT) or High Voltage Ride Through (HVRT), reactive current injection during and after the fault, restoring active power and frequency variations. In addition, by depending on this comparison and through studying the Malaysian grid standards, there is a similarity to USA standard thus this paper presents a proposal of FRT capability and frequency deviation for the Malaysian electric grid.

Keywords: fault ride-through, grid code, photovoltaic system penetration.

INTRODUCTION

In the years before, the photovoltaic generation of electrical energy has become a reality. Consequently, there are thousands of PVPP integrated with power system in many regions and countries. In the past, the penetration of solar energy was very small compared to the conventional generation system but in recent period, the grid connected to PV system increased dramatically [1].

Figure-1 shows that more and more PV power all over the world is reaching 40 GW in 2010 of installed PV capacity with a remarkable increase of 94% over 2009 [2, 3]. Also, there is a gradual increase in the last four years by about 30 GW or more per year. In 2014, the installation of PV plant around the world reached 177 GW higher than 2013 by around 40 GW [3].

Grid codes are not new topics in the power system utilities. It began to appear 18 years ago. The grid codes differ from country to another according to the characteristics and regulation of the national power system. Firstly, the grid codes were applied to the transmission system as a set of operation specifications and technical guidelines for traditional power plant that is integrated with power system [4]. Next, grid code has been amended and improved in subject to the continuous changes and new technical requirements such as FRT, reactive current injection and restoring active power, which has been newly absorbed to the GCs for large wind power plants (WPP) integration in some countries such as Denmark, Germany, UK, Canada, Ireland and Spain. Nowadays, these requirements are being adapted for PV plants. The issue of grid code requirements for WPP has already been studied in the literature. The most recent comparison of the international regulation of latest

national GCs concerned with penetration of wind farm to the grid that were done in [5] and can be used as reference for photovoltaic energy. Finally, from the previous information above, there is a massive growing in PV energy so the disconnections from the grid during disturbances are no longer possible. This led to the elaboration of the same requirements as WPP for the connection of PVPP to the Medium Voltage (MV) and Low Voltage (LV) level networks when more and more PV plants are installed.

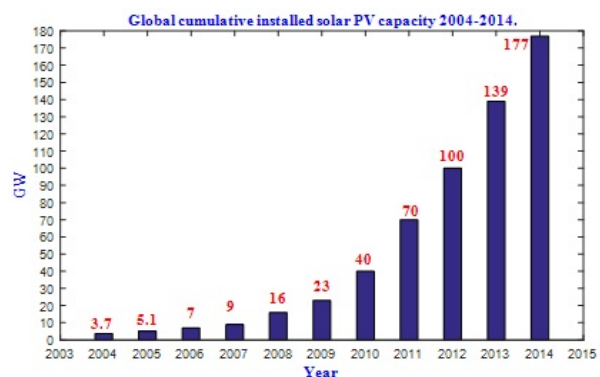


Figure-1. Global cumulative installed solar PV capacity 2004-2014.

Annexation FRT and other requirements to GCs concerning penetration of the PV system to the electric power network is a new topic. Previously, the PV plants connected with the distribution network were not permitted to take any action during the disturbances and had to disconnect directly in case of grid fault. Recently,



with the significant rise of the PV farm size, it is required to keep PV units working under either normal or abnormal conditions. Germany and Spain as a leader in the production and installation of PV technology are adopting these new requirements in their GCs [6-8]. On July 2010, German grid code stipulated that PV plant had to be capable to make a limited contribution for the dynamic network support while from January 2011, it was recommended that the PVPP should provide full dynamic network support [2, 6, 9]. Italy has recently adopted a new version of the grid code for distributed generation systems, explicitly including PV, CEI 0-16, 2012 and CEI 0-21, 2014 [10]. Japan had released FRT requirement and measures of PV distributed system in 2011 by the Energy and Industrial Development Organization (NEDO) [11]. The USA applied the requirement for PV integration according to IEEE 1547 standard [12] while Puerto Rico Electric Power Authority (PREPA), which is one of the main public electric power corporations in the United States had released technical requirements for interconnecting wind and solar generation [13]. Australia imposes the requirement in AS4777 standard, where the last update was in 2013 [14] and it follows National Electricity Rules, version 63, which was published by (AEMC) in 2014 [15]. Finally in Malaysia on 21 December 2010, the Grid Code and Distribution Code has been issued by the Energy Commission Malaysia (ECM) but these two codes did not address the FRT capability either for wind or PV integration [16].

