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Multiple Current Control Strategies for an Optional Operation of VSC Linked to an Ineffectual Point in the Power System Beneath Diversified Grid Conditions

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Abstract: The grid and the structure will be analysed in various stages for its performance. The evaluation will be done in multiple stages. To analyse the response of current controller in grid the PI controller is used as a gain parameter for various grid structures and the response of the controller in grid is analysed.

Key words: Voltage Source Converter (VSC), Decoupled Double Synchronous Reference frame-PLL (DDSRF-PLL), Synchronous Rotating Reference Frame Phase Locked Loop (SRF-PLL), gain parameter, grid

INTRODUCTION

Now a days, the increase of global warming has risen over a limit and this raising process made up with the human around the world (Blasko and Kaura, 1997a). These examples in a survey in Europe, the energy sector alone contributes with 80% of the green house gas emissions (//europa.eu/legislationsummaries/energy/europeanenergypolicy/l27067en.htm). So the day by day demand is increasing throughout the world. Due to this the other possibilities to produce the energy has been comes in order and their inventions are take places.

The flexibility and sensational of new renewable energy sources are implemented and creates a great impact in this revolution. For these innovative system needs some gross core in its production to carry out the need (Bollen, 1999).

The usage of power electronic devices has become an essential part for the usage and implementation of the renewable energy generation systems. In that the Voltage Source Converter (VSC) solution is becoming a flexible modular solution due to its performance on reversible flow in DC-voltage control and the high performance control system (Chakraborty *et al*., 2009).

VSC have different control structures for various applications in that current controlled VSC for grid connection is evaluated and implemented as its best (Brod and Novotny, 1985). The current controller having the inner control loop system of a cascaded control system which appears to be the most commonly used control structure (Dannehl *et al*., 2009). With current control as the inner control loop system, the entire operation will base on the current controller performance.

A stable system operation is performed in the control system under every grid condition but for weak grid condition systems, caused by a high range of grid impedance is a major issue that is to be the challenge for controlling in VSC (Bajracharya *et al*., 2008). There has been so far given little intention towards the controlling operation of a VSC in with a weak grid while considering the dynamics of the inner current control loop and the interaction between the converter and the grid impedance (Tungpimolrut *et al*., 1992; Cobreces *et al*., 2007). Remote faults in transmitting power systems results in voltage dips through the power system (Kwon *et al*., 1998a). In some areas with high share of decentralized distributed generation, there is an grid code requirements for generator ”ride-through” where the generator is imposed to stay connected during transient faults.

In balanced and unbalanced condition, changes in voltage will occur and affect the operation of the converter in various ways. Hence, the current control of the VSC should be able to handle operation under both balanced and unbalanced conditions (Gullvik, 2007).

The main theme of this study is to monitor, compare and justify the different current control strategies for weak grid by adopting VSC techniques in power system. These are the proposed current control strategies are going to analyze:

- The Decoupled Proportional Integrator (PI) controller in the synchronous rotating reference frame
- Two dual PI controller implemented in the separated positive and negative-sequence rotating reference frame

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- The PR controller in the stationary reference frame
- The two level independent phase current hysteresis controller
- The three level hysteresis controller in the synchronous rotating reference frame:
    - A conventional Synchronous Rotating Reference Frame Phase Locked Loop (SRF-PLL), designed to handle symmetrical grid conditions
    - A synchronous rotating reference frame SRF-PLL with notch filter to filter out the oscillations that occur during asymmetrical conditions
    - A Decoupled Double Synchronous Reference Frame-PLL (DDSRF-PLL) that decouples the components of the positive and negative rotating reference frames

To evaluate and compare the dynamic response and the stability limits for the different current control structures and their respective grid synchronization techniques, simulation studies. The response to step changes in current reference, operation under various weak grid conditions and the limits of stable operation of the converter have been investigated by the simulations.

In lack of simple mathematical models with general validity under weak grid conditions, a state space model of the system with a PI controller and a conventional PLL has been tried indentified. This has not been completely fulfilled and the obtained results are analyzed with reference to physical considerations based on the electrical circuit and on traditional control theory (Suul *et al*., 2009).

