Abstract—This paper investigates the operation of a current controlled Voltage Source Converter (VSC) under weak grid conditions caused by large grid impedance. Three different current controller structures are investigated; the conventional decoupled PI-controller in the synchronously rotating reference frame, Proportional Resonant (PR) controllers in the stationary reference frame, and the phase current hysteresis controllers. The different control strategies are studied by simulation, and the results show how large grid impedances can influence the dynamic response of the system. It is further discussed how the interaction between the current controllers, the Phase Locked Loop (PLL) and the grid inductance can trigger instability when the voltage measurements are highly influenced by the operation of the converter. The results indicate that the tuning of the PLL and the way of utilizing the phase information is of large importance for the stability and dynamic response of the control system.

Index Terms—Current Control, Stability, Voltage Source Converter, Weak grid

I. INTRODUCTION

The amount of renewable energy sources integrated into the power system has grown rapidly during the last years, and significantly increased utilization of renewable energy is considered a necessity for the future electricity supply system. Different types of energy sources have different characteristics with respect to the operation of the power system, and power electronic equipment is continuously becoming a more important part of renewable generation systems because of more stringent requirements for grid interconnection. Especially the Voltage Source Converter (VSC) topology is becoming a standard, modular, solution for many applications due to its capacity for reversible power flow, for DC-voltage control and for implementation of high performance control systems [1].

Although many different control structures have been developed for VSC’s in various applications, cascaded control systems based on an inner current control loop appears to be most commonly used [2]-[3]. With current control as the inner loop of the control system, the overall operation will however depend on the performance of the current controllers. This has led to a significant attention in literature towards development and evaluation of different current control structures for the VSC [3]-[5].

The control system of a VSC should be designed for stable operation under every grid condition, but weak grid conditions caused by a high value of the grid impedance is one issue that can challenge the control of the VSC. Still, there only exist a few studies considering VSCs connected to a weak grid while taking into account the dynamics of the inner current control loop and the interaction between the converter and the grid impedance [6]-[7].

The motivation of this paper is therefore to investigate, compare and evaluate the operation of different current control strategies when a VSC is connected to a weak point in the power system where there is high impedance between the converter and a stiff grid voltage. The following three control structures are chosen for the investigation: 1) Decoupled PI Current Controllers implemented in the synchronously rotating dq-reference frame [2], [9], [12]; 2) Proportional-Resonant (PR) Current Controllers in the stationary reference frame [3], [15]-[18]; 3) independent phase current hysteresis controllers [7], [19].

To examine the dynamic response and the stability limits of the VSC with different current control structures, simulation studies with the PSCAD/EMTDC simulation software have been carried out. The responses to steps in the reference values and in the grid voltage have been compared under weak grid conditions, and the limits of stable operation of the converter have been investigated by trial and error simulations. In lack of simple mathematical models with general validity under weak grid conditions, the obtained results are analyzed with reference to physical considerations based on the electric circuit and on traditional control theory.

This paper, and the presented results, should be considered as an introductory study of how the operation of a VSC can be influenced by high impedance in the grid. The results will also indicate how the nonlinearities caused by reference frame transformations and the orientation of the PLL make it challenging to establish accurate mathematical models that can be used for linearization and systematic analysis of stability and parameter sensitivity by tools from traditional control theory. Further efforts in refining mathematical models with general validity as a starting point for stability investigations under weak grid conditions will be a natural line for future continuation of the presented work.

II. SYSTEM UNDER INVESTIGATION

The configuration used as basis for the investigations is shown in Fig. 1. The model includes a two-level VSC with a DC-capacitor, an LCL-filter in the grid side, a
III. OVERVIEW OF INVESTIGATED CURRENT CONTROL STRATEGIES

An overview of the basic structure used for all the evaluated current controllers is shown in Fig. 3. For the linear controllers, the output voltages are used for generating PWM signals, while the modulation is inherent to hysteresis current controller. The current control and modulation is thus indicated by a common block in the figure. In addition to the current controller, the modulation and the PLL, the system also includes an active damping algorithm to damp oscillations in the LCL-filter. The active damping is based on high-pass filtering of the voltage measurements at the filter capacitors, and the output signals are subtracted from the current reference, as shown in Fig. 3.[10]

As a basis for description and tuning of the different current controllers, the configuration from Fig. 1 and Fig. 3 will be investigated with the main parameters as given in Table I. The converter used as an example is rated for 2.5 MVA and operated at 690 V RMS nominal line voltage, and a desired switching frequency of 3 kHz is assumed. The LCL-filter is designed with relatively small inductance and large capacitance. This is usually a desired characteristic with respect to cost in industrial applications, but a small inductance can also be a disadvantage with respect to stable operation in a weak grid as will be discussed later.