This paper introduces comparative study for different national grid codes especially FRT requirements concerning penetration of the PV system to the power network. Also, it proposed FRT regulation regarding PV farm connection to the Malaysian grid.

GRID CONNECTION REQUIREMENTS FOR PV SYSTEM

In case of steady state operations, PV generating units need to operate in range around the rated voltage and frequency to be archived at the Point of Common Coupling (PCC) and therefore, the PV plant required to maximize the output power, a so-called Maximum Power Point Tracking (MPPT) [17].

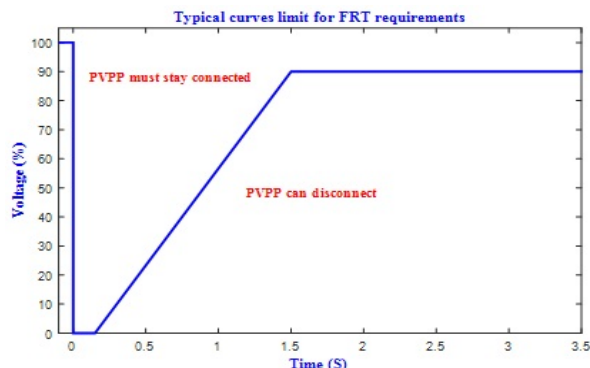


Figure-2. Typical limit curve for FRT requirements.

During abnormal condition and because of PVPP system has become an important part of the total network generation, thus GCs require from PV plant some of the common requirement to ensure the two important aspects, which are security and stability of power supply. These common requirements are FRT capability with regard to LVRT and HVRT, active and reactive power limitation during and after the fault, absorbing or injecting reactive current to support PCC after recovery period and frequency deviation [2]. FRT is described by a time against voltage characteristic, denoting the minimum requirement from the PV plant in case of voltage dip. Figure-2 illustrates the typical limit curve for FRT. If the voltage dip occurs above the limit line of Figure-2, the PV power units should remain in operation. On the other hand, they can disconnect in case of voltage dip below this limit. The voltage provided in Figure-2 generally match to voltage at PCC, voltage sag and also depending on grid code requirements [18].

The FRT requirement also includes fast recovery of active and reactive power to the nominal values after the voltage of system returns to the normal operation.

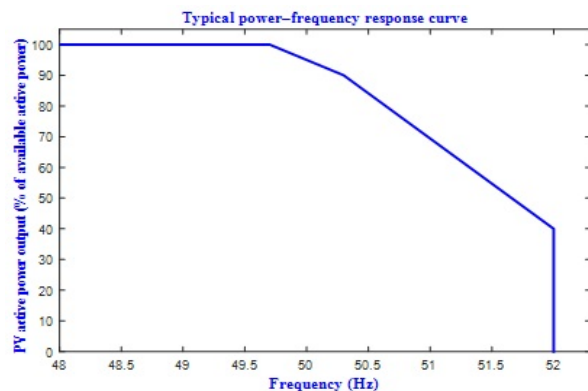


Figure-3. Typical power-frequency response curve.

Figure-3 illustrates the typical power-frequency response curve and explains that in case of over frequency region, there must be a reduction of active power in relation to positive frequency deviation and vice versa and these reduction and injection rate values differ from GC to other. For instance, the German GC stipulated that if the frequency is above 50.2 Hz, the PV plant has to reduce the active power by 10% per minute of the nominal value and after exceeding the threshold limit, active power must be restored with a gradient of 40% per Hz [2, 6, 18].

