Synchronization Stability of a Grid Forming Converter Under the Effect of Current Limit in Voltage Dips with VI Based Current Limiting Method: Analysis and Solution

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Keywords

« Grid forming », « Droop control », « Current limiter », « Virtual impedance », « Synchronization stability », « Fault ride-through »

Abstract

This article deals with the synchronization stability in voltage dips of a Grid Forming Converter (GFC) operating with Virtual Impedance based current limiter. In the event of a grid fault, if the converter can't evacuate the active power while limiting the current, stability issues arise. In this paper this effect is analyzed, and a solution is proposed.

Introduction

Currently most of the inverter-based resources (IBRs) available in transmission and distribution power system are based on Grid Following Converter (GFL) and it causes reduction to the total electrical grid inertia. With the high share of IBRs, the grid stability is an important phenomenon and the GFL doesn't have the ability to ensure it. The solution towards grid stability is the GFC which can operate in a stiff grid voltage while providing voltage and frequency support in normal and highly variable conditions [1]. The exchange of current between the converter and grid depends on the impedance that connects them (For two voltage sources) and for large voltage difference, the current can be higher than the nominal value. This high current can occur under the highly variable conditions such as short circuits, phase jumps and with connection of large loads. These highly variable conditions are very critical for the GFC, and it requires the use of current limiter. Over the years different current limiting methods have been proposed for GFC based on the current saturation control algorithm [2, 3]. But with these control algorithms, while limiting the maximum current, the system can become unstable because of the wind-up in the outer power loops [4]. For the synchronization during the grid faults, some authors have proposed switching the control to a PLL based current control [5]. With this, the main drawback is to implement a fault detection algorithm along with the setting of the triggering condition [4].

A new innovative approach has been developed known as Virtual Impedance (VI) where the effect of the physical impedance is emulated when the current output exceeds the nominal value [6, 7, 8, 9]. Compared to the current saturation control algorithm, the VI based current limiting method provides better performance in terms of limiting the current but the stability of GFC is still an issue [6] [9]. One of the main goals of this article is to highlight this issue for which a GFC with a VI is used as a base case.

Regarding the transient and synchronization stability, different analysis have been found such as Adaptive droop gain with respect to the current magnitude [6], Adaptive droop gain with respect to the AC voltage amplitude [6], Enhanced fault recovery using dynamic damping [7], synchronization with the virtual power angle generated from VI [8] etc. Among the studies regarding the synchronization stability, another control method that has been found is the use of virtual active power as feedback that is calculated by the voltage and unsaturated current measured at the point of common coupling (PCC) [10]. Based on this control method, The authors in ref [10] has solved the synchronization stability issue within the grid fault event, but in terms of Low Voltage Ride Through (LVRT) capability, the information with reactive power injection has not been clearly defined. This same idea of the Virtual active power has been introduced in this article as one of the techniques that incorporates the VI for the synchronization stability. With this control method, both the synchronization stability and LVRT capability has been studied.

Both LVRT capability with adequate reactive power injection and synchronization stability during and after the voltage dips are essential grid code requirements [11, 12, 13]. Considering these requirements, in this article, a new control structure has been proposed. Based on the VI current limiting method, a control subsystem is added which is the adaptive active power set point in the Active Power and Frequency droop (P-f droop). The main goal of this article is to solve the synchronization stability during and after a voltage dip event. To do so, three methods are compared, which are, the base case of the GFC with only VI, the virtual active power feedback (presented in [10]) and the proposed adaptive active power set point. Besides the stability, the performance during the LVRT in terms of reactive power is also analysed.

The stability analysis is carried out using Matlab-Simulink. For the GFC converter model, a three-level neutral-point-clamped (NPC) is considered arbitrarily as it is one of the most widely used converter topology, However, this article mainly focuses on the control strategy of the converter and the implications towards the converter characteristics are not within the scope of this article.

In this article firstly a widely used grid forming control with a VI based current limitation method is presented as a Base Case. Then the Virtual Active Power Control structure along with the proposed solution of Adaptive Active Power Set Point are presented. Afterwards, some voltage dips are simulated to highlight the stability issues with the Base Case. In order to prove the correct performance of the proposed solution, some comparative analyses have been performed between the Virtual Active Power Control and the proposed solution. Finally, a conclusion has been made based on the performed analysis.