THREE PHASE SYSTEMS

A symmetrical three phase voltage source can be represented by three voltage vectors with the same length and the phase shifted with 120 degree with respect to each other as described in Eq. 1:

$$\begin{matrix} V_a \\ V_b \\ V_c \end{matrix} = \begin{matrix} V\cos(\omega t) \\ V\cos\left(\omega t-\frac{2\pi}{3}\right) \\ V\cos\left(\omega t+\frac{2\pi}{3}\right) \end{matrix} \qquad (1)$$

If the symmetrical system is connected with a common isolated neutral the currents and the voltage for the three phase system fulfils the conditions of Eq. 2:

$$i_a+i_b+i_c=0 \qquad (2)$$

The power system can be large and complex with several nodes that connects a number of lines with transformers and generators or loads. During calculation of the performance of one particular node without doing a full scale analysis of the entire network, the network can be represented with its thevenin equivalent in Fig. 1.

This thevenin equivalent which is shown in Fig. 1 and the calculation of Z can be found by the fault level Sk at the node by Eq. 4:

$$V_a+V_b+V_c=0 \qquad (3)$$

Where, Sk is calculated from short circuit analysis of the power system and V is the nominal line to line voltage at the node. The thevenin equivalent voltage Vg can be taken as the nominal voltage at the point of interest. The fault level can now be expressed by the X/R ratio in Z = R+jX.

The fault level is an important parameter not only during fault conditions but it is also predicting the performances during normal operation as it defines the strength of the network at the particular point. A weak grid is a network or a part of a network where the fault level is low that is if Z is high and indicates that the node voltage is fragile with respect to changes in active and reactive power flow at the node (Suul *et al*., 2009).

Symmetrical components: The positive, negative and zero-sequence ideally, the voltages and the currents will be perfectly balanced and symmetrical which leads to greatly simplified analysis. However, this is not always the case. To analyze the three phase system under unbalanced conditions, ethically breaks unbalanced systems into three balanced sequences. A positive, negative and zero-sequence (Kazmierkowski *et al*., 1989).

The theory of symmetrical components comes from a study written by Fortes cue in 1918 (Brittain, 1998). The study demonstrates that N set of unbalanced phases could be expressed as the sum of N symmetrical sets of balanced phases. The unsymmetrical voltage and currents are found by superposition of the three sequences. The voltage can be written as in Eq. 4 and the phases of the three phases in the positive, negative and zero-sequence:

$$\begin{matrix} V_a \\ V_b \\ V_c \end{matrix} = \begin{matrix} V_a^- \\ V_b^- \\ V_c^- \end{matrix} + \begin{matrix} V_a^- \\ V_b^- \\ V_c^- \end{matrix} + \begin{matrix} V_a^0 \\ V_b^0 \\ V_c^0 \end{matrix} \qquad (4)$$

Where:

$$h=e^{j\frac{3\pi}{3}}$$

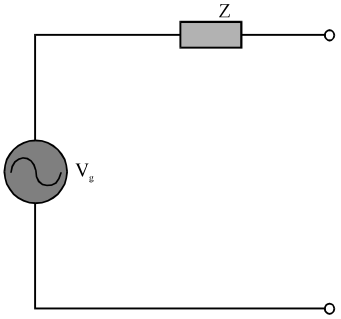

Fig. 1: The grid thevenin equivalent

The steady state vector representation has been derived by Anderson (1973) and can be written as in Eq. 5 and becomes as in Eq. 6 in the time domain (Chang *et al*., 1994). A zero sequence current may be present when there is a path in addition to the three lines (Aldabas *et al*., 2006):

$$\begin{matrix} V_a \\ V_b \\ V_c \end{matrix} = \begin{matrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{matrix} \begin{matrix} V_a^+ \\ V_a^- \\ V_a^0 \end{matrix} \qquad (5)$$

$$\begin{matrix} V_a \\ V_b \\ V_c \end{matrix} = \begin{matrix} V^+\cos(\omega t) \\ V^+\cos\left(\omega t-\frac{2\pi}{3}\right) \\ V^+\cos\left(\omega t+\frac{2\pi}{3}\right) \end{matrix} + \begin{matrix} V^-\cos(\omega t+\varphi^-) \\ V^-\cos\left(\omega t-\frac{2\pi}{3}+\varphi^-\right) \\ V^-\cos\left(\omega t-\frac{2\pi}{3}+\varphi^-\right) \end{matrix} + \begin{matrix} V^0\cos\left(\omega t+\varphi^{-0}\right) \\ V^0\cos\left(\omega t+\varphi^{-0}\right) \\ V^0\cos\left(\omega t+\varphi^{-0}\right) \end{matrix} \qquad (6)$$