The basic requirements and performance criteria for the current controller of a VSC are listed in [4], [13]. Ideal reference tracking with zero steady state error and high dynamic response should be achieved at the same time as the switching frequency should be limited. The parameterization of the different current controllers will be discussed in the following subsections.

A. Proportional Integral (PI) Controllers in the Synchronous Reference Frame

In steady state, the dq-reference frame is rotating in the same angular speed as the voltage vector. Hence, the electrical components in the synchronous rotating reference frame behave as DC-quantities, and a PI controller is capable of obtaining zero steady state error. The PI current controllers in the dq-reference frame can usually be tuned by the Modulus Optimum criteria applied to the open loop transfer function of the current control loop as given by (3) [9], [14]. The d- and q-axis controllers are decoupled by the use of a forward term as seen in Fig. 4 a), to remove the coupling term in (2) and achieve independent control of the d- and q-axis currents. The controller also includes a feed-forward of the measured voltage at the filter capacitor. The open loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn</td>
<td>2.5MVA</td>
</tr>
<tr>
<td>Vg</td>
<td>22kV</td>
</tr>
<tr>
<td>Nf/Ns</td>
<td>0.69:22</td>
</tr>
<tr>
<td>Vdc</td>
<td>1.2kV</td>
</tr>
<tr>
<td>fs</td>
<td>50Hz</td>
</tr>
<tr>
<td>fs</td>
<td>3000 Hz</td>
</tr>
<tr>
<td>Lf</td>
<td>30µH = 0.05 pu</td>
</tr>
<tr>
<td>Rlf</td>
<td>0.2 mΩ = 0.01 pu</td>
</tr>
<tr>
<td>Cg</td>
<td>1671µF = 0.10 pu</td>
</tr>
</tbody>
</table>
transfer function of (3) is therefore representing (2) with ideal decoupling and feed-forward of the filter voltage.

The controller parameters resulting from the Modulus Optimum are given by (4), where $r$ is the RL-time constant of the filter inductor, $r$ is the per unit resistance of the inductor and $T_o$ is a time constant representing a first order approximation to the PWM operation and the filtering effects in the control system. By Modulus Optimum, the integral time constant is designed to cancel out the RL-time constant of the filter, and the proportional gain is designed to achieve a gain equal to 1 of the system closed loop transfer function for as high frequency as possible. This corresponds to designing the system for a damping coefficient of 1/2.

$$H_{dq,OL}(s) = \frac{1}{(1+s\tau_i)} \left( \frac{1}{1+s\tau_p} \right) \left( \frac{1}{1+s\tau_e} \right)$$ (3)

$$K_{p,pm} = \frac{r \cdot r}{2T_o}$$ (4)

Fig. 5 a) shows the response to a unity step in the d-axis current reference for a controller with parameters given by (4). For this simulation, the converter is operated with a fixed DC-link voltage and the filter inductor of the converter is connected directly to an ideal, strong grid. The simulation is carried out with an average model of the VSC, to show the response of the current controller without the influence of the switching ripple [20]. This current response can be used as a reference when considering the simulations that will later be presented for a converter connected to a weak grid with high total impedance.

B. Proportional Resonant (PR) Controller in the stationary reference frame

The PR controller is equivalent to the PI controller in the synchronous reference frame, but with the controller transfer function transformed into the stationary alpha-beta reference frame. The transformation results in the transfer function, given as $H_{OL,PR}$ in (5), describing a resonant structure that will operate as an amplitude integrator for signals at the resonant frequency. This corresponds to a filter transfer function with infinite gain at the line voltage fundamental frequency. Since the PR-controller is a transformation of the PI-controller transfer function in synchronous rotating reference frame into the stationary reference frame, the parameters in the PR controller is kept the same as for the PI-controller although the integral gain $K_i$ is used to express the integral time constant. The PR-controller as shown in Fig. 4 b) is therefore able to provide zero steady state error for fundamental frequency sinusoidal current references [15]-[17]. As seen in the figure, the operation of the PR-controllers is also relieved by using the measured voltages in the stationary reference frame as feed-forward terms added to the output of the controllers.

