Investigation on the Role of Power Electronic Controlled Constant Power Loads for Voltage Support in Distributed AC systems


* Norwegian University of Science and Technology/Department of Electrical Power Engineering, Trondheim, Norway
** Politecnico di Milano/Dipartimento di Elettrotecnica, Milan, Italy

Abstract—distributed AC power systems with large percentage of constant power loads (CPL) are susceptible to potential voltage stability problems under abnormal operating conditions. The design of the control system of the CPL can greatly influence the power system stability. Regulated converters with high bandwidth control systems can act as CPLs, exhibiting a negative incremental resistance in a wide frequency range. This article first investigates the effect that a large share of CPLs will have on the voltage stability of distributed AC systems during voltage dips. The influence of introducing reactive current control by active rectifiers on the CPL instability, and the resulting contribution to the overall voltage stability is investigated and evaluated. Results of time domain simulations show how the design and tuning of the converter control structure greatly affects the stability of the system. The critical clearing time of the system is selected as a measure of the transient stability limit for investigating and comparing the cases of CPLs with and without reactive current control. The increased transient stability limit observed is enabled by reactive current control capability of the power converter with minor modifications on the control strategy. Centralized reactive compensation by a STATCOM is used as reference to compare with distributed compensation by the CPLs. Results shows that required distributed injection of reactive current is lower compared to the rating of a centralized STATCOM.

I. INTRODUCTION

Today, more than 40% of the electrical energy is controlled by some form of power electronic system. By the year 2015 it is expected that this share will increase up to 80% [1]. This is mainly because of the developed functionality of power electronics systems to convert, control and condition electric power according to the needs of the different loads and for the purpose of energy savings and efficiency improvements. Converter systems for grid integration of uncontrollable renewable energy sources have also been a topic of fast development during the last decade. In the same way, the operation of power systems is being influenced by the development of high power semiconductors and the introduction of FACTS devices [2]. On this basis power electronics is rapidly becoming the enabling technology to efficiently use, distribute and generate electrical energy.

For the design and control of converter units, the main focus have traditionally been on the loads as individual components of the power system and less on the converter as an active component of the system that can greatly affect overall system performance and stability. For power system studies considering applications of power electronics systems, the focus has been on power flow control, control of voltage by reactive power compensation and the design of damping controllers and power system stabilizers for suppressing oscillatory modes of the system. Still, the role of power electronics in the use of electrical energy has not been extensively investigated with a systematic approach in distributed AC systems from the system stability point of view.

The stability of regulated loads, compared to traditional passive loads, has for long time been investigated in DC distribution systems. The negative incremental resistance instability of CPLs can cause voltage collapse or system oscillations by small signal stability problems [3]-[5]. For distributed DC systems, several criteria have been investigated to ensure stability in systems with large share of CPLs [9]-[13]. Comparable stability criteria have not yet become common subject of research for distributed AC systems with high share of CPLs [16]. Some of the earliest documented cases of instabilities caused by the negative incremental resistance in AC systems are the 400 Hz aircraft electric systems, spacecraft systems, and electric ships [6]-[8]. As reported in [14]-[16], such loads have negative incremental resistance characteristics and can cause negative resistance instability in a wide frequency range.

This paper investigates the role of the CPLs and their control systems in the stability of AC systems with large share of CPLs. A typical distributed AC system with CPLs and other types of loads is modeled in Matlab Simulink to investigate and compare the behavior during abnormal operating conditions. Observing that the increase of CPLs in the AC system has a detrimental effect on the voltage stability, this paper investigates the effect of introducing reactive current control by the CPLs. Fast reactive power compensation will increase the power transfer capability of the power system and can in this sense help increase the robustness and the stability margins of the power system. This will increase the capability to tolerate higher shares of constant power loads in the system during steady state operation and transient conditions. The additional functionality of reactive current control by the loads is investigated on the assumption that all CPLs in the system are based on Voltage Source
Converters (VSC) with force-commutated semiconductors and pulse width modulation techniques [17]. The influence of the reactive current compensation on the negative resistance instability is assessed by observing the effect on the critical clearing time (CCT) of the system in case of voltage drops.

Simulation results on the system presented in the paper indicates how the transient stability limit can be increased by incrementing the current rating of the semiconductor devices and allowing for injection of reactive current in a distributed manner by each CPL during voltage dips. A comparison between the distributed compensation of reactive power and the centralized reactive compensation by a STATCOM is presented. The results obtained indicate that a lower per unit current rating is needed with distributed compensation by CPLs compared to the centralized STATCOM. The extra functionality of reactive current injection by the loads will be achieved by modifying the internal control strategy of the converter driving the CPL, and the required increase of current rating will depend on grid parameters.

