COMPATIBILIZING MULTIFUNCTIONAL PHOTOVOLTAIC CONVERTERS WITH BRAZILIAN STANDARDS: ANALYSIS AND DISCUSSION

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***Abstract* – Multifunctional Photovoltaic Converters (MPVC) are an emerging technology that comprises the advantages of grid-tie and off-grid inverters, as well as Uninterruptable Power Supplies (UPS). MPVCs present several particularities in comparison to grid-tie and off-grid photovoltaic inverters that are not covered by current Brazilian photovoltaic standards. This manuscript analyzes existing conflicts for application of MPVCs in current Brazilian standards and discusses some solutions to mitigate them. This study is important because discuss possible adjustments in current standards to contemplate MPVCs.**

***Keywords* –Multifunctional photovoltaic converters, standard, converter classification.**

I. INTRODUCTION

Conventional photovoltaic (PV) inverters can be classified as grid-tie and off-grid [1]-[3]. Grid-tie inverters inject the power from the PV panels direct into the grid in a unidirectional power flow. Off-grid inverters work without grid connection and utilize batteries to store energy from PV panels, providing energy to the loads during periods without sunlight. In recent years, it had been proposed the Multifunctional Photovoltaic Converters (MPVCs), also known as hybrid converters [4], that are another type of PV inverters which add characteristics of both grid-tie and off-grid ones.

MPVCs converters operates in three distinct modes [5]: i) Grid-feeding mode, when it supplies energy to the main grid as a conventional grid-tie inverter; ii) Grid-sinking mode, when it sinks current from the grid to recharge the batteries; and iii) Grid-forming mode, when it forms an internal grid to supply energy to critical loads, while the grid is off. Figure 1(a) presents a diagram showing the power flow of a conventional grid-tie inverter, while Figure 1(b) shows the power flow of a MPVC when all its functionalities are employed. Due to these operation modes, MPVCs can be better characterized as an integration of grid-tie inverters and uninterruptable power supplies (UPS), instead of grid-tie and off-grid inverters [6].

Brazilian National Institute of Metrology, Quality and Technology (INMETRO) requires that all grid-connected inverters sold in Brazilian market must comply with the requirements of the ABNT NBR IEC 62116 [7] and ABNT NBR 16149 [8]. These standards are based on international standards like VDE 0126 (German), CEI 0-21(Italian), and IEC 61727 [9]. These standards cover only grid-tie PV inverters with unidirectional power flow from PV modules to the grid. However, these standards do not cover some particularities of MPVC such as switching between grid-feeding mode and grid-forming mode and intentional islanding.

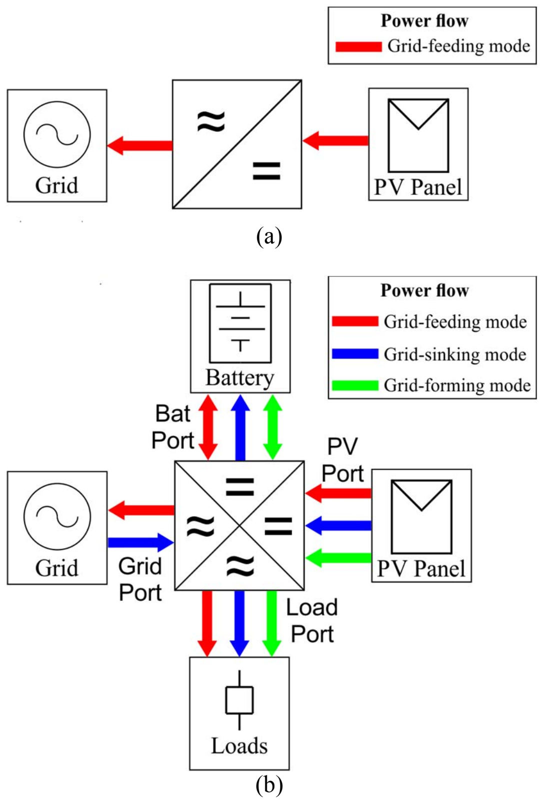

Fig. 1. Possible power flow in PV converters.
(a) Grid-tie inverter. (b) MPVC.

Standards that address the features or impacts of the battery systems connected to the grid are still under development. Standards like UL 1741 and UL 62109 cover some topics [10] such as Battery Storage Systems (BSS) connected to the grid [11]-[13] but not specifically MPVCs.

