Abstract: This article investigates how power electronic interfaces for loads provide reactive power in case of abnormal voltage conditions. An evaluation of voltage support is done for different values of voltage sags when the power electronic interface provides with reactive current. The stability margins of the distributed system are investigated for different types of loads and it is proved that the higher the share of controlled constant power loads in the system the higher the critical clearing time of the voltage. The incremental current rating of the converter when providing additional reactive current is investigated. Comparison is made between a centralized STATCOM and distributed reactive current compensation implemented in the form of controlled constant power loads, it is observed that it is always advantageous to use distributed compensation because the amount of reactive current injected is lower for achieving the same stability margins of the system.

Keywords: Distributed Energy Systems, Constant Power Loads, Voltage Source Converters, STATCOM

I. INTRODUCTION

Unlike the large traditional electric power system, the distributed energy system is a small or medium scale power generation system. Being close to the load centre this scheme has the advantage of having small transmission distances and transmission voltages and therefore low transmission losses [1]. An increasing practice these days is to connect loads and sources to the three phase AC system through the power electronic interfaces. Different ways of handling these interfaces greatly affect the operation and compensation of these power systems. By allowing injection of reactive current by power electronic interface would give the possibility to support the system voltage [2]. Operating margins of the electric grid stability, reliability and efficiency can be substantially improved [1]-[2]. Among electric loads, Constant Power Loads (CPLs) interfaced to the grid by active rectifiers, are one of the most destabilizing types of loads under abnormal voltage conditions [1]-[5]. CPL is a load which draws a constant amount of active power irrespective of any drop in the system voltage. The behaviour of CPL during different levels of fault is simulated in PSCAD/EMTDC software package. A drop in the voltage results in an increase in the active component of current and vice versa, leading to negative incremental resistance. This phenomenon is discussed in this paper and the results show that the injection of the reactive current by the controller could be an effective remedy for this. Simulation results presented in the paper show how the voltage stability margins can be greatly improved with different shares of controlled constant power loads. Distributed reactive current compensation has been investigated and is proved to be more advantageous compared to the centralized compensation by a STATCOM.

II. SIMULATION MODEL

The schematic representation of the investigated system is shown in Fig.1, it represents a real distributed generation connected to the grid and three constant power loads connected along the line. The line is connected to the main grid through the inductance Lg, and there is an inductance L corresponding to the line between the three different loads. The constant power load is a tightly regulated Voltage Source converter (VSC) absorbing constant power and is able to inject reactive power into the network and thereby providing ancillary service to the grid. DC side is supposed to behave as a constant DC power source. Fig. 2 shows the CPL from converter filter to DC-link and load. The voltage source
converter consists of IGBT switches with anti-parallel diodes that will conduct reverse current. Switching of IGBT is done by a pulse width modulation (PWM) technique at a frequency of 5 [kHz]. The load is modelled as a dependent current source that use a manually specified value of power divided by measured dc voltage [6]. Vector control technique is used for the regulation of AC/DC converter. In this way an independent control of active and reactive component of the current can be achieved. If we are able to control the DC link voltage to a constant value the active input voltage to the controller can be kept as constant [3]. This is achieved by the implementation of a DC link controller in the control strategy. The controlled DC voltage produced by these PWM rectifiers is much higher than that produced by the diode rectifiers[7],[8]. PWM converters have the inherent capability to compensate for the voltage drop by injecting reactive component of the current [9]. For a CPL to behave as an active front end converter and to be able to inject an additional reactive component of the current, an AC voltage controller is also implemented. It works in a way that it injects the reactive power into the network under abnormal voltage conditions and becomes inactive at the end of the fault. The next section will illustrate the negative input resistance exhibited by the load in this simulation model.

III. IMPACT OF CONSTANT POWER LOAD ON VOLTAGE

Negative resistance or negative differential resistance (NDR) is a characteristic of electrical circuit element during which at a specific range of voltage the current decreases as a function of voltage [5]. For a CPL an increase in voltage will result in a decrease of the active component of the current and a decrease in voltage will result in an increased active component of current. The input resistance $R_{cpl}$ is defined by the ratio of small-signal changes in input voltage over the small-signal input current:

$$R_{cpl} = \frac{\Delta V}{\Delta I}$$

and this value will depend on the converter operating point. The negative input resistance can be calculated by considering that the input power and output power of a CPL are equal, that is;

$$P_{in} = P_{o} = v \cdot i \text{ and } v = \frac{P}{i}.$$
a reduction of 1.2% and 2.2% in the active component of current can be seen which is because of a slight improvement in the voltage thereby keeping the power of the CPL constant. The curves in Fig. 7 and Fig. 8 demonstrate the negative resistance characteristics of the CPL for all the studied cases confirming the inverse relation between voltage and current. However, there is a small improvement in the negative resistance curve when more reactive current is injected which is vital for the improvement of the stability margins of the system as it will be explained in subsequent sections.