Certain codes impose that the reactive current generated by PV plant must be increase during the faults, in order to support the system voltage as conventional synchronous generators increase its excitation during disturbance via Automatic Voltage Regulator (AVR) action. Recently, many codes imposed the reactive power regulation capability that is affected by supply amount of reactive power or by a particular power factor. Figure-4 explains the typical requirements for power factor



variation with respect to active power of wind or PV farm [5, 18].

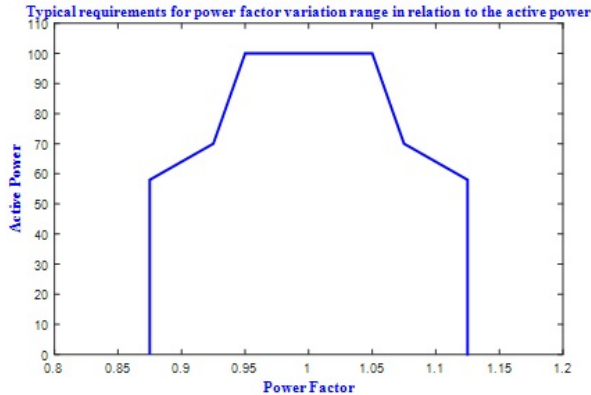


Figure-4. Typical requirements for power factor variation range in relation to the active power.

COMPARISON OF DIFFERENT GRID CODES CONCERNING FRT CAPABILITY

In this section, FRT characteristic should be analysed and compared for different GCs at different countries and the differences should be explained regarding the varying power system topologies. Furthermore, short term voltage control requirements by reactive current injection during fault and restoring active power will be investigated within the relevant GCs.

1. Low Voltage Ride Through (LVRT) Capability

The GCs states that the PVPP should withstand grid voltage dip (sag) to certain percentage of the nominal voltage as in some cases down to zero for specific duration. In this duration, PV units should operate normally without any disconnection. After faults' clearance, PV system must restore both active and reactive power fast enough to pre-fault value. Some codes stipulate that PVPP should feed the grid with reactive current to support the system voltage like traditional synchronous generators. This ability is called LVRT [2, 6, 12, 19].

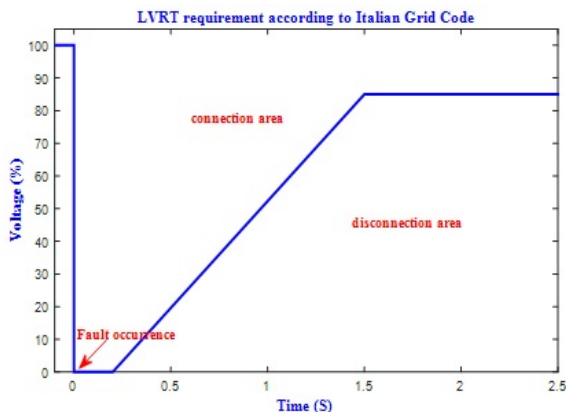


Figure-5. The Italian LVRT requirement.

The international GCs comprise of LVRT curves are relatively similar to Figure-2 however, their characteristic may vary from one system to another. Figure-5 displays that Italian GC that requires PVPP to withstand faults and still connected to the system within 200ms when the voltage at connection point of PV system drop down to zero. If the voltage at connection point recovered to 85% of the rated voltage within 1.5 s after fault occurrence, PV units shall remain under continuous operation without tripping off [10].

Table-1. LVRT requirements in international grid codes.