Base Case: GFC Control Configuration With VI

The GFC control mechanism that has been used in this article as a Base Case is based on the droop control with a VI. This control structure has been widely used in different literature [6, 7, 8, 9] and even some prototypes have been developed [14, 15]. The control algorithm performed in this control structure are in dq reference frame and the equations of the voltage and frequency droop control used are provided below.

$$V_{d\_droop} = V_d^* - n_q\,(Q - Q^*) \tag{1}$$
$$f_{droop} = f^* - m_p\,(P - P^*) \tag{2}$$

The output frequency and voltage from this droop equations are f_{droop} & V_{d_droop} where the frequency output is used to generate the angle Θ_{GFC} of the converter. The voltage output of the droop controller is fed into the VI. The outputs of the VI are the d and q reference voltages which are used to regulate the voltages V_d and V_q at the PCC. These regulated voltages are then converted to abc reference frame where the angle Θ_{GFC} is used for the conversion. The overall structure of the GFC control is provided below.

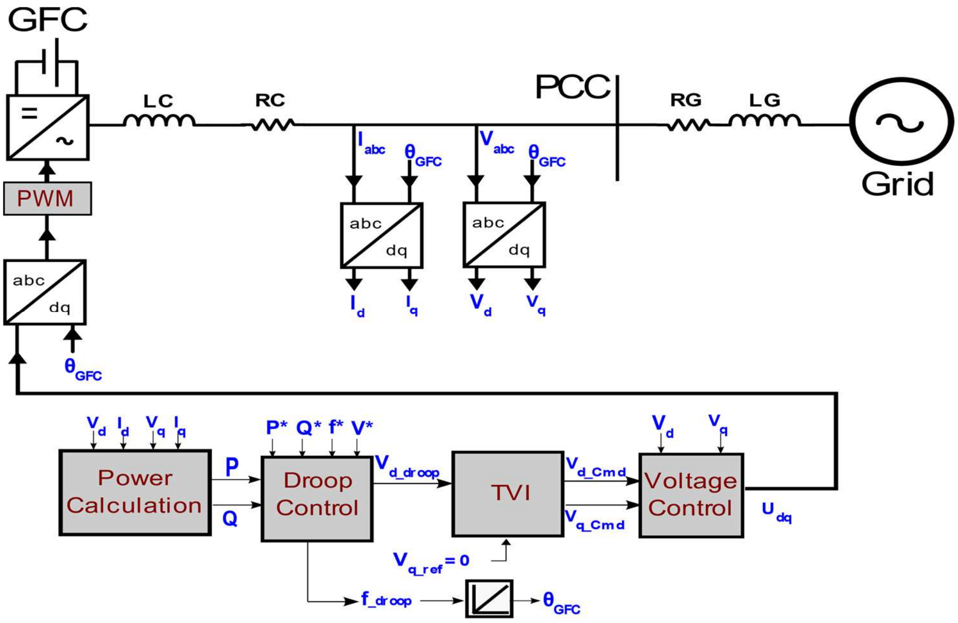

Fig. 1: Base case control Structure of the GFC

The voltage controllers used in this control method are PI based structures with anti-windup. The upper and lower saturation values for this anti-windup was provided as 1.2 PU and 0.85 PU respectively. The VI used in this control algorithm is to limit the fault current and it is only activated when the peak current of the converter current exceeds its threshold current value. The equation for calculating the peak current is provided below.

$$I_{Conv} = \sqrt{I_d^{\,2} + I_q^{\,2}} \tag{3}$$

The threshold current value is usually provided less than the maximum current value. The equation to determine the virtual impedance is provided below.

$$\begin{cases} X_{vi}\,(I_s) = K_{VI}\,|I_{Conv} - I_{thresh}|\; if\; I_{Conv} > I_{thresh} \\ X_{vi}\,(I_s) = 0, if\; I_{Conv} < I_{thresh} \\ R_{vi}\,(I_s) = X_{vi}/(\frac{\rho X}{R}) \end{cases} \tag{4}$$