Considering the classification of MPVCs using UPSs concepts, the objective of this manuscript is to address the conflicts between the ABNT NBR 16149 and some features of the MPVCs and how these regulations impact the performance of MPVCs. This discussion is important to adapt current standards or give fundamentals for the development of new standards which address all possible functionalities of MPVCs, incentivizing the uses of this technology.

II. CLASSIFICATIONS OF MULTIFUNCTIONAL PHOTOVOLTAIC CONVERTERS

MPVCs require grid and load compatibility standards. Standard ABNT NBR 16149 can be considered for compatibility of MPVCs with the grid. For requirements of compatibility to the load it is considered the IEC 62040-3 as follows [14]:

A. Classification based on configuration

1) Passive stand-by: This configuration has a dc/ac converter which operates as current-source during grid-feeding mode and as a voltage source during grid-forming mode. This configuration can be classified as Voltage and Frequency Dependent (VFD) according to IEC 62040-3 because the voltage and frequency supplied to the loads are imposed by the grid when it is connected. Figure 2 shows a block diagram for a conventional passive stand-by configuration. This configuration presents some conflicts between grid and load compatibility requirements since it is used a single dc/ac converter.

2) Double-conversion: This MPVC configuration has two conversion stages. One dc/ac converter is used at the grid side and other dc/ac converter at the load side. This type of MPVC can be classified as Voltage and Frequency Independent (VFI) by the IEC 62040-3. A block diagram of a conventional double-conversion MPVC is shown in Figure 3. In this configuration, there are no conflicts between grid and load compatibility requirements, because they are addressed by different dc/ac converters.

3) Line-interactive: This configuration has a single dc/ac bidirectional converter and includes a power interface or impedance to stabilize the voltage magnitude at the load's side. Therefore, it can be classified as Voltage Independent (VI) by IEC 62040-3. A block diagram of a conventional line-interactive MPVC is shown in Figure 4.

B. Classification based on interruption interval

1) With interruption: in this class, the duration of the voltage interruption during commutations between modes is high enough to turn the loads off. As a result, this type of MPVC cannot be considered a UPS. Brazilian grid code PRODIST classifies interruptions into two definitions, as shown in Table I.

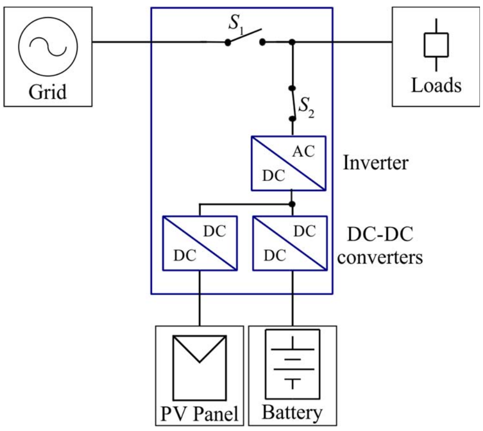

Fig. 2. Block diagram of MPVC with passive stand-by configuration.

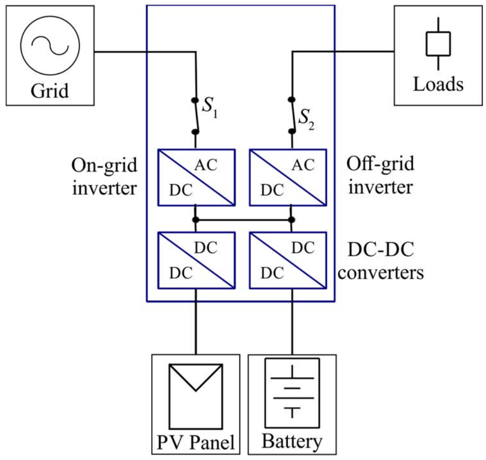

Fig. 3. Block diagram of MPVC with double-conversion configuration.