GC Country	During Fault		After Fault	
	V _{min} (%)	T _{max} (s)	V _{min} (%)	T _{max} (s)
Germany	0.0	0.15	90	1.5
Italy	0.0	0.2	85	1.5
Spain	20	0.5	80	1.0
Japan >2016	30	1.0	80	1.5
Japan < 2016	30	1.0	80	1.0
Australia	0.0	0.45	80	0.45
USA	15	0.625	90	3
Denmark	25	0.14	75	0.75

The German GC stipulated ride-through the fault when the voltage drop to zero for the maximum duration of 150 ms, followed by the voltage recovery to 90% of the rated voltage at PCC in 1.5s as shown in Figure-6 [2, 20]. The LVRT requirements in Spanish GC are less onerous than German or Italian, which require PVPP to withstand the disturbance with voltage drop down to 20% within 500 ms followed by the voltage restoration to 80% during the next 1 s. The USA GC imposes that the voltage drops to zero for the duration of 0.625 ms and then decrease to 15% from the nominal value followed by the voltage recovery to 90% within 3 s. The Australian GC is more restricted than others because it has to increase the voltage to 80% after being drop to zero in the same time of 450 ms. Table-1 shows the LVRT requirement enforced by Italian, German, Spanish, USA, Japanese, and Australian GCs concerning to PV penetration and Danish GC concerning with wind farm but can be used for PV system [18]. Figure-7 shows the data compared in the table above at one graph.

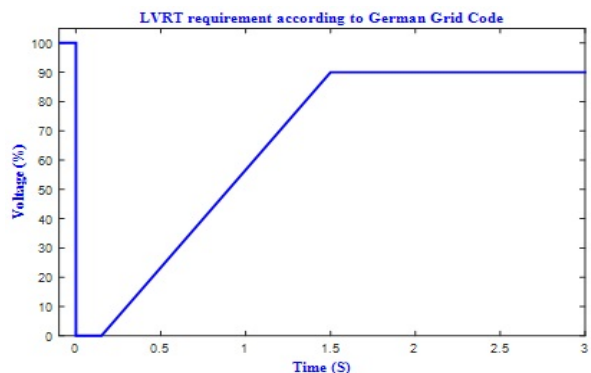


Figure-6. The German LVRT requirement.

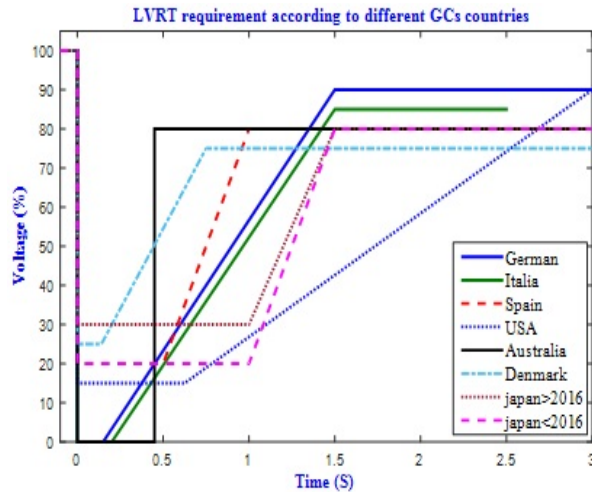


Figure-7. Comparison of LVRT requirement at different GCs.

High voltage ride through (HVRT) capability

Voltage swell occurs by single line to ground fault or sometimes by switching on large capacitor banks. Nevertheless, voltage swell grid fault is less common than voltage sag. To keep the system stable and secure, GCS tackle this problem by acquiring HVRT requirements for generating plant, which does not have any synchronous generators [5].

Figure-8 explains HVRT requirements according to CEI 0-21 Italian GC that requires PVPP to withstand faults and still connected to the system within 100 ms when the voltage at connection point of PV system increase to 125%, followed by the voltage recovery to 115% from the rated voltage at PCC in 500 ms [10]. Table-2 below compares the HVRT requirements of various GCs. It is clear that Australia and Spain have the strictest regulation, which requires PV system to withstand voltage swell of 130% of nominal voltage.