Here, K_{VI} is the reactance gain and $\frac{\rho X}{R}$ is the reactance to resistance ratio. With large value of $\frac{\rho X}{R}$, the VI has more inductive elements. In this control mechanism the values of K_{VI} , I_{thresh} and $\frac{\rho X}{R}$ are provided as 7.5, 1.1 PU and 4 respectively. After the inclusion of the VI, the d and q sequence voltage equation become like this,

$$V_{d\_cmd} = V_{d\_droop} - (I_d R_{vi}) + \left(I_q X_{vi}\right) \tag{5}$$
$$V_{q\_cmd} = V_{q\_ref} - \left(I_q R_{vi}\right) - (I_d X_{vi}) \tag{6}$$

Here, V_{d_cmd} and V_{q_cmd} are the voltages that are fed to the voltage controllers. V_{d_droop} and V_{q_ref} are the voltage references, where V_{d_droop} is coming from the droop and V_{q_ref}=0. $(I_d R_{vi}) - \left(I_q X_{vi}\right)$ is the voltage drop due to the VI in the d sequence and $(I_q R_{vi}) + (I_q X_{vi})$ is the voltage drop across the q sequence due to the VI.

The general parameters of the Converter and Grid used for the simulation purpose is provided in the table below.

Table I: General Parameters of the Converter and Grid

Parameter	**Symbol**	**Unit**	**Value**
Grid Voltage	V_{Grid}	Volt (Phase to Phase RMS)	600
Nominal Power	S_n	MW	2
Nominal Frequency	F_n	Hz	50
Grid Inductance	LG	mh	0.10313
Grid Resistance	RG	ohm	0.0022
Filter Inductance of the Converter	LC	mh	0.086
Filter resistance of the Converter	RC	ohm	0.01
Threshold Current	I_{thresh}	PU	1.1
Maximum Current Limit	I_Limit	PU	1.2
P-F Droop Constant	mp	-	0.02
Q-V Droop Constant	nq	-	0.05

The Base Case of the GFC with VI is not sufficient to provide post fault synchronization in the event of voltage dips [6] [9]. For this reason, the base case in this control structure is improved with two different control methods of virtual active power feedback and the proposed adaptive active power set point in the P-f droop. The detail description of these two control structures is provided below.

VI With Virtual Active Power Feedback (VI_P_Virt) [10]

The first method that has been used in this article, is the addition of virtual active power generated by the VI in the active power and frequency droop control which is explained in more detail in [10]. In the event of fault, the measured active power of the GFC includes the saturated current and with this the active power output becomes insensitive in the change of phase. For this reason, the problem of synchronization occurs. In order to counter this saturated current, the virtual active power can be used in the event of fault. The equation to calculate the Virtual Active Power is provided below.

$$P_{Virt} = \frac{V_{in\_Virtual} \times V_{out\_Virtual}}{X_{vi}} \sin(\delta) \quad (7)$$

Here, $V_{in\_Virtual}$ is the modulas of V_{d_droop} and V_{q_ref}. $V_{out\_Virtual}$ is the modulas of V_{d_cmd} and V_{q_cmd} which are the outputs of the VI. X_{vi} is the inductance of the VI and δ is the angle difference between $V_{out\_Virtual}$ and $V_{in\_Virtual}$.

Proposed Control: VI With Adaptive Active Power Set Point in P-f Droop (VI_Adaptive_PSET)

From the GFC control perspective, the active power and frequency regulation of GFC can be made by changing the set point frequency or by changing the active power set point or by changing both. In order to provide fault ride-through capability by injecting more reactive power in the event of fault, a logic has been implemented in the active power set point of GFC. In this control method, the frequency set point of GFC is maintained as 1 PU and only the active power set point is changed. The equation for the active power set point is given as,

$$P_{Set_{Effective}} = P\_Set_{Gain} \times P_{Set} \tag{8}$$

Here, $P_{Set_{Effective}}$ is the effective active power set point that is given to the GFC. P_{Set} is the initial active power that is applied to the GFC. P_Set_{Gain} is the gain that varies based on the converter voltage and the condition for this is provided below.

$$\begin{cases} P_{Set_{Gain}} = 1, if\ V_{Conv_{Mod}} > 0.85\ PU \\ P_{Set_{Gain}} = 0.5 + (V_{Conv_{Mod}} - 0.85) \times K, if\ 0.5 < V_{Conv_{Mod}} \leq 0.85 \\ P_{Set_{Gain}} = 0, if\ V_{Conv_{Mod}} \leq 0.5\ PU \end{cases} \tag{9}$$

In equation (9) at 0.85 PU voltage, the value of $P_{Set_{Gain}}$ is considered as 0.5. Based on this the slope for the linear equation is found out to be, K= (0.5-0) / (0.85-0.5) = 1.4286.