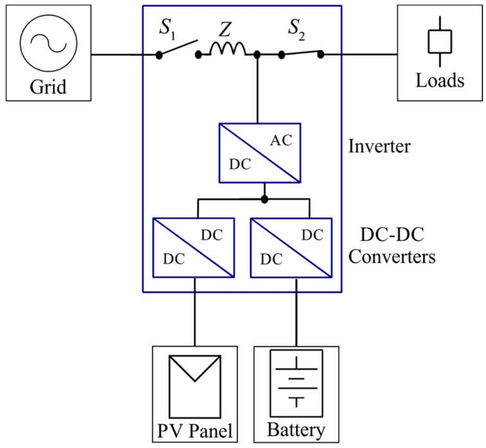

Fig. 4. Block diagram of MPVC with line-interactive configuration.

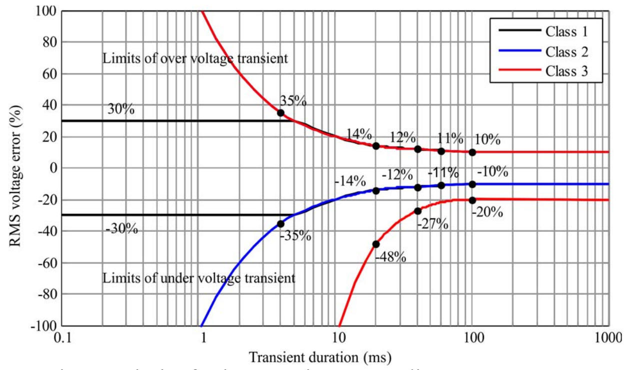

Fig. 5. Limits for interruptions according IEC 62040-3.

TABLE I- Interruption definitions by PRODIST

Interruption definitions	Interruption interval
Momentary	t < 3 s
Temporary	3 s < t <180 s

2) Without interruption: transient responses do not turn the loads off, so the MPVC can be considered a UPS. IEC 62040-3 classifies UPS into three classes, as shown in Figure 5. Class 1 does not allow interruptions and class 3 allows a maximum 10 ms voltage interruption.

III. DISCUSSION ABOUT COMPATIBILIZATION OF MULTIFUNTIONAL PV CONVERTERS TO STANDARD NBR 16149

Conventional grid-tie PV inverters in Brazil must comply with standards ABNT NBR 16149 and ABNT IEC 62116 with the test conditions described in ABNT NBR 16150 [16]. The following requirements must be complied:

1. Maximum flicker
2. Maximum continuous current injection
3. Maximum current harmonics and THD
4. Power factor regulation
5. Reactive power regulation
6. Disconnection by over/under voltage
7. Disconnection by over/under frequency
8. Active power control in over frequency
9. Automatic reconnection after grid stabilization
10. Out-of-phase automatic reconnection
11. Active power control
12. Reactive power control
13. Remote disconnection support
14. Low Voltage Fault Ride Through (LVFRT) support
15. Protection against DC side polarity reversal
16. Protection against overload
17. Anti-islanding protection

Some of these requirements may have conflicts when directly applied to MPVCs, as follows:

A. Power quality

1) Grid-tie operation in grid-feeding or grid-sinking mode: ABNT NBR 16149 imposes limits to individual harmonic and total harmonic distortion (THD) of the injected current. However, MPVC in grid-sinking mode also absorb current from the grid. In this case it is more reasonable to consider the requirements of individual harmonics and THD for ac-dc converters. However, this issue has not yet been explored and should be addressed in future regulations.

2) Off-grid operation in grid-forming mode: Considering that loads connected to the MPVC are designed to be fed by the grid, the MPVC voltage shall have at least the same power quality of the grid voltage. Therefore, the individual harmonics and THD of voltage supplied to the loads in grid-forming mode must be evaluated. Two standards that could be applied to define the voltage quality are shown in Figure 6: i) Brazilian grid code PRODIST; and ii) UPS standard IEC 62040-3.