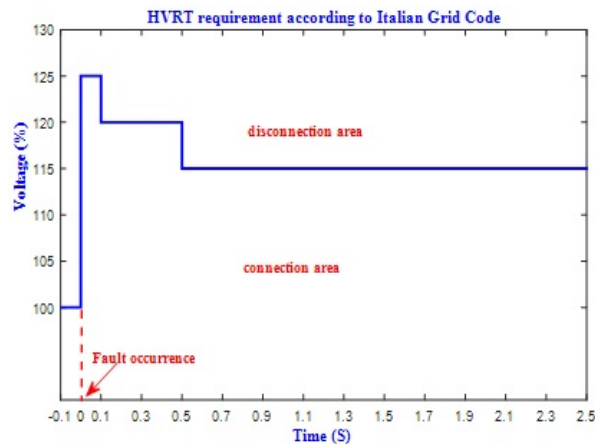


Figure-8. The Italian HVRT requirement.

Table-2. HVRT requirements in international grid codes.

Country GCs	During Voltage Swell	
	$V_{max}(\%)$	$T_{max}(s)$
Germany	120	0.1
Italy	125	0.1
Spain	130	0.25
Australia	130	0.06
USA	120	1.0

Reactive current (RC) injection during FRT

Some GCs impose that PVPP should support the network by generating reactive power during faulty operation to support and restore the grid voltage rapidly [2, 6, 7].

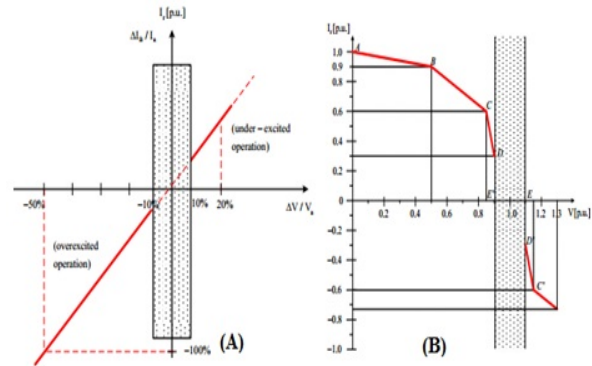


Figure-9. Reactive current requirement during faults according to (A) Germany - (B) Spain GCs [2].

The voltage support requirements are shown in Figure-9 where German GC require injection of reactive current outside the voltage dead band by $\pm 10\%$ and it depends on the percentage of voltage drop, where the dead band lies in the range from $0.9 V_N$ to $1.1 V_N$. Therefore, the voltage controller should take action in less than 20 ms (maximum 30 ms) after fault clearance while the PV units should not absorb any RC from the system [2], [6]. Concurrently, the Spanish GC require that PV system must inject/absorb the RC according to ABCDE polygonal curve shown in Figure-9 (B). In case of overvoltage, the behavior should be mirrored but, when the voltage becomes higher than 130%, the disconnection is required by protection relays. Moreover, once the fault was cleared, the voltage controller will be kept enabled for at least 30 s after voltage level re-enters the normal operation range. The RC can be reduced to zero if the voltage falls to lower than 50% of the nominal voltage [7]. USA GC stipulated that during fault, the PV system should operate on RC injection mode. This mode will be implemented with reactive current drop characteristics with slope from 1% to 5% with injection of RC outside voltage dead band, which is $\pm 15\%$ [13]. During voltage sag, the Danish GC needs wind farm to support a maximum RC according to 1.0 times the nominal current of it. This can also apply for PV



farm [18]. On the other hand, Australian GC requires that with 1% reduction of voltage at PCC should be provided with 4% reactive current [15].

