Abstract—The aim of this paper is to propose a protection strategy for the voltage generator based inverter against the large load currents. This strategy proposes an algorithm for generators output current limiting. It depends on decreasing the amplitude of the voltage reference in case of over current on generator output current. We aim to give the source a behavior similar to that of a voltage source in series with a virtual resistance. This resistance is activated only above a certain current threshold. Simulation results for the application of this strategy on resistive and resistive-inductive load will be demonstrated, in this paper. The effectiveness of the proposed current limiting method was tested on high load current resulting from the asynchronous motor start-up. The last part will discuss the implementation of this current limiting strategy on real time simulation environment RT-LAB. An experimentation using Power Hardware in the Loop and real-time simulation was realized to verify the theoretical analysis.

Index Terms-- Current limitation, Distributed generator, Micro-grid, Protection, Virtual resistance, Voltage source Inverter (VSI).

I. Introduction

The liberalization of electricity market and the significant and rapid growing of distributed generation sector due to the trend for a large integration of renewable energy in electrical power systems provide impetus to highly reliable good-quality electrical power generation. Generally, three-phase voltage inverters have been widely used in this new sector of power system. Therefore, the need of these inverters, has introduced the necessity of achieving a high power quality with low output distortion [1]-[2]. In power system with distributed energy, the low voltage distributed energy sources, such as gas micro turbine, photovoltaic system, wind turbines, storage devices, such as flywheel supercapacitor, batteries, and controllable load form an energy system structure named micro grid [3]. The distributed generators must be adapted to behave as a voltage source by using three-phase voltage inverter with at least an output LC filter [4]. One of the most important problems which happens continuously in distribution systems and micro grids and affects the voltages generators stability is the very high load current. So, in case of fault condition, the simultaneous disconnection of for the distributed generators leads to a reduction in power dispatch and increases the system instability. Therefore, it is necessary that the distributed generators based power electronic inverters are kept connected during the very high output current demand [5]-[6]. In [5], the authors propose an algorithm for protecting the micro-generators based inverter by the RL feed-forward and flux-charge-model feedback algorithms. Where, the authors in this last reference have introduced a series Voltage Source Inverter in order to mimic a large RL or L impedance for limiting the output current.

Recently, the virtual impedance has been widely applied in several researches. This was used in [7] to adjust the output impedance of the distributed units by adding virtual resistors or reactors [8].

The authors in [9]-[10] use the virtual impedance for power repartition between the inverter connected in parallel. In this paper, to prevent the flow of large output current and hence protect the generator, a specific strategy has been deduced to maintain the current in an acceptable level. This strategy, depending on the virtual resistance algorithm, consists in reducing magnitude of the voltage reference when detecting the output over current. This paper is divided into three sections; the first present the principle of the virtual resistance method. Validation of this method on resistive and inductive–resistive load was tested in simulation in the second part of this paper. Whereas the third part studies the application of the proposed algorithm on an experimental platform using power Hardware in the Loop and real time simulation.
II. GENERAL PRINCIPLE OF THE METHOD

Fig. 2 shows a block diagram of the structure of this strategy. The studied system is composed of a PWM converter voltage source generator with LC filter. Voltage and current control was already realized on [2]. The active power control and the primary frequency control were also already realized on [4].

The principle of this method based on decreasing the amplitude of the voltage reference in case of over current on generator output current. In order to limit the current, we aim to give our source a behavior similar to that of a voltage source in series with a virtual resistance. This resistance is activated only above a certain current threshold. We define a threshold value of effective current $I_{\text{lim}}$ below this value the virtual resistance is not activated. The source phase voltage $v_c$ applied to the load is fixed and equal to $v_{c0}$:

$$v_{c1\text{REF}}(t) = v_{c01\text{REF}}(t) = V_0 \sqrt{2} \sin(\alpha t)$$

$$v_{c2\text{REF}}(t) = v_{c02\text{REF}}(t) = V_0 \sqrt{2} \sin(\alpha t - \frac{2\pi}{3}) \tag{1}$$

$$v_{c3\text{REF}}(t) = v_{c03\text{REF}}(t) = V_0 \sqrt{2} \sin(\alpha t - \frac{4\pi}{3})$$

When power exceeds the limit, we insert Virtual resistance. In these conditions, the reference voltage applied to the LC filter during the current limit is calculated as follows:

$$V_{\text{CREF}} = V_{c0\text{REF}} - R_{\text{virt}}(I - I_{\text{lim}}) \tag{2}$$

Thus, we can represent the voltage source based converter circuit, taking into account the virtual resistance; with virtual scheme (see Fig. 2).