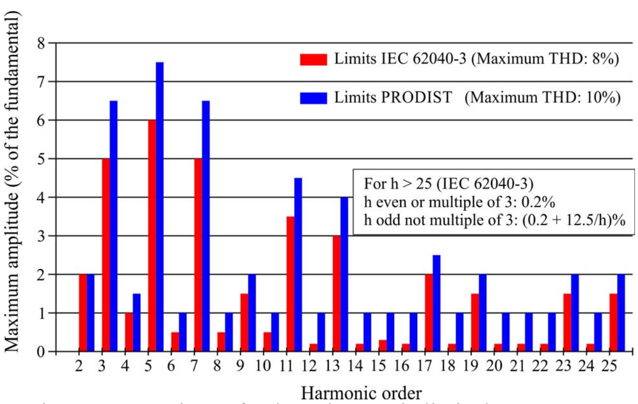

Fig. 6. Comparison of voltage harmonic limits between IEC 62040-3 and PRODIST

B. Voltage limits for disconnection

Conventional grid-tie inverters operating as grid-feeders do not control the grid voltage magnitude. However, for protection purposes, automatic disconnection is carried out when occur grid overvoltage or undervoltage. On the other hand, when MPVCs operates as grid-forming mode, it must guarantee the quality of voltage supplied to the loads. As a result, the magnitude voltage limits could be tighter than those considered in grid-tie converters.

For the double conversion and line interactive MPVC configurations, the magnitude of voltage supplied to the loads is independent from the grid. Consequently, voltage disconnection limits defined in NBR 16149 can be considered at the grid side even if a tighter load voltage range is considered at load side. However, for the passive stand-by configuration, the voltage supplied to the loads is the same of the grid when the converter operates in grid-tie mode.

Figure 7 shows that the limits of voltage magnitude for disconnection according to NBR 16149 are inappropriate according to Brazilian grid-code PRODIST. However, these limits are the same to the class 3 of IEC 62040-3, which is acceptable for most loads. Therefore, in order to keep using the magnitude voltage limits of NBR 16149 for MPVC disconnection, the following strategy could be adopted:

1. For double conversion or line interactive configurations, the NBR 16149 limits can be applied to the grid side, and a tighter voltage range can be applied to the loads, such as the PRODIST appropriate range or the IEC 62040-3 – class 1 or 2.
2. For passive stand-by configuration, the loads must support the range of IEC 62040-3 – class 3, which is equal to the disconnection limits of NBR 16149. Therefore, this MPVC configuration cannot be employed for supplying special or sensitive loads (Class 1 or 2 of IEC 62040-3).

It is worth mentioning that for operation in grid-sinking mode there are no standards definitions for undervoltage or overvoltage disconnection. For the passive stand-by configuration, due to load compatibility, the NBR 16149 limits should be applied also for grid-sinking mode. However, for double conversion and line-interactive configurations this voltage range could be wider. This issue has not yet been explored and should be addressed in future regulations.

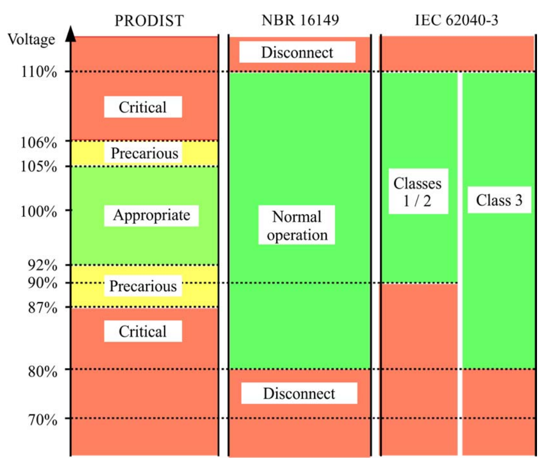

Fig. 7. Voltage limits comparison between PRODIST, NBR 16149 and IEC 62040-3

C. Frequency limits

Figure 8 shows the expected conventional grid-tie inverter response due to grid frequency actually imposed by the NBR 16149. The grid-tie inverter operates normally between 57.5 Hz and 60.5 Hz. An active power reduction curve is activated when the grid frequency is between 60.5 Hz and 62.0 Hz, and the inverter shall disconnect within 200ms when the frequency is below 57.5 Hz or above 62.0 Hz.

The frequency limits have the same concerns presented for the voltage limits. The MPVC could provide to the load a tight frequency regulation, but this is not possible for the passive stand-by and line interactive configurations. These configurations operate at grid frequency during grid-tie operation. Therefore, to provide to the loads the ideal frequency range of PRODIST (59.5 Hz to 60.5 Hz), these configurations would have to disconnect in a frequency range not compatible with ABNT NBR 16149, as shown in Figure 9. Furthermore, the “Active power control in over frequency” feature would be lost.