Synchronization Assessment of the GFC During Voltage Dips

The IBRs should be connected to the grid in the event of voltage dips by providing voltage support by means of reactive power injection [16, 17, 18]. For that, the evacuation of active power during grid faults is an important factor for IBRs [11]. In general, this active power evacuation depends on many factors such as, the fault duration, fault depth, pre fault operating point of active power, Total system inertia etc [19]. This active power evacuation has a direct impact on the GFC in terms of both protection and stability as the GFC control uses the active power to synchronize with the grid.

It is well known fact that, in order to have stable operation, the phase angle difference between different busbars should not exceed 90° and the preferable phase difference is suggested to be ±30° [20]. During a grid fault event pole slipping may occur where the power generating unit loses synchronism to the transmission or distribution system it is connected to [21]. The main reason of the pole slipping in GFC is found out to be the P-F droop characteristic during fault [9]. If during a voltage dip event, the active power cannot be evacuated, the angle difference between the converter and the grid starts to increase significantly. For this, the whole system may lose synchronization and the angle difference will be found at the next stable regions where the equilibrium point lies at the ±2π periods [22].

In order to highlight these problems of active power evacuation, pole slipping and de-synchronization of the GFC, the base case with VI current limiting method is tested with 50% voltage dip for different time duration and with different active power generation point. The results are provided below.

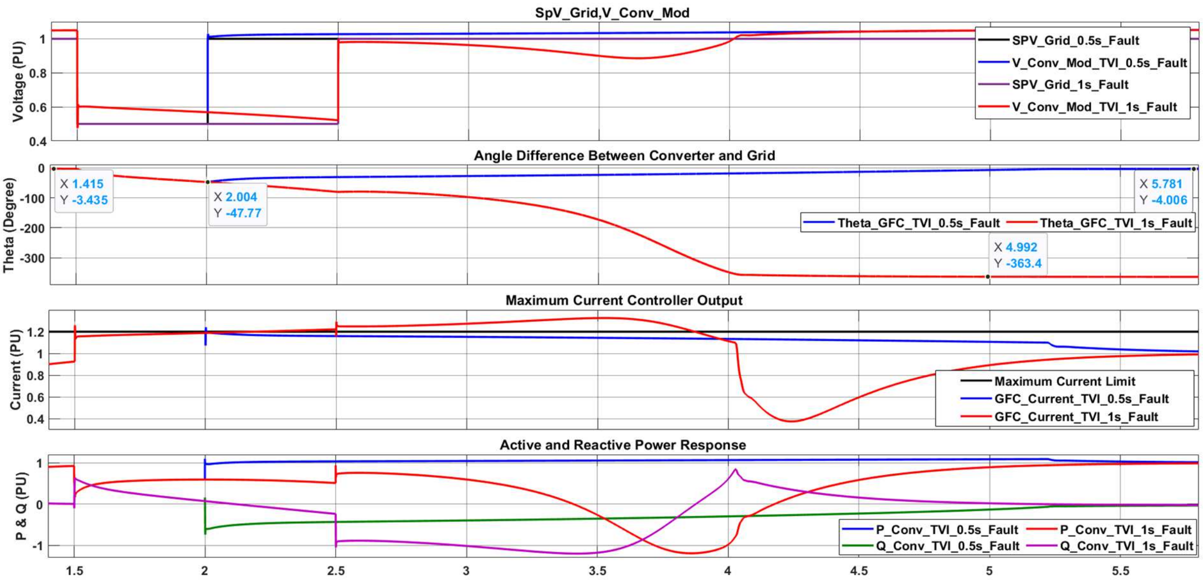

Fig. 2: Output of the Base Case GFC with VI for 500 ms and 1s Time Faults while GFC initially operating at P=1 & Q=0

Fig. 3: Output of the Base Case GFC with VI for 1s and 1.5s Time Faults while GFC initially operating at P=0.75 & Q=0

From Fig. 2 it can be observed that, for 1s fault where GFC is operating at its rated active power (P=1 & Q=0), the VI operation for current limitation doesn't work properly as the active power cannot be evacuated and the impossibility to evacuate the required active power makes the de-synchronization process for the GFC. The angle difference with the grid surpasses 90º and finds another stable point. Similar to this, in Fig. 3 with 1.5 seconds of fault the de-synchronization process and the failure of the VI in terms of maximum current limitation are observed. From Fig. 2 with 500 ms fault and from Fig. 3 with 1 second of fault, it can be observed that the VI operation for maximum current limitation works (as the stability limit is not reached) but the post fault synchronization after the fault is very slow.