Restoring active power

Active power is the important part in the electrical system, so after the clearance of the fault, the generation of active power restoration at limit rate is an essential thing. Once the fault is cleared, the reactive power should feed-in immediately and rise to the original value with a limited ramp rate of 20%/s and 10% in case of not disconnected and short disconnection respectively according to German GC [2, 6] while in Spanish code, the PV system should restore the active power smoothly within 250 ms [7]. Danish GC stipulated that if the voltages representing 90% and 1.1% of nominal voltage, the reduction of maximum power must not be greater than 10 % [4] whereas the USA PREPA standard requires an immediate increase in active power production of at least 10%/s [13].

ACTIVE AND REACTIVE POWER SUPPORT WITH FREQUENCY VARIATION

Reactive power can be defined as property of the generating units to maintain the voltage level within limits at the PCC. According to USA grid code, the PVPP must work continuously with power factor varying from 0.9 capacitive to 0.9 inductive in case of dynamic and continuous operation at their rated output power [13]. In Germany, the PVPP should be able to operate with power factor in the range of 0.95 lagging to 0.95 leading depending on the voltage at PCC [4, 6]. Table-3 summarizes the reactive power regulations for other countries [7], [10], [15].

Table-3. Power factor limits in different grid codes.

GC Country	Power Factor (PF)	
	Leading (Cap.)	Lagging (Ind.)
Germany	0.95	0.95
Italy	0.95	0.95
Spain	0.91	0.91
Australia	0.90	0.95
USA	0.90	0.90

During deviation of frequency, the disconnection of PV plant may cause instability and therefore GCs state restrictive actions. For instance, according to Figure-6, the German grid code requires that all PV units have to reduce their active power when the frequency is above 50.2 Hz with a gradient of 40%/Hz of available power. The growth of the active power again is allowed immediately when the frequency is below 50.05 Hz. From another side under 47.5 Hz and above 51.5 Hz, the plant must be disconnected from the grid [6].

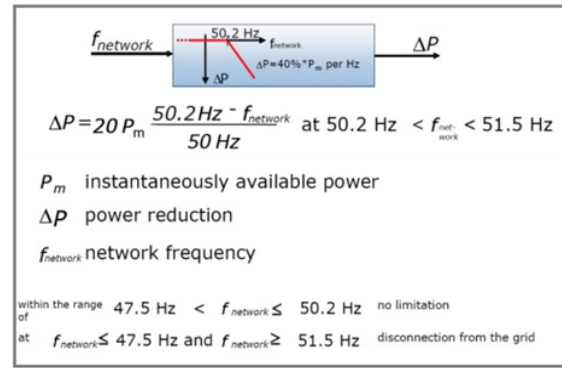


Figure-10. Active power reduction in case of over frequency [6].

THE PROPOSED FRT FOR MALAYSIAN GRID

Malaysia is considered as one of the countries that has electrical grid with good reliability and stability. In 2010, Energy Commission Malaysia (ECM) had published the grid code and distribution code (DC) for Malaysian grid. These codes are used by utility companies like Independent Power Producers (IPPs) and Tenaga Nasional Berhad (TNB) that serve as the main guidelines in electricity supply operation and to ensure the electricity supply in Peninsular Malaysia remains secure and reliable. These two codes are not mentioned in the regulation such as FRT or any other requirement at abnormal conditions for the generating plant, which does not have any synchronous generators connected directly to the grid either PV or wind plants [16]. Furthermore, Malaysia is very suitable for PV installation because of the weather conditions, which has a high radiation throughout the year. Additionally, the Malaysian government started to support this type of energy in 2011 where the fund has increased to 1.6% in 2014 [21]. After studying the Malaysian grid code and distribution code then comparing them with the other GCs mentioned above, this study proposed FRT requirements for PV system connected to MV network in Malaysia.