Double-conversion configuration does not have this concern, since it separates the load from the grid. However, passive stand-by and line interactive configurations could disconnect from the grid considering two possible features: i) disconnect in a tight frequency range, in order to support sensitive loads, with the drawback of losing ABNT NBR 16149 compatibility; or ii) the loads shall support the ABNT NBR 16149 frequency range, so the MPVC can be compatible with this standard. This issue should be addressed in future regulations.

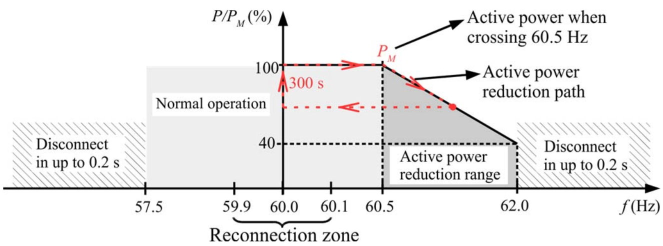

Fig. 8. NBR 16149 inverter response to grid frequency

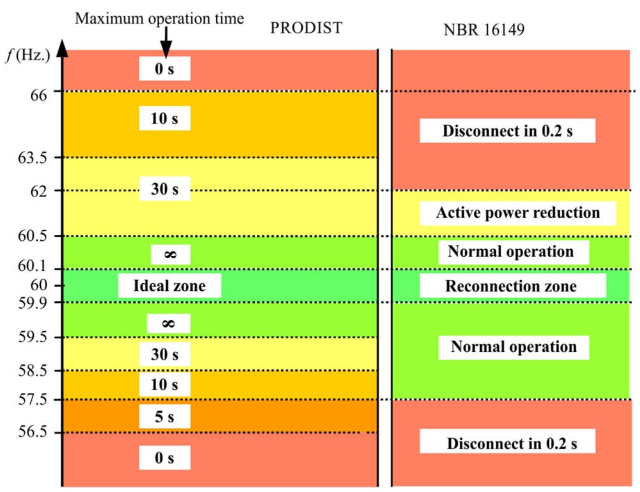

Fig. 9. Frequency limits comparison between PRODIST and NBR 16149

D. Reconnection

According ABNT NBR 16149 grid-tie inverter must wait between 20 s to 300 s to inject power after grid stabilization. This requirement is not applicable for power consumption. Therefore, when MPVC operates in grid-sinking mode, it could immediately reconnect after grid stabilization. However, future regulations must address this possibility.

E. Low Voltage Fault Ride Through (LVFRT)

In order to avoid inappropriate disconnection due to voltage sags, conventional grid-tie PV inverters with nominal active power equal or higher than 6 kW must not disconnect from the grid within the time intervals shown in Figure 10. Conventional grid-tie PV inverters must keep connected to the grid for a period between 200ms to 300ms after the voltage sag, being allowed to disconnect only if the grid is not restored within this period.

These LVFRT requirements can be applied for MPVC with double conversion configuration without affecting the load’s supply. For passive stand-by and some line-interactive configurations, the LVFRT directly affects the load power supply, because the MPVC must keep connected for 200 or 300ms during a voltage fault. The consequence of this limitation is that these MPVC configurations cannot be classified as “without interruption”, because the interruption interval is higher than 10 ms (Class 3 of IEC 62040-3).

Figure 11(a) and (b) shows the effect of the LVFRT requirements to a load connected to a converter. A grid voltage interruption occurs at instant t_1, but the MPVC can disconnect only at t_2, which is 200 ms after the fault. Between t_1 and t_2, the converter keeps injecting current into the grid, but the load voltage is zero. After t_2, the converter finally switches to off-grid mode and the load power supply is restored. Most loads do not support this interruption interval without shutting down, so the MPVC is classified as “with interruption”, and cannot be considered a UPS. Figure 12(a) and 12(b) shows simulation results for same conditions of Figure 11 but without considering the LVFRT requirements. LVFRT is not mandatory for grid-tie inverters with lower power than 6 kW. The grid voltage interruption occurs at t_1. As soon as the sag is detected by the MPVC, the grid is disconnected, at t_2. The load voltage interruption takes about 10 ms, so the MPVC can comply with IEC 62040-3 – class 3, being classified as “without interruption” and can be considered a UPS. Simulation results for the MPVC with passive-standby configuration presented in Figure 13.