II. NEGATIVE INCREMENTAL RESISTANCE PHENOMENA

Generally constant power loads in an AC system are connected to the grid by a controlled or uncontrolled rectifier. For a constant power load defined at the converter terminals, an increased voltage will result in a reduced active current component and a reduced voltage in an increased active current component.

Fig. 3 a) shows an induction motor load driven by an AC/DC/AC converter based on controllable switches and Fig. 3 b) shows how this load is modeled in the simulation study by an AC/DC power electronic converter based on controllable switches driving the induction motor that behaves as CPL. It is assumed that the DC side behaves as DC constant power load. The variable resistance in the DC link is used to modulate the power level of the load for the different operating points investigated.

The regulation of the AC/DC converters is done implementing the standard voltage vector oriented control [19]. By controlling the DC link voltage to a constant value, the active power input to the converter is kept constant. This is carried out in the system model shown in Fig. 2 which was implemented in Matlab/Simulink.

Since the input active power to the converter is constant in a wide range of operating conditions, provided that the controller works properly, the v-f characteristics of the CPL is investigated by first considering the incremental input resistance \( R_i \). This value is given by the ratio of small signal changes in input voltage over small signal input current:

\[
R_i \approx \frac{\Delta V}{\Delta I} \tag{1}
\]

The value of the incremental input resistance will depend on the converter operating point. The negative input resistance can be calculated assuming that the input and output power of the constant power load are equal, that is \( P_{in} = P_{out} = v \cdot i \) and \( v = P/i \). Differentiating the voltage with respect to the current gives

\[
\frac{dv}{di} = -i^2 \frac{P}{i} = -\frac{v^2}{P} = -R_i \tag{2}
\]

Equation (1), (2) shows the general expression to calculate the small-signal input resistance of a constant power load. The AC constant power load considering small signal variations behaves as a negative resistance. This resistance is also non linear depending upon the current and voltage for the given operating point [16].

For the case under investigation the concept of negative incremental resistance is verified by a simulation study on the model presented in this paper. On the system model of Fig. 2, the input current to the converter is measured for different levels of voltage dips at the terminal of one of the AC/DC converters driving the CPL. The CPL current is expressed in pu based on the CPL rating (25% of the generator rating).

The result can be observed in the plot of Fig. 4 showing the typical negative incremental resistance characteristics.
of CPLs. Due to this, the resistance is known as negative input resistance, where any increment in input voltage will cause a decrease in input current and vice-versa.

Having verified the negative incremental resistance phenomena, in the next section simulations are carried out to investigate the voltage transient stability limit when the system is only loaded with CPLs and when the system is loaded with a combination of different type of loads. The cases of low, medium and high share of CPLs in the system loading are investigated.

III. DISTRIBUTED AC SYSTEM WITH CONSTANT POWER LOAD (CPL)

Fig. 1 shows a distributed AC system connected to a stronger main grid. The system is composed by a distributed generation and several loads connected along the line. This simplified configuration is chosen to study the effect of constant power loads (CPL) in the system when the line voltage drops. Since the purpose is to understand the influence of CPLs in the stability limits of the system, this simplified configuration provides a good platform for a conceptual understanding before going into more extensive studies in larger systems. The investigation is done on the assumption that some of the loads that are fed from the source will be tightly regulated power electronic converters that behave as CPLs. To implement the extra functionality of reactive current control, it is assumed in this paper that the CPLs are loads controlled by active front-end converters. The case of CPLs with controllable grid side converter and the extra functionality of reactive current control is compared to the case of CPLs without reactive current control (unity power factor). It should be noted that compared to loads that are interfaced to the grid by diode or thyristor rectifiers, the advantage of controllable grid side converters with reactive current control will be more obvious.

A. Simulation model of the distributed AC system

In the power system configuration shown in Fig. 2 the asynchronous generator represents a wind turbine feeding power to a line with 3 CPLs. The line is connected to the main grid by the inductance \( L_g \) and there is an inductance corresponding to 3 km of transmission line between the different loads.

To investigate the transient behavior of the system voltage with CPLs and observe the stability limits, a three-phase line to ground fault is simulated at point A. The model can also consider induction motor load directly connected to the line, accounting for part of the total load. The CPLs are modeled as shown in Fig. 3 and controlled in the way schematically represented in the same figure so as to keep the input power to the load constant. In the simulation model, the load is represented by an AC/DC converter in which the power in the DC link represents the power being fed into the load. A more realistic representation of the load as a motor drive system is shown on Fig. 3 a). Each CPL is modeled to take 25% of the wind turbine power rating.