IV. IMPACT OF REACTIVE CURRENT INJECTION ON STABILITY MARGINS

To understand the effects of controlled CPLs on the stability margins of the system, simulation model presented in Fig. 1 is considered. The load is modelled as a dependent current source that uses a manually specified value of power divided by measured DC voltage [6]. A DC link voltage controller is implemented to keep the DC voltage constant thereby ensuring a constant power being fed into the load. An AC voltage controller is implemented in the control design to inject the reactive power into the network. Three cases with different load conditions are investigated and the effect of controlled CPL is observed on the stability limits of the system.

Case 1: 80% CPL

Two CPL models are used, with each CPL taking 40% of the power generated by the induction generator. A three-phase line to ground fault is simulated at point A. Fault resistance is varied to get a voltage drop equal to 20% of the nominal voltage. Several simulations are carried under this condition to obtain the critical clearing time (CCT) which is the maximum time before the system becomes unstable due to voltage collapse. In the first simulation, AC voltage controller is kept inactive and CCT is measured. Fig. 9a shows the simulation result. In the second simulation, AC voltage controller is kept active, only during the fault and 0.2 pu reactive current is allowed to be dispatched into the network to compensate for the voltage drop. Fig. 9b presents the simulation result. A considerable difference in the CCT can be observed. When the AC voltage controller is active, the CCT is 1.18 seconds compared to the previous case with CCT 645 ms when no reactive current compensation is allowed.

<table>
<thead>
<tr>
<th>Case</th>
<th>Regulation</th>
<th>CCT</th>
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<tbody>
<tr>
<td>Case 1: 80% CPL</td>
<td>P constant only</td>
<td>645 ms</td>
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<tr>
<td>80% CPL</td>
<td>P constant and Iq</td>
<td>1.18 s</td>
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<tr>
<td>Case 2: 40% CPL, 40% induction motor</td>
<td>P constant only</td>
<td>468 ms</td>
</tr>
<tr>
<td>40% CPL, 40% induction motor</td>
<td>P constant and Iq</td>
<td>660 ms</td>
</tr>
<tr>
<td>Case 3: 20% CPL, 60% induction motor</td>
<td>P constant only</td>
<td>340 ms</td>
</tr>
<tr>
<td>20% CPL, 60% induction motor</td>
<td>P constant and Iq</td>
<td>480 ms</td>
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Case 2: 40% CPL and 40% Induction motor

Stability of the system is investigated when the amount of load controlled by converters (CPLs) and that of uncontrolled one is equal. Two CPL are taking 40% of the total power generated by the induction generator and the third CPL is replaced with an induction motor also taking 40%
of the induction generator power A three phase line to ground fault is simulated to obtain a voltage drop equal to 20% of the nominal voltage and critical clearing time (CCT) is observed. In the first simulation AC voltage controller is kept inactive and the CCT is measured. Fig. 10a shows the simulation result. In the second simulation AC voltage controller is set active only during the fault and 0.2 pu reactive current is allowed to be dispatched into the network to compensate for the voltage drop by both the CPLs. Fig. 10b presents the simulation result. Again a big increase in the CCT is observed for the case when controlled CPLs are used.

Case 3: 20% CPL and 60% Induction motor

In this case the amount of load controlled by converters (CPLs) is less and that of uncontrolled one is high. Two CPLs are taking 20% of the power generated by the induction generator and the third CPL is replaced with an induction motor taking 60% of the power generated. In the first simulation AC voltage controller is kept inactive and the CCT is measured. Fig.11a shows the simulation result. In the second simulation AC voltage controller is kept active during the fault and 0.2 pu reactive current is injected by both the CPLs. Fig.11b presents the simulation result. A big improvement in the stability margins is obtained for the later case. Fig.11c shows the induction generator completely losing control of its torque when the system becomes unstable.

The results from all the studied cases are presented in table 1 and signify the role of controlled CPL in improving the stability margins of the system. The best case is when the share of controlled CPLs is higher and the worst case is when the induction motor load is higher and the share of uncontrolled CPLs is lower. Therefore, the more the amount of load being controlled by CPLs the higher the stability limits of the system. However this improvement in the stability margins of the system comes at a cost of an increased current rating of the converter.