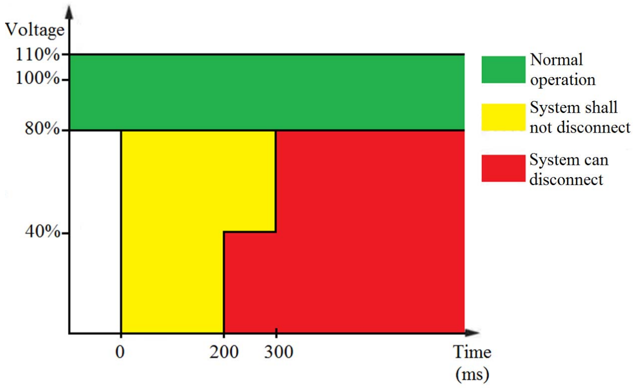

Fig. 10. Requirements of low voltage fault ride through - LVFRT

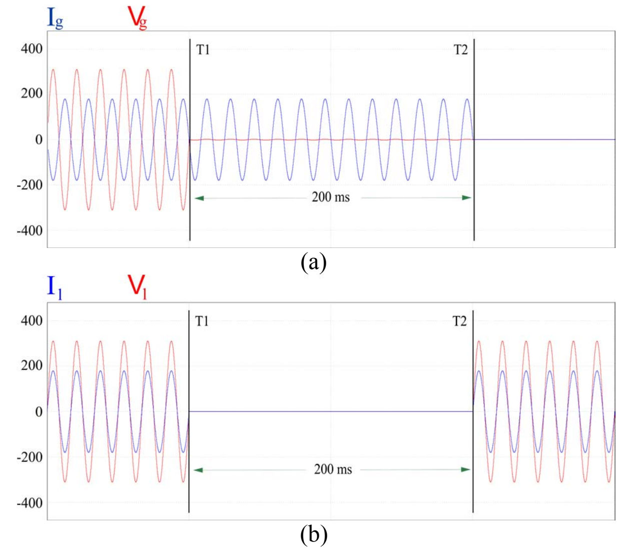

Fig. 11. LVFRT simulation for passive stand-by with P > 6 kW. (a) Voltage and current at grid. (b) Voltage and current at load

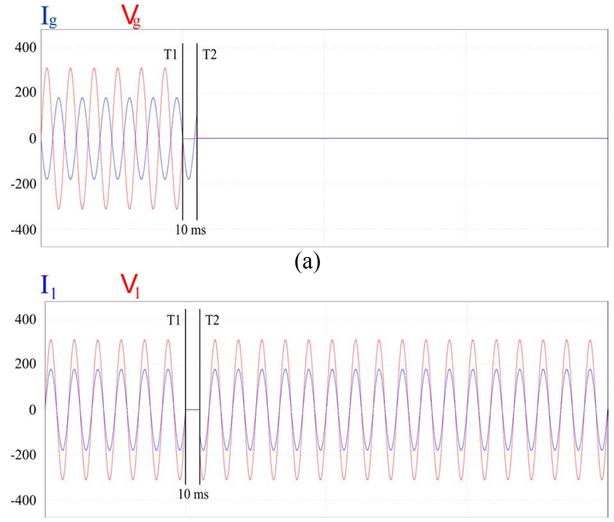

Fig. 12. LVFRT simulation for passive stand-by with P < 6 kW. (a) Grid voltage and current. (b) Load voltage and current

It is important to highlight that the LVFRT requirements for the passive stand-by configuration heavily compromises one of the main features of MPVCs: the integration of UPS and grid-tie inverters. Therefore, when the LVFRT is required, the loads shall support voltage interruptions, otherwise a double conversion configuration shall be employed.

IV. IMPORTANT ISSUES ON MPVC OPERATION NOT CONVERED BY ABNT NBR 16149

MPVCs can have an important role in the smart grids concept supporting grid and power systems. New standards are being developed to cover the following topics [17, 18]:

1) *Grid and system support:* current Brazilian standards cover some relevant issues related to grid support such as active and reactive power injection control. Some countries with high PV penetration such as Germany have presenting problems related to reverse power flow in medium voltage (MV) and high voltage (HV) power lines [18, 19].To mitigate this problem, the government studies to subsidize the use of batteries, forcing them to be charged only during the peak renewable energy generation and feed back to the grid during energy demand peak. A limitation to the charging rate and state of charge of batteries is also studied [18-20]. Furthermore, the batteries can be used to improve the already existing support systems in the PV converters, absorbing or feeding energy in function of over/under voltage and frequency conditions. The possibilities that batteries add to the power systems are not yet fully covered and still are on study. MPVCs could anticipate all these conditions and should include characteristics to offer control to system operators.