From the performed analysis it can be concluded that the use of a virtual impedance for limiting the current fails to provide LVRT capability as the angle stability is not guaranteed. Besides that, the reactive power injection is not adequate either. After an initial surge of reactive power at the beginning, decreases to zero. If the fault is long enough it also can reach negative values.

Along with the pre fault operating point of active power and the severity of the fault, the time duration for post fault resynchronization and desynchronization of GFC also varies depending on this emulated inertia [19]. Within the performed analysis, both the resynchronization and desynchronization time after the fault is more than 1 second which is not desirable in many grid codes [11]. So, it can be concluded that, the Base case only with VI cannot provide the LVRT capability and the synchronization stability.

Comparative Simulation Results of LVRT Capability and Synchronization Stability

Now a comparative analysis has been performed with the VI_P_VIRT control and proposed VI_Adaptive_PSET control in terms of LVRT capability and synchronization stability where the simulations are performed with a voltage dip of 50% for 1 second with GFC operating in its rated power (P=1 PU, Q=0 PU). The simulation results are provided below.

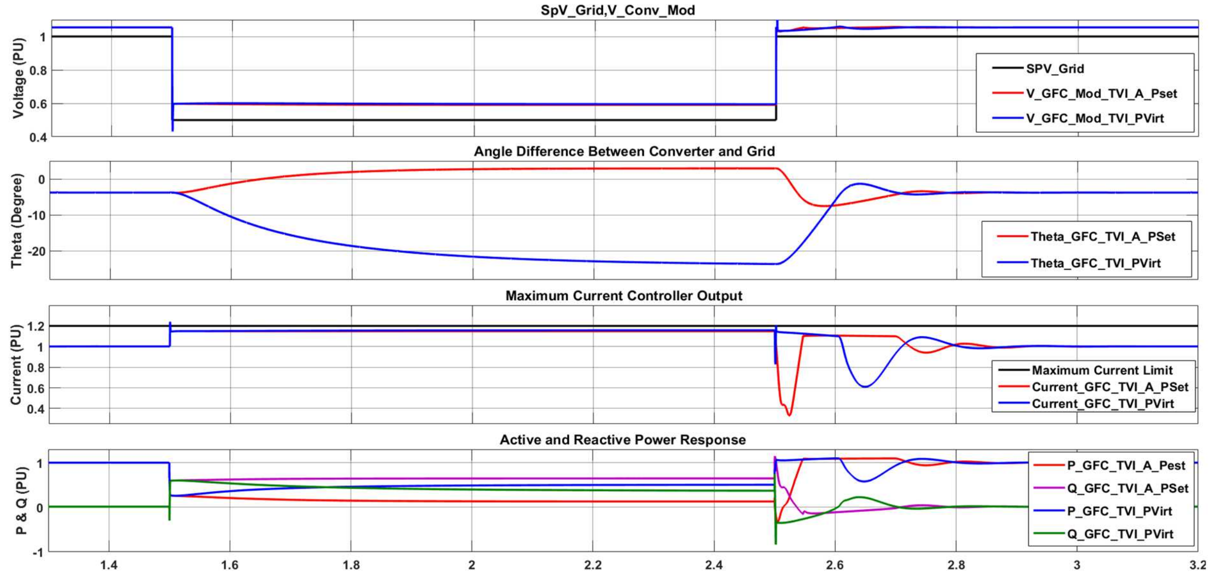

Fig. 4: Comparative results of the VI_P_Virt & VI_Adaptive_PSET for GFC (P=1, Q=0)

From the comparative results seen from Fig. 4 it can be concluded that the issue with the maximum current limitation and post fault synchronization seen with the base case (only the VI) is solved with both VI_P_VIRT and VI_Adaptive_PSET control. In terms of grid synchronization, the performance of the VI_Adaptive_PSET is better as it provides less angle difference between the GFC and the grid. Also, VI_Adaptive_PSET method provides more reactive power injection during faults. Therefore, with VI_Adaptive_PSET, both the LVRT capability and synchronization stability is achieved during the voltage dips.