In practice, the calculation of the voltage reference will be made in Park reference frame. We define the quadratic current component $I_d, I_q$.

$$\vec{I} = I_d + jI_q \quad ; \quad I^2 = I_d^2 + I_q^2$$

With: $V_{\text{CREF}}$: Ideal voltage source of value $V_0$ rms.

$I_{\text{lim}}$: Current $I_{\text{lim}}$ with the same phase as the current $\vec{I}$

This complex equation can be represented by a vector diagram.

When power exceeds the limit, we insert Virtual resistance. In these conditions, the reference voltage applied to the LC filter during the current limit is calculated as follows:

$$V_{\text{CREF}} = V_{c0\text{REF}} - R_{\text{virt}}(I - I_{\text{lim}}) \tag{2}$$

Thus, we can represent the voltage source based converter circuit, taking into account the virtual resistance; with virtual scheme (see Fig. 2).
From (3), we can deduce the relationship describing the reference voltage value to be applied during the current limitation based on current:

\[ V_{\text{REF},q} + R_{\text{virt}} (I_q - I_{\text{limq}}) = \pm \sqrt{(V_{\text{COREF}})^2 - (R_{\text{virt}} (I_d - I_{\text{limd}}))^2} \]

\[ V_{\text{REF},q} = \pm \sqrt{(V_{\text{COREF}})^2 - (R_{\text{virt}} (I_d - I_{\text{limd}}))^2} - R_{\text{virt}} (I_q - I_{\text{limq}}) \] (4)

The two components of current limit are calculated according to the rms value of the total.

\[ I_{\text{limd}} = \frac{I_d}{\sqrt{I_d^2 + I_q^2}} \times I_{\text{limit}} \]

\[ I_{\text{limq}} = \frac{I_q}{\sqrt{I_d^2 + I_q^2}} \times I_{\text{limit}} \] (5)

From (4), we can then calculate the \( \text{rms} \) value of \( V_{\text{COREF}} \) by components of axis and \( q \) axis current. We can consider three cases of load, resistive, inductive and capacitive.

(a) : Current in quadrature (lag) with \( v_c \)

(b) : Current in quadrature (lead) with \( v_c \)

(c) Current in phase with \( v_c \)

Fig. 4 Vectors of voltages in case of three loads: purely inductive, purely capacitive and purely resistive

It has been assumed that a theoretical short-circuit current can be the maximum current that the source provide by issuing a zero voltage. In practice, this current will never be reached but it will be used to size the virtual resistance. We choose the virtual resistance so that the short-circuit current is equal to two times the limit current:

\[ I_{cc} = 2 \times I_{\text{limit}} \]

\[ R_{\text{virt}} = \frac{V_{\text{COREF}}}{\Delta I} \]

\[ \Delta I = I_{cc} - I_{\text{limit}} \] (6)

A. Validation on resistive-inductive load

The current limit is also composed of two components. From (4) we can deduce the relationship describing the value of the reference voltage to be applied during the current limitation based on current:

\[ V_{\text{REF},q} = \pm \sqrt{(V_{\text{COREF}})^2 - (R_{\text{virt}} (I_d - I_{\text{limd}}))^2} - R_{\text{virt}} (I_q - I_{\text{limq}}) \]

Where \( I_{\text{limit}} = I_n \), considering that the strategy applies when the current reaches its nominal value.

The current limitation strategy was integrated into the control system of converter in order to obtaining a voltage source capable of facing the problem of over current resulting from over loading. We choose for this application a voltage source based on power converter (15 KVA) corresponding output voltage \( V=231V \) and current rating \( I_{\text{eff},n} = 21.6A \), the load has a resistance \( R_{\text{virt}} = 4\Omega \).

From (6),

\[ R_{\text{virt}} = \frac{V_{\text{COREF}}}{I_{n,q}} = \frac{\sqrt{3 \times 231}}{\sqrt{3 \times 21.6}} = 10.67 \Omega \]

Equation (4) has been implemented to achieve the limitation of the current taking into account the two components of the direct and quadratic current. The values of resistance and inductance of the load are given as follows:

\[ L = 10\text{mH}; R = 4\Omega \]

Then the output calculated current is:

\[ I = \frac{V_{\text{COREF}} + R_{\text{virt}} I_{\text{limit}}}{\sqrt{(R + R_{\text{virt}})^2 + (\omega L)^2}} \]

\[ I = \frac{231 + 10.67 \times 21.6}{\sqrt{(4 + 10.67)^2 + (2 \times \pi \times 50 \times 10^{-3})^2}} = 30.75A \]

In Fig. 5, the current \( \text{rms} \) value is about 30A that is equal to the same calculated value. We notice, in Fig. 6, that the voltage decreases because of the voltage drop on the virtual resistance.