2) *Short circuit protection:* Short circuit (SC) is not a concern in conventional grid-tie PV inverters because PV arrays present intrinsic short circuit limitation. On the other hand, when inverter is fed from batteries, it can supply a very high current to the grid in the same situation [21, 22]. Moreover, in passive-standby and line-interactive configurations, if a short circuit occurs at the loads it results in overcurrent in some MPVC components. For both cases, the overcurrent can cause damage as well as risks of fire. Therefore, MPVCs must have short-circuit protection.

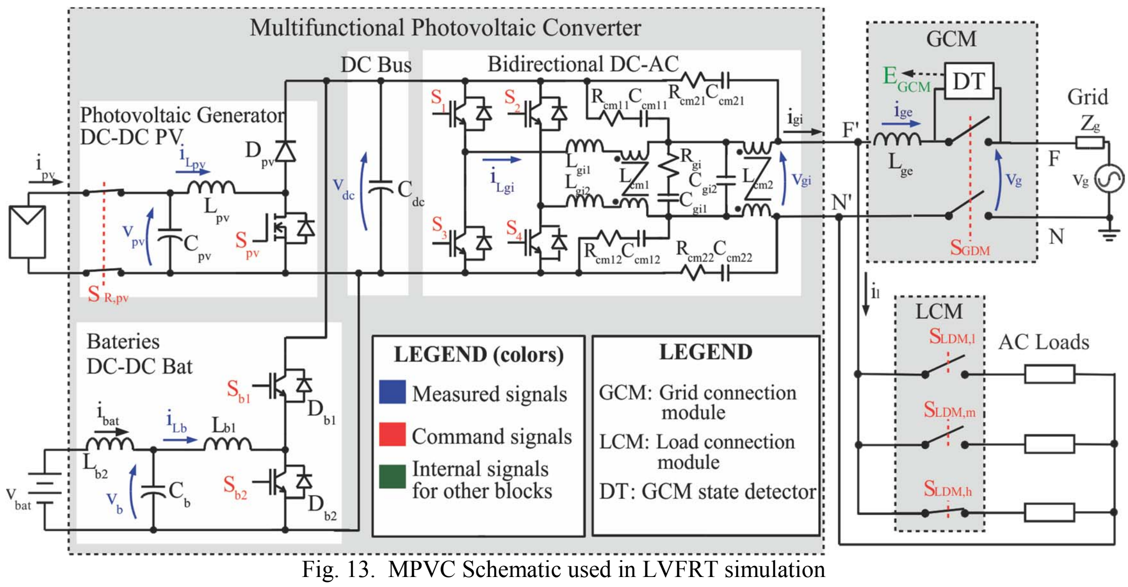

Fig. 13. MPVC Schematic used in LVFRT simulation

3) *Battery inverted polarity:* Protection against incorrect battery connection must be considered to avoid overcurrent when operator plug batteries with wrong polarity.

4) *Commutations among operation modes:* some tests should be made in all MPVCs to ensure that the transition between grid-feeding and grid-forming modes and vice-versa do not cause any voltage or current surge that could damage the loads or the MPVC. Furthermore, the switching time between modes should be measured and compared to the product plate, allowing customers to know if that product is suitable for their needs.

V. CONCLUSION

Grid compatibility and load compatibility requirements may have conflicts when applied to MPVCs. Double-conversion configuration is not affected by these conflicts because they are addressed by different dc-ac converters. For stand-by and line-interactive configurations, these conflicts can impact on their functionalities. So, in order to comply with the requirements of MPVC, new standards must be created or current Brazilian standards should be extended to cover this application.

This manuscript contributes for the discussion of MPVC standards considering grid and load compatibility. Further discussion can be performed considering the effects of these requirements on the grid, external control and ancillary services.

REFERENCES

[1] H. Wang and D. Zhang, "The Stand-alone PV Generation System with Parallel Battery Charger", *2010 International Conference on Electrical and Control Engineering*, pp. 4450-4453, 2010.