The frequency of power system in Malaysia is normally 50 Hz and must be controlled through the limits of 49.5 Hz to 50.5 Hz. In case of circumstance, the system frequency should fall to 47 Hz or increase to 52 Hz. The operator or designer of the plant or apparatus should enable it to operate with the following ranges, between 47.5-52 Hz and the continuous operation is required and during the range of 47-47.5 Hz, it should be operated at least 10s each time the frequency is less than 47.5 Hz. In normal operation, the Malaysian grid code stipulated that generators should supply rated output power for the power factor limit between 0.85 lagging and 0.95 leading [16]. According to this requirement and IEEE 1547 standards [12] used by TNB company because up till now, TNB has not apply the Malaysian DC as they are using other standards such as IEC and IEEE in implementing distributed generation in the grid [21], the active power output in percentage depending on the irradiation versus



frequency response capability at PV PCC is proposed for Malaysian grid system as shown in Figure-11.

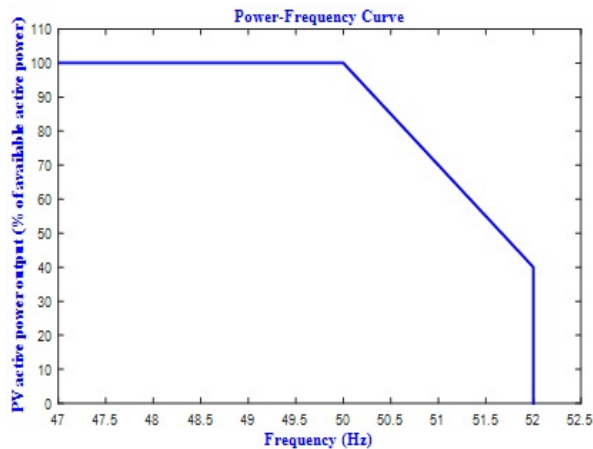


Figure-11. Proposed power–frequency response curve.

In general, the nominal high voltage at Malaysian grid is 66 kV and above and the typical voltage ratio for station transformer are being 132/11 kV, 275/11 kV or 500/11 kV while the unit transformer, which is connected directly to generating units terminal have typical voltage ratio of 33/11 kV and 15/66 kV and this system is almost similar as in USA [16]. In addition, USA applies the IEEE 1547 standard to integrate PV system to the grid and the Malaysian TNB power company uses the same standard for conventional distribution generator. As a result from studying and comparing the different GCs mentioned above and the Malaysian standard, it was found that the most suitable GCs requirement regarding FRT capability for PV system connection in Malaysia is the USA GC where the PVPP shall remain connected to the system in case of voltage sag, swell in the connection area between the two lines as specified below in Figure-12, which illustrates the proposed LVRT and HVRT for Malaysian grid.

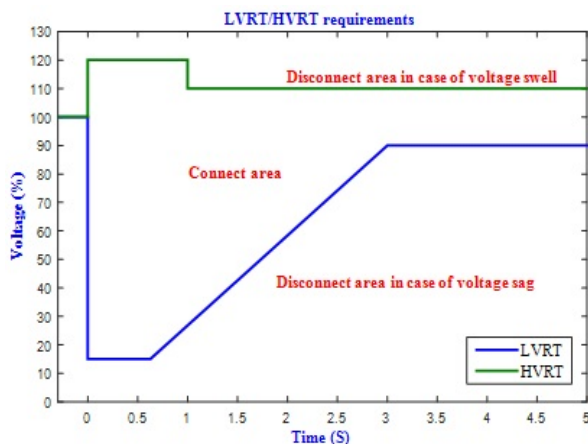


Figure-12. The proposed FRT requirements.

CONCLUSIONS

In this paper, an overview of different national GCs technical requirements especially FRT capability are presented for the connection of PVPP to the power grid. Besides, from the comparison and a study on Malaysian standard and codes, this study found that the most similar GC requirement to the USA regulations accordingly is FRT requirements for integration of PV plant to Malaysian grid. The proposed FRT is the beginning and may be amended by the Malaysian transmission/distribution system operator according to different criteria. The objective of these requirements is to provide the PV system with the control and rules that are necessary for a secure, reliable and economic operation of the system. If PVPP can perform reliable supporting tasks to the grid that means it has the potential to be one of the future power production plants.

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