Fig. 5 The \text{rms} value of load current

Fig. 6 LC filter output voltage
III. REALIZATION AND EXPERIMENTAL STUDY

A. Power Hardware In the Loop (PHIL) simulation

An experimental setup based on a real-time simulator is developed to validate the theoretical dynamic study of the whole system. We use a Power Hardware In the Loop (PHIL) simulation technique to validate the current limiting strategy. HIL is commonly used to test actual control system in interaction with real-time simulation [1]. In case of PHIL, a power device is tested so it needs the use of a high band-with power amplifier between the real-time simulator and the device itself (See Fig. 7). This power amplifier generates a three phase voltage source which magnitudes are delivered by the simulator. The sensors placed on the device under test are giving some data (current, voltage) which are introduced in the simulator thanks to Analog Digital Converter.

B. Experimental facility

The structure under study (Fig. 10) is composed of two main parts: The first one is the virtual environment implemented, in RT-LAB real time simulator [12]-[14]. It contains the model of solid-state inverter with LC filter controlled by the proposed explained strategy. The second part is the actual system which represents the physical elements of the studied power system. A 15 kW power amplifier (10 kHz Bandwidth) is used to connect the simulated network to the actual one.

C. Experimental results and discussion

To validate the effectiveness of the current limiting strategy of the converter, it has been integrated into the voltage generator control system and then implemented on Real Time Simulator RT-LAB. In a second step, the voltage generator has been connected with a load represented by an asynchronous motor via a power amplifier. In fact, the asynchronous motors require a large start-up current equal to 6-7 times to the rated current. It is then required, from a protection point of view for power electronic equipment, to limit this current. In fact, the start-up phase of the induction motor can show the moment of validation phase current limiting and invalidate it at the end of the startup phase. The studied system parameters were presented on TABLE 1

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>STUDIED SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC filter resistance (Rs)</td>
<td>0.1 ohm</td>
</tr>
<tr>
<td>LC filter inductance (Ls)</td>
<td>1 mH</td>
</tr>
<tr>
<td>LC filter capacity C</td>
<td>20 µF</td>
</tr>
<tr>
<td>Operation voltage magnitude</td>
<td>400 V ph-ph</td>
</tr>
<tr>
<td>DC bus voltage</td>
<td>760 V</td>
</tr>
<tr>
<td>Asynchronous motor real power</td>
<td>3 kW</td>
</tr>
<tr>
<td>Asynchronous motor rated current</td>
<td>10.9 A</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Active load</td>
<td>0.5kW</td>
</tr>
<tr>
<td>Inverter rating power</td>
<td>5.5 KVA</td>
</tr>
</tbody>
</table>

In Fig. 10, we present here the required procedure to startup the induction motor and connecting the amplifier to the machine. The strategy for current limiting was realized on Matlab Simulink and has been inserted into the real time simulation environment of RT-LAB; Fig. 10 shows the monitoring system to achieve the requested connection. We set current limit and virtual resistance to thresholds values in order test the strategy. We choose a power converter of 5.5 KVA, corresponds to a rated current $I_{\text{limit}} = 8.4$. The virtual...
resistance is then calculated $R_{\text{virt}} = 28.8 \Omega$. The results shown in the next figures are similar to those in the first test, noting that the startup current in this test is limited to a peak value $I_{\text{peak}} = 21$ A that corresponds to $I_{\text{eff}} = 14.8$ A.

At $t=6.5$s the asynchronous motor was connected to the PWM voltage source inverter. We notice in Fig. 13 that after the over current detection, the output voltage decreases by a value corresponds to the voltage droop on the virtual resistance (cf. Fig. 9).

In consequence to the voltage magnitude reduction, the output and filter current was limited to a calculated peak value $21$ A (cf. Fig. 9, Fig. 10). Which correspond to $I_{\text{eff}} = 14.8$ A, we notice here that the current was limited to a value less than $2 \times I_{\text{limit}}$ ($2 \times I_{\text{limit}} = 2 \times 8 = 16$ A).

Fig. 12 presents that estimating load frequency always rests in its acceptable value thanks to the voltage control system in an islanded operation mode [4].

**IV. CONCLUSION**

In this paper, a current limiting algorithm for the PWM voltage source inverters was proposed. A strategy based on the virtual resistance used in this paper for this purpose. Validation on resistive and resistive-inductive loads was realized on simulation study. The experimental results prove the effectiveness of the strategy. For the future work, a test of this method will be realized when connecting the PWM voltage source inverter with another classical voltage source.

**V. REFERENCES**