[2] C. Daniel Schwertner, L. Bellinaso, H. Hey and L. Michels, "Supervisory control for stand-alone photovoltaic systems", *2013 Brazilian Power Electronics Conference*, pp. 582-588, 2013.

[3] L. de Souza Ribeiro, O. Saavedra, S. de Lima and J. de Matos, "Isolated Micro-Grids With Renewable Hybrid Generation: The Case of Lençóis Island", *IEEE Transactions on Sustainable Energy*, vol. 2, no. 1, pp. 1-11, 2010.

[4] *Photovoltaic Systems - classification* (in portuguese), Brazilian Society of Standards, *ABNT NBR Std. 11704,* 2008.

[5] W. Choi, Yujiang Wu, D. Han, J. Gorman, P. Palavicino, W. Lee and B. Sarlioglu, "Reviews on grid-connected inverter, utility-scaled battery energy storage system, and vehicle-to-grid application - challenges and opportunities", *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, pp. 203-210, 2017.

[6] L. Bellinaso and L. Michels, "Multifunctional Photovoltaic Converters - Classification And Requirements For Grid And Load Compatibility", *Eletrônica de Potência*, vol. 21, no. 2, pp. 126-137, 2016.

[7] *Test procedure of islanding prevention measures for Utility-Interconnected photovoltaic inverters* (in portuguese), Brazilian Society of Standards, ABNT NBR IEC Std. 62116, 2012

[8] *Photovoltaic (PV) systems – Characteristics of the utility interface* (in portuguese), Brazilian Society of Standards, *ABNT NBR IEC Std. 16149,* 2013.

[9] H. Figueira, H. Hey, L. Schuch, C. Rech and L. Michels, "Brazilian grid-connected photovoltaic inverters standards: A comparison with IEC and IEEE", *2015 IEEE 24th International Symposium on Industrial Electronics (ISIE)*, pp. 1104-1109, 2015.

[10] S. Rangarajan, E. Collins, J. Fox and D. Kothari, "A survey on global PV interconnection standards", *2017 IEEE Power and Energy Conference at Illinois (PECI)*, pp. 1-21, 2017.

[11] *Connecting and operating storage units in low voltage netwoks*, Verband der Elektrotechnik (VDE), Elektronik und Informationstechnik, 2013.

[12] *Grid Compatibility certified by TÜV SÜD,* TÜV Süd, *2015*.

[13] K. Kairies, D. Magnor and D. Sauer, "Scientific Measuring and Evaluation Program for Photovoltaic Battery Systems(WMEP PV-Speicher)", *Energy Procedia*, vol. 73, pp. 200-207, 2015.

[14] *Uninterruptible power systems (UPS) – Part 3: Method of specifying the performance and test requirements,* IEC Std. 62040-3, 2011.

[15] "*Procedures for the distribution of electric energy in the national electricity system – PRODIST – Module 8 – Quality of electricity" (in portuguese)*, National Electricity Energy Agency, PRODIST – revision 7, 2015

[16] *Photovoltaic (PV) systems — Characteristics of the utility interface — Conformity test procedure (in portuguese)*, Brazilian Society of Standards, ABNT NBR Std. 16150, 2013.

[17] S. Siddiki, S. Islam, A. Alahmed, Y. Alharthy, G. Chaudhry and M. Siddiki, "Grid interactive PV system with battery backup — The viable alternative solution for power crisis in Rajshahi, Bangladesh", *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016.

[18] M. Resch, J. Bühler, M. Klausen and A. Sumper, "Impact of operation strategies of large scale battery systems on distribution grid planning in Germany", *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 1042-1063, 2017.

[19] S. Mirhassani, H. Ong, W. Chong and K. Leong, "Advances and challenges in grid tied photovoltaic systems", *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 121-131, 2015.

[20] M. Alam, K. Muttaqi and D. Sutanto, "Mitigation of Rooftop Solar PV Impacts and Evening Peak Support by Managing Available Capacity of Distributed Energy Storage Systems", *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3874-3884, 2013.

[21] H. Rahimi-Eichi, U. Ojha, F. Baronti and M. Chow, "Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles", *IEEE Industrial Electronics Magazine*, vol. 7, no. 2, pp. 4-16, 2013.

[22] E. Naderi, H. Seifi and M. Sepasian, "A Dynamic Approach for Distribution System Planning Considering Distributed Generation", *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1313-1322, 2012.