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**Table 1:**

<table>
<thead>
<tr>
<th>Case Description</th>
<th>CCT Improvement</th>
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<tbody>
<tr>
<td>Case 1: 60% CPL and 40% induction motor without reactive current compensation</td>
<td></td>
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<tr>
<td>Case 2: 40% CPL and 60% induction motor with reactive current compensation</td>
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</tr>
<tr>
<td>Case 3: 20% CPL and 60% induction motor with reactive current compensation</td>
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V. INCREASE IN THE CURRENT RATING OF THE CONVERTER FOR PROVIDING REACTIVE CURRENT TO THE GRID

For investigation of the increased current rating of the CPL, two CPL model is considered, each taking 25% of the total induction generator power. Several simulations are carried out for taking different levels of voltage drop. During the fault the voltage cannot be kept constant and CPL injects maximum amount of reactive current to make the system stable. Fig. 12 presents the simulation results. If there is no additional injection of reactive current, the total current rating required by the converter are represented by only the active component of current $I_t^*$. When there is injection of reactive current by the converter the additional rating required is represented by the difference between $I_t^*$ when there is no injection of reactive current and the total current $I_t$ in case of injection of reactive current. The total current $I_t$ represents the quadratic sum of active and reactive components of current. For all levels of voltage drops the value of $I_t^*$ is higher than the value of only active component of current $I_d$ when converter injects the reactive current. This is because of the slight improvement in the voltage on the converter terminal as a result of reactive compensation, keeping the power drawn by the CPL constant. This improvement in the voltage is prominent as the same values of the fault resistances were used for both the cases. It can also be seen that the deeper the voltage drop the higher the amount of reactive current injected to keep the system stable. However this increase in reactive current is not proportional to the decrease in the active component of the current. Therefore the required extra current rating of the converter are higher when drop in the voltage is deeper. Upto 60% of voltage drop this increase in the current rating is only 0.07 pu, which could be considered as an acceptable rise. This to a large extent also depends upon the control strategy implemented. However this rise in the current ratings of the converter could be compensated by an increase in the number of CPL producing reactive current connected to the line. Then a small amount of injected reactive current would be quite sufficient to achieve the same stability limits as would have achieved by lower number of CPLs injecting higher amount of current. In the next section simulations are carried out to compare the total reactive current injected by a centralized STATCOM with the case when the system is loaded with distributed CPLs with reactive current control.

VI. DISTRIBUTED INJECTION Vs CENTRALIZED COMPENSATION

In this section an investigation is done in order to know whether it is advantageous to implement distributed compensation by CPLs compared to a centralized STATCOM. For this, different simulations are performed for different values of fault durations and the fault resistance is decreased up to a value beyond which the system is no more stable. Therefore, a comparison between the system with the STATCOM placed at the terminal of the transformer and two non-controlled CPLs is made with the case of two or three CPLs with reactive current control without a centralized STATCOM. The total power taken by the load in all these cases is kept to 50% of the induction generator power. Fig. 13 shows the results of these simulations. It is quite evident that the total reactive current injected by the centralized STATCOM is higher for all the fault durations simulated than the sum of reactive current injected by the CPLs. In fact the sum of reactive current injected in the case of three CPLs is even lower than the sum of reactive current by the two CPLs for all the fault durations to keep the system stable. For a fault duration of 100 ms, total amount of reactive current injected by one CPL belonging to a group of three distributed CPLs is almost four times lower than the total amount of reactive current injected by the centralized STATCOM. Therefore, it
can be concluded that the higher the number of controlled CPL, the lower the total amount of current rating of the installed converters. Also implementation of two CPLs looks to be more efficient and optimal instead of a single centralized STATCOM with higher current rating. This lower current capacity can however be at the expense of an increase in the cost of the installed equipment.

VII. CONCLUSIONS

Efficient use of constant power loads interfaced through power electronic converters is demonstrated. Simulations are done in PSCAD/EMTDC software to verify the typical negative resistance behaviour associated with constant power loads and it is shown how this destabilizing effect can be reduced by the injection of reactive current and by reduction of the active component of current when the voltage is slightly improved by injecting reactive current. The stability limits of the system has been investigated under different load conditions and critical clearing time of the voltage is measured. It is demonstrated that the stability margins of the systems are higher for a case when there is an injection of reactive component of current by the CPL than the case when there is no reactive compensation. The higher the number of controlled CPL acting as a load the higher the critical clearing time of the system. The incremental current rating of the converter is studied and it is concluded that the deeper the drop in the voltage the higher the current rating required for the converter to keep the system stable. Finally, a comparison is performed between the total reactive current capacity of a centralized STATCOM and distributed compensation by the CPLs. The comparison proves advantages to the distributed reactive current compensation by the CPLs connected through power electronic converters rather than one centralized compensating device.

REFERENCES