The reactive current control introduced is based on standard control techniques that are known from implementation in dedicated converter systems for reactive power control such as the STATCOM [18],[19] and for reactive power by the power electronic converters of wind turbines and other distributed generators [20],[21].

B. Voltage Transient Behavior and CCT

To investigate the effect of the CPLs in the transient behavior of the system voltage, a three-phase to ground fault is simulated to obtain a voltage drop equal to 20% of the nominal voltage. Simulations are carried under this condition to obtain the critical clearing time (CCT); that is the maximum time before the system becomes unstable due to voltage collapse. Fig. 5 a) and b) shows simulation results of two cases of CPL in the system; 80% share of CPLs with and without control of reactive current. The influence of the control of reactive current by the CPLs can be seen by the difference in CCTs between the two cases. Table 1 summarizes critical clearing times (CCTs) obtained for the system in Fig. 2 for several shares of CPLs with reactive current control, and for 80% share without reactive current control. The results show that the worst situation corresponds to Case 1 with 80% share and no reactive current control. The best situation is Case 4 with the same amount of CPLs with reactive current control [22]. The system shows to be more stable if a higher amount of the load is controlled by the use of CPLs. This is because of the extra functionality of reactive current control to support the system voltage. This extra functionality can however be at the expense of an increment in the required current rating of the semiconductor devices in the AC/DC converter that regulates the CPLs.

C. Required incremental current rating of the CPL for providing additional reactive current support

Fig. 6 shows simulation results of the converter current components for several levels of voltage dips. In this figure, \( I_d \) represent the active current component, \( I_q \) the reactive current component and \( I_t \) the total current drawn by the CPL. The incremental current magnitude \( \Delta I \) is defined as the difference between the total current \( I_t \) including the \( I_d \) component and the active current \( I_d \) for the case of no reactive compensation.

For each voltage drop level a different value of \( \Delta I \) is found considering that two CPLs draw 50% of the generated power. During the fault, the voltage cannot be
kept at the initial value but the converter is injecting the maximum amount of reactive current. The results observed in Fig. 6 indicate that the deeper the fault the higher the required $I_q$ to maintain the system stable.

The different current components of Fig. 6 are defined by equation (3), and the relation between them is graphically illustrated in the vector diagram of Fig. 7, referred to the synchronously rotating $dq$-reference frame that is oriented after the grid voltage vector at the converter input filter.

$$I_t = \sqrt{I_d^2 + I_q^2}$$  \hspace{1cm} (3)

The presence of the $I_q$ component implies an increased total current $I_t$ with respect to only the active current $I_d$. In the presence of inductance in the grid connection, injection of reactive power to the grid will however increase the voltage at the converter terminals. As indicated by (4), an increased voltage on the terminals of a CPL will therefore result in a reduced active current component.

$$I_q = \frac{P}{V}$$ \hspace{1cm} (4)

For the case with reactive current support by the CPL, it can be seen from the combination of (3) and (4) that according to the value of the grid inductance, there exist an operating range where the total current can decrease with increasing reactive current. Therefore there will be a value of $I_q$ that gives the minimum total current $I_t$ as it is illustrated by Fig. 8. The figure is plotted for illustration based on calculations on a simple radial system with similar parameters as the system simulated in Fig 6. Curves both for nominal grid voltage and a 20% voltage drop are given, that indicate how the minimum point of the total current is affected by the voltage drop level and by the value of the grid inductance. It is seen also how the required reactive current support for attaining the minimum total current is higher for higher voltage drop levels.

The value of $I_q$ corresponding to the minimum attainable $I_t$ should be of interest for further investigations and for consideration as one possible criteria influencing the design stage of the converter driving the CPL. As it can be clearly seen both from Fig. 6 and from Fig. 8, the needed current to a converter supplying a CPL will increase with the depth of a voltage sag that the system should tolerate, regardless any reactive compensation. The reactive current injection that corresponds to the minimum total current in the converter of the CPL can also be considered interesting from the system stability point of view since it provides some margin to the stability limit of the system at the same time as it defines the minimum possible rating of a converter that should handle a specified voltage dip.