$$H_{OL,PR}(s) = \left( \frac{K_p + \frac{2K_s}{s + \alpha_0}}{\alpha_OL_0} \right) \left( \frac{1}{1+s\tau_p} \right) \left( \frac{1}{1+s\tau_e} \right)$$ (5)

By using the same parameters as designed for the PI-controllers in the dq-reference frame, the PR-controller should also be expected to have the same dynamic response. This is verified with the step-response shown in Fig. 5 b), under the same conditions as explained for the PI-controllers.

C. Independent Hysteresis Current Control of phase currents

The hysteresis controller in the stationary alpha-beta reference frame is shown in Fig. 4 c). Since the modulation is embedded into the current controller for this control strategy, the whole system is included in the figure. The three phase currents are controlled separately.
by using the error between the reference value and the measured value. The upper switch in one leg is turned on when the corresponding error exceeds the upper tolerance band, and is kept on until the current error reaches the lower tolerance band. Because the three-phase system has isolated neutral point, there is however an interaction between the three phases that can lead to current deviations larger than the tolerance band specified for the phase currents [4]. In general, the hysteresis control provides robustness with a relative independence of load parameters, but do not have constant switching frequency.

To give a good base for comparison between the three control structures the tolerance band of the hysteresis controller is selected so that the average switching frequency will be the same as the switching frequency for the linear current controllers.

The response to a step in the d-axis current reference for the hysteresis controller is given in Fig. 5 c) for the case with direct connection to a strong grid. For simulating the hysteresis controller, it is however not possible to use an average model of the converter, since the switching signals are generated directly from the current deviation. The simulation is therefore carried out with a switching model of the converter, but the measured currents are averaged over the period between the last two switching instants before transforming the measurements into the dq-reference frame. Therefore, some remaining ripple caused by the switching actions and current variations due to the random and chaotic nature of the hysteresis controllers can be seen in the figure.

IV. COMPARISON OF THE CONTROL STRUCTURES

To investigate the performance of the different current controllers under weak grid conditions, further simulations are carried out. The simulated system is still characterized by the parameters from Table I, but the converter will now be connected to a weak grid. The controller parameters resulting from the discussion in the previous section are summarized in Table II.

To isolate the response of the current controllers from the control of the power flow in the converter, the simulations are still run with a fixed DC-link voltage.

A. Response to Step Change in Current

To observe the dynamic response, the system is first exposed to a step change in \( i_{d,ref} \) from 0 to 1.0 pu while \( i_{q,ref} \) remains at 0. The weak grid is represented by an inductance of 0.2 pu and a resistance of 0.025 pu, and the grid inductance is thus 4 times larger than the filter resistance. This makes the voltages at the filter capacitors, and by that the signals used for synchronization to the grid, to be highly influenced by the operation of the converter itself. The main results are shown in Fig. 6, and to limit the visual disturbance caused by the ripple currents, only the current at the grid side of the filter is plotted.

The PI controller is simulated for three different cases. The blue graph is showing the PI controller with the parameters shown in Table II, while the red graph showing the response when the feed-forward of the measured d- and q-axis voltage components is replaced by a constant d-axis voltage of 1 pu and the q-axis voltage of 0 pu. The black graph is showing the response when the PLL is tuned 5 times slower than described in Table II. It can be seen by the blue graph that the PI-controller results in an oscillatory response with relatively poor damping, which is significantly different from the results in a strong grid.

Fig. 6 is also showing the internal phase error signal of the PLL, and it can be seen that for the PI-controller this angle has similar oscillations as the response in the current. This is mainly because the current response following the step in the reference value is causing an oscillation in the filter voltage, and therefore also in the phase angle deviation of the PLL. Additionally, the use of the d- and q-axis voltage components measured at the capacitors as feed-forward terms introduces a further disturbance to the current controller when the voltage is oscillating. The interaction of the current controller with the PLL and the influence of the feed-forward terms is therefore the main cause of the oscillating current response seen in Fig. 6 a). It can also be seen from the same curves that the oscillation frequency is reduced and the damping of the oscillations are increased when tuning the PLL slower.