Testing of the Proposed Solution with Different Level of Voltage Dips

It has been found that, the time GFC takes to return to its normal operation after the voltage dips is proportional to the severity of the event [23]. The dipper the voltage dip, the bigger will be the amount of curtailed active power. So, the depth of the fault is an important parameter that determines the stability. In order to validate this statement and to check the good performance of the proposed solution for all possible voltage depths, some simulations have been performed for a short period of time (140 ms) with different depth of voltage dips. The simulation results are provided below.

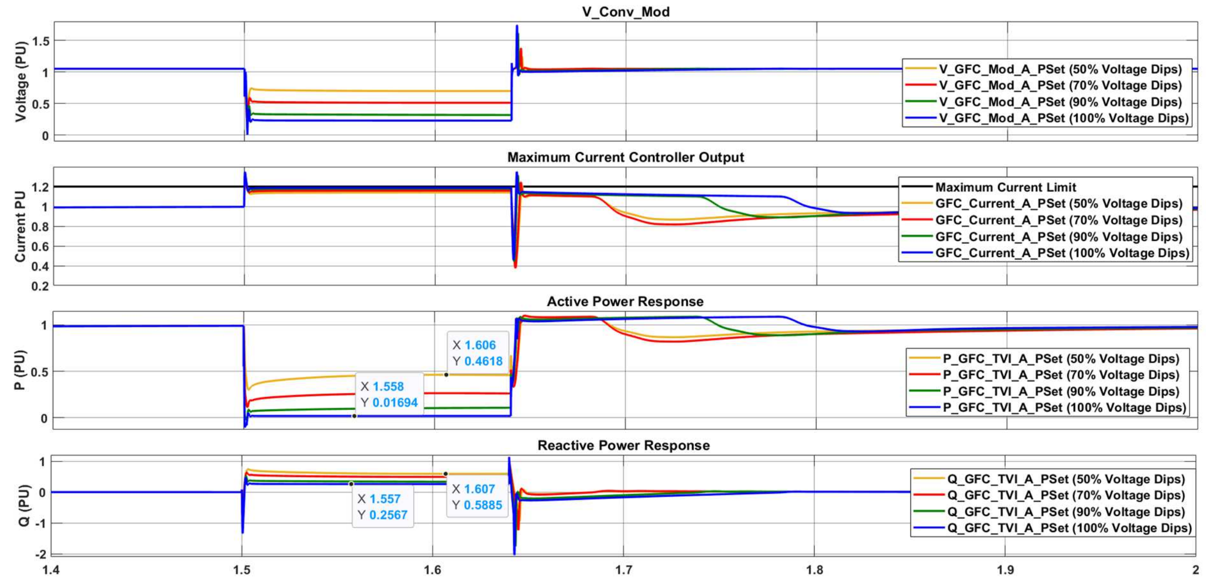

Fig. 5: Testing of the LVRT capability of GFM with VI_Adaptive_PSET control in different level of voltage dips for 140 ms (GFC initially operating at P=1, Q=0)

From Fig. 5, it can be observed that for all the voltage dips performed, the GFC quickly enters into the current limiting operation and in all cases the reactive power injection is significant, supporting the grid voltage. Although the transition from normal operation to the current limiting method is similar for all the voltage dip events, the transition from current limiting method to the normal operation at the end of voltage dip varies depending on the curtailment active power

Conclusion

The VI solves the current limiting problem, but the stability at some operation points was still an issue. For instance, when the active power cannot be evacuated, as analyzed in Fig. 2 & Fig. 3. To solve this issue many authors have provide new control methods. From all of them, one of the most promising from the authors point of view was the use of Virtual Active Power as feedback in the P-F Droop [10]. This control solved the stability issue, but as seen from the comparative results in Fig. 4, the voltage support during faults was still missing. From the performed comparative results in Fig. 4 & Fig. 5, the proposed Adaptive Active Power Set Point solution is proven to be effective for solving both issues, but not all the current limitation cases were considered. The effects with phase jump and rate of change of frequency (RoCoF) in high frequency change has not been examined for the current limitation in this article. This control method should be tested against those grid fault events also.

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