---

**TABLE I. CCTs for different loading types and regulation of CPLs**

<table>
<thead>
<tr>
<th>Type of loading</th>
<th>Regulation</th>
<th>CCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: 80% CPL P constant only</td>
<td>162 ms</td>
<td></td>
</tr>
<tr>
<td>Case 2: 20% CPL, 60% induction motor P constant and $I_q$</td>
<td>187 ms</td>
<td></td>
</tr>
<tr>
<td>Case 3: 40% CPL, 40% induction motor P constant and $I_q$</td>
<td>238 ms</td>
<td></td>
</tr>
<tr>
<td>Case 4: 80% CPL P constant and $I_q$</td>
<td>510 ms</td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 5 Critical clearing times CCT for a) 80% share of CPL without reactive current control and b) 80% share of CPL with reactive current control implementation

Figure 6 Incremental $\Delta I_d$, $I_q$, $I_t$ and $I$ of the CPL as function of voltage drop $\Delta V$

Figure 7 Vector diagram illustrating the relation between current components of the converter driving the CPL
D. CPLs with reactive current control vs. centralized STATCOM

In order to evaluate the extra functionality of reactive current control in each CPL, a comparison is made with operation of a single converter dedicated to control of reactive current and configured as a STATCOM. Several simulations have been performed in order to investigate whether there is an advantage on implementing distributed compensation rather than centralized compensation with a STATCOM to compensate for the voltage drop. For this purpose, a comparison between the system with the STATCOM and two CPLs without reactive current control was made with the case of two or three CPLs with reactive current control without a centralized STATCOM. For making a fair comparison, in all cases presented in Fig. 5, the total amount of load in the system was kept constant at 50% of the wind generator rating. The amount of reactive current component \( I_q \) that these devices inject for supporting the voltage is plotted in Fig. 9. In the simulations, the centralized STATCOM is located as shown by the dashed line in Fig. 2. From the results in Fig. 9, it can be seen that distributed reactive compensation with three CPLs seems to be more convenient for voltage drop compensation than the cases with fewer number of CPLs or centralized STATCOM. This is corresponding to what is expected from theoretical calculations of static stability limits of systems with distributed shunt compensation [23]. It should also be noted that because the total current rating of the CPL is not increasing proportionally with the reactive current capability, the total installed converter rating will be lower with CPLs than with CPLs and STATCOM.

It can also be observed that there is a breakeven point at 300 milliseconds at which STATCOM and two CPLs require the same \( I_q \). For the case of 3 CPLs there is no breakeven point and the required \( I_q \) is lower than for the STATCOM for all duration of faults. However, the extent of this will depend on several factors such as type, duration and location of a fault, size of the loads, the \( R/X \) ratio of the system and the control strategy implemented. These factors will also have influence on the design of the converter system and controller of the CPLs.

IV. CONCLUSIONS

Effects of negative incremental resistance of CPLs in distributed AC systems is presented and discussed. The phenomena is explained and verified by simulation on a simplified power system model with high share of CPLs. The paper investigates the benefits of introducing the extra functionality of reactive current control in the CPLs control strategy to allow for the injection of reactive current in the event of voltage dips to support voltage stability. The transient stability limit has been investigated for different combinations of CPLs and induction motor loads. The CCT was the selected performance index to compare the investigated cases by simulations. The results indicate that the larger the number of CPLs that controls the reactive current, the larger the stability margin. The required reactive current rating of the semiconductor switches of the AC/DC converters when all CPLs in the system inject some reactive current is compared with the required rating of a centralized reactive compensation device placed on the secondary side of the transformer after the generator. The comparison gives advantages to the distributed reactive current compensation by the converter driving each CPLs rather than one centralized compensating device.

It is important to note that if future loads will support the system voltage by injecting reactive power, a different approach is needed in the design stage of CPL drive system in addition to the individual optimization typically done by manufacturers to fulfill standards such as grid codes, THD and EMC requirements. These are not necessarily sufficient to achieve what would be optimal from the point of view of the system performance and operation, especially during abnormal operating conditions such as voltage dips.

V. FURTHER WORK

Further work will be focused on the analytical investigation of the critical share of CPLs in the system to be compared with the critical share of CPLs with extra functionality of reactive current control to ensure voltage stability. This study will take into account the overall power system parameters and will attempt to identify the degree of extra loading that the system can be subjected to without jeopardizing the system stability. A stable region of operation based on the power system parameters and required fulfillment of grid codes for distributed AC
systems can be identified based on the above mentioned criteria. The role of CPLs with reactive current control for voltage support can be further investigated in relation to Low Voltage Ride Through (LVRT) in distributed AC systems.

The simplified system introduced in this paper for understanding the effect of CPLs in the stability limits could be further extended into the analysis of more complex power systems models such as the IEEE 29 bus system. Dynamic stability limits related to the converter control system is another vast area open for investigation in relation to the CPLs influence.

REFERENCES