The PR controller is simulated for two different cases, and the curves in Fig. 6 b) are representing the parameters used in Table II while the black curves are representing the case when the PLL tuned 5 times slower. It can be seen from the blue curves that the PR-controller is giving a more damped response under the conditions of Table II than the PI controller. This difference in response is not obvious since similar results should be expected from these two controllers. However, a change of current in a weak grid is implying a transient change of phase angle and therefore also a transient in the local frequency that can be estimated at the terminals of the converter. The PR-controller is however only expected to give similar results as the dq-oriented PI-controllers for fundamental frequency signals. The change of phase angle caused by the weak grid conditions will therefore make the PR-controller to transiently operate outside the resonant frequency, leading to a reduced gain and a more damped response.

When the PLL is tuned to respond slower, the PR controller and the PI controller acts more or less similar, since the transient response of the phase angle at the filter

<table>
<thead>
<tr>
<th>CONTROLLER PARAMETERS</th>
</tr>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>( K_{PR} )</td>
</tr>
<tr>
<td>( \tau_{PLL} )</td>
</tr>
<tr>
<td>( K_{PI} )</td>
</tr>
<tr>
<td>( \tau_{PI} )</td>
</tr>
<tr>
<td>Hyst. Lim.</td>
</tr>
</tbody>
</table>

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capacitors and the influence on the PLL is reduced for both the two controller structures. The PLL is then also having a stronger filtering effect that limits the influence from the converter operation on the synchronization to the weak grid at the cost of a slower response.

From the results of the linear current controllers in Fig. 6, it can also be noted that there is a slow response in the current after the main oscillatory transient caused by the current controllers. This slow elimination of the steady-state error is similar for both the dq-reference frame PI-controller and for the PR-controller, and becomes more pronounced when the grid becomes weaker.

The hysteresis controller is simulated only under the conditions of the PLL described in Table II and the results are shown in Fig. 6 c). As expected, the hysteresis controller has a quick response with low oscillation and a short overshoot. However, there is a small steady state error in the response originating from the fact that the hysteresis controllers is not controlling the average value of the current but only the maximum deviation from the reference value. The control of current in the hysteresis controller is however almost independent of the phase angle, that is only used for transformation of the current reference into the stationary reference frame. As long as there is sufficient voltage margin between the DC-link voltage and the grid voltage, the hysteresis controller will not be significantly influenced by the rest of the control system. The hysteresis controller can therefore be used as a point of reference for discussing the interaction between the PLL and the rest of the control system.

The different interaction between the current controller and the PLL can be further commented by considering how the phase angle information is used. The PI controllers are based on using the angle from the PLL to transform the measured current into the synchronous rotating reference frame and then transform the voltage reference output of the current controller back to the stationary reference frame for generating the switching states. The PR controller and the hysteresis controller are however using the same angle only to transform the current reference from the synchronous reference frame into the stationary reference frame. Although the PI- and PR controller should be equivalent, the results show to be quite different. These differences in the simulation results give an indication on how the nonlinear interaction between the current controller and the PLL through the phase angle used for the reference frame transformations influence the stability of the system. This explanation is supported by the observation in Fig. 6, where the response of the PI and PR controller are close to identical, when the influence of the PLL is reduced for both controller structures. However, a slower tuning of the PLL will result in slower overall response of the control system, and reduced accuracy in transient control of active and reactive power flow.

**B. Response to a Voltage Drop**

To give a wider base of observations, the system is also exposed to a voltage drop in the stiff grid from 1.0 pu to 0.7 pu, while $V_{dc \text{ref}}$ and $V_{grid \text{ref}}$ are kept constant at respectively 1.0 pu and 0 during the simulation. The result for the different control structures is shown in Fig. 7. At the instant when the voltage drop occurs, it can be seen from Fig. 7, that the current has a significant overshoot before it is controlled back to 1.0 pu. This
current is going through the weak grid, influencing \( v_f \) and the internal phase angle deviation of the PLL. This interaction can be most clearly seen in the oscillating response in the PI controller. The PR controller and the hysteresis controller are also experiencing the peak in the current, but as explained earlier the interaction between the current controller and the PLL is weaker for these controllers, leading to a less oscillatory response than the PI controller. To show the influence of the PLL on the PI controller, the system is further simulated with the PLL tuned 5 times slower than the parameters given in Table II, and shown as the black graph in Fig. 7a). As expected the current response acts more similar to the PR controller, confirming that the controller responses become more equal with a limited influence from the PLL.

C. Investigation of Stability Limits

To further investigate the influence of the grid inductance, the inductance value in the simulation model is increased until the system reaches a point of instability. The first investigation is based on a step in \( i_{d,ref} \) from 0 to 1.0 pu. The results are shown in Table 3, where it can be seen that the PR-controller is stable for a larger range than the PI-controller. The hysteresis controller is not as dependent on the angular position from the PLL as the linear control structures, but the reference is transformed from dq-reference frame to abc-reference frame by use of the angle from the PLL. If the grid inductance is so large that the angular error in the PLL becomes significant during the transient response, the references will be distorted, and the controller becomes unstable because of this effect. Due to its non-linear operation, the hysteresis current controllers are therefore making the system to reach instability caused by distortions for a lower value of the grid inductance than the PR-controller.

The same investigation is performed on the current controllers with PLL tuned 5 times slower, showing an increased stability limit for both the PI controller \( (L_g=0.72\text{ pu}) \), the PR controller \( (L_g=0.82\text{ pu}) \) and the hysteresis controller \( (L_g=0.84\text{ pu}) \). This further verifies that a control system with reduced dynamic performance will be more stable in a weak grid.

Table III also shows the stability limit, when the VSC is controlled to consume reactive power, simulated as a step change in \( i_{q,ref} \) from 0 til 1 pu. The stability limit for this step change is lower for all three controllers investigated compared to when the system is exposed to a step change in \( i_d \). The weak grid is represented by a line which is significant more inductive than resistive. A change in \( i_q \) will give a higher voltage drop than a change in \( i_d \), and as described in the previous sections, a voltage drop results in an overshoot in the d-axis current and then consequently in the angle divagation, which again gives a more unstable system caused by the PLL being unable to detect this change.

The stability limit is also investigated for a voltage drop in the grid from 1pu to 0.7 pu with a constant \( i_{d,ref}=1.0\text{ pu} \) and shown in Table III. It can be seen from

<table>
<thead>
<tr>
<th>Method</th>
<th>Step in ( i_d )</th>
<th>Step in ( i_q )</th>
<th>Step in ( v_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI-controller</td>
<td>0.32 pu</td>
<td>0.29 pu</td>
<td>0.255 pu</td>
</tr>
<tr>
<td>PR-controller</td>
<td>0.46 pu</td>
<td>0.365 pu</td>
<td>0.36 pu</td>
</tr>
<tr>
<td>Hysteresis abc</td>
<td>0.38 pu</td>
<td>0.30 pu</td>
<td>0.29 pu</td>
</tr>
</tbody>
</table>
the table that the grid inductance at the stability limit is slightly lower than for the step change in \( i_{q} \). It can be seen in Fig. 6 and Fig. 7, that the overshoot in the current and in the angular deviation is higher for a step change in \( i_{d} \). The overshoot in the current and the internal angular deviation increase with increasing inductance in the grid. At the value given in Table III the overshoot gets so high that the PLL and the current controller is unable to detect its reference, and the system becomes unstable.

V. CONCLUSION

This paper presents an initial investigation on the influence that large grid inductance values has on the response and stability of current controllers for Voltage Source Converters. It is verified that a large grid inductance can make the control system to become unstable, and that the interaction between the PLL and the current controller plays a significant role in provoking such instability mechanisms. This is particularly the case for the PI-controllers in the synchronous reference frame. The interaction between the PLL and the controllers implemented in the stationary reference frame is however appearing indirectly through the transformation of the current references into the stationary coordinates, and these control strategies are therefore more robust with respect to a large grid inductance. However, also the PR- and the hysteresis current controllers can become unstable with a high grid inductance when the operation of the PLL is highly influenced by the converter itself. It is shown that the stability limits of the system are increased by using a slower PLL and allowing for a larger transient phase angle deviation between the PLL and the voltage at the filter capacitors. This will however lead to a slower and less accurate dynamic control performance of the control structures. For stability studies of converters operating in weak grids, correct representation of nonlinearities interactions between the PLL and the current controllers will therefore be critical. This stresses the importance of establishing mathematical models that consider these phenomena, when attempting to carry out a complete analysis VSCs operating in weak grids.

VI. REFERENCES