Positive and negative sequence in an unbalanced system that is exposed to an unbalance at a certain instant. The negative and the zero-sequence are initially set to zero. At the moment the unbalance occurs, the amplitude of the positive sequence voltage is set equal to 0.7 and the amplitude of the negative sequence is set equal to -0.3.

The zero sequence is unchanged, equal to zero. As seen from the figure, the unsymmetrical and unbalanced system is decomposed into two symmetrical and balanced systems (Kazmierkowski and Sulkowski, 1991).

THE VOLTAGE SOURCE CONVERTER (VSC)

There are different ways of converting and inverting voltage with power electronic devices. For distributed generation the state of the art is the two levels three phase converter. For high power wind turbines a three-level neutral point clamped VSC is an option. Also, matrix converters and multilevel converters are developing and been implemented in distribution power generation systems (Blaabjerg *et al*., 2006).

This proposed research will focus on the control of a three-phase two level VSC. Two levels three phase converter as seen in Fig. 2 the VSC contains shunted diodes and switches (Brod and Novotny, 1985). The diodes are mandatory because bidirectional current flow has to be fulfilled by the semiconductor switches in the VSC. The switches which usually are IGBTs are turned on and off by a control trigger signal. Different strategies for triggering the switches are dependent on the control method (Kazmierkowski and Malesani, 1998).

By use of a linear controller the switches are triggered by comparing three sinusoidal control signals, phase shifted 120° with respect to each other with a saw tooth signal. The sinusoidal signal has the same frequency as the 1st harmonic of the output voltage and the saw tooth signal has the same frequency as the switching frequency. This method, called the sinus modulation can be used when the switching frequency is at least 20 times the 1st harmonic frequency (Martins *et al*., 1998).

For non-linear controllers the switching signals are determined by the choice of voltage vector. The different voltage vector representations are presented in switching in the VSC. If the switches are seen as ideal and the blanking time of the switches are ignored, the output voltage of the converter is independent of the current, since the switches in one of the legs are always on (Kazmierkowski and Malesani, 1998). To prevent the PWM from going in to over modulation and to attend a stabile system, the DC side of the voltage must be at least as in Eq. 7:

$$V_{DC} \geq \frac{2\sqrt{2}}{\sqrt{3}} V_{LL} \qquad (7)$$

Harmonic injection: For operation of the voltage source converter using a perfect sine wave as modulation reference do not give the optimum use of the DC-side voltage of the converter for systems with isolated neutral. By decreasing the peak of the phase voltage and maintaining the peak of the 1st harmonic, the use of the DC voltage can be increased (Kazmierkowski and Dzieniakowski, 1993).

This can be achieved by injection of the 3rd harmonic or every 3rd harmonic multiple in the phase voltage. This harmonics will cancel out in the line to line voltage, since it is injected in all three phases. The use of the DC voltage will increase by a factor 1.155. From (Houldsworth and Grant, 1984) the 3rd harmonic injection for optimal use of the DC-link voltage can be implemented at the modulation reference as:

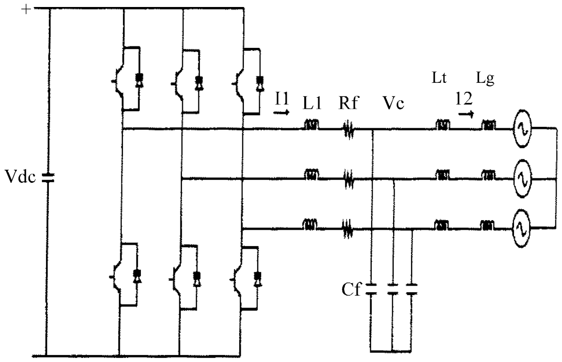

Fig. 2: Two level-three phase voltage source converter

$$V_a = \sin\omega t + \frac{1}{6}\sin 3\omega t \tag{8}$$

$$V_b = \sin\left(\omega t - \frac{2\pi}{3}\right) + \frac{1}{6}\sin 3\left(\omega t - \frac{2\pi}{3}\right) \tag{9}$$

$$V_c = \sin\left(\omega t - \frac{4\pi}{3}\right) + \frac{1}{6}\sin 3\left(\omega t - \frac{4\pi}{3}\right) \tag{10}$$

Switching in the VSC: By use of different combinations of the switches in the converter the voltage vector can be represented by eight space vectors. Since, the three phases are shifted 120° with respect to each other, combination of the six switches on the three legs and phases will create voltage vector representations (Blasko and Kaura, 1997b).

LCL-filter: The high frequency harmonics in voltage and current, generated by the high frequency switching in the VSC can be suppressed by the use of a LCL-filter. The LCL-filter consists of two inductors in series and a capacitor shunted between them. Compared to a filter with the use of a single inductor, the damping of the switching harmonics, at lower switching frequency, improve by using a LCL-filter.

In much application, when there is a transformer in the interface between the VSC and the grid, the leakage inductance in the transformer can be used as the second filter inductance. Kazmierkowski and Sulkowski (1991) is proposed a method for designing the LCL filter. The total inductance of the filter should be as small as possible to realize fast tracking and high dynamics and still handle the ripple in the current. The selection of current ripple is a trade off between the size of L1, switching losses and inductor coil and core losses (Mo *et al.*, 2003). The choice of the capacitor is done based on the evaluation of the reactive power in the capacitor and in the inductance.

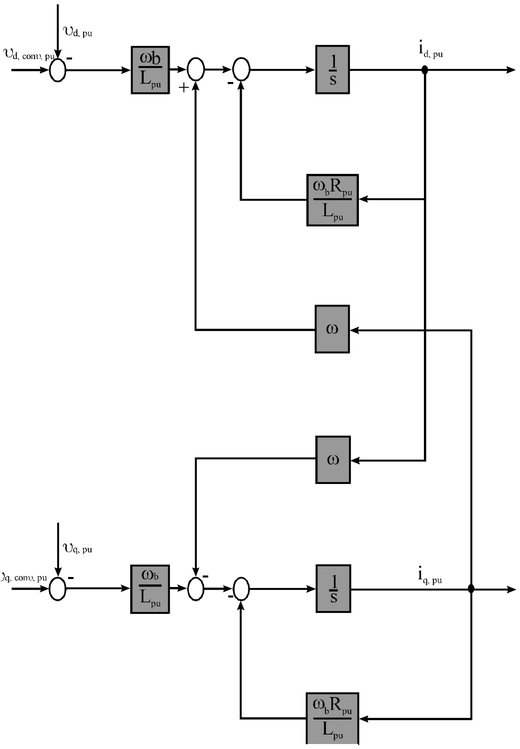

Fig. 3: Block diagram of VSC

Mathematical model: When designing the control structure for the current, it is useful to have a model of the converter to design the controller properly. Blasko and Kaura (1997b) is presented a mathematical model for a three phase voltage source converter. The system is assumed balanced. This model includes the effect of the switches and the switching function. This gives the block diagram of the VSC as shown in the Fig. 3.

State-space model of the LCL circuit: The state space model presented in this switching in the PWM can be mathematical modelled as a time delay for control manners. The d-q representation in a synchronous reference frame is shown in equation describe the system under investigation. The LC-circuit is described in Eq. 11 and shown with per unit values-values in Fig. 4. To include the capacitor in the filter and the weak grid thevenin equivalent inductance that influences the point of synchronization, Eq. 11 is added to the mathematical model:

$$(1+x)^n = 1 + \frac{nx}{1!} + \frac{n(n-1)x^2}{2!} \tag{11}$$

The switches and the physical consequences of the voltage on the converter side of the filter being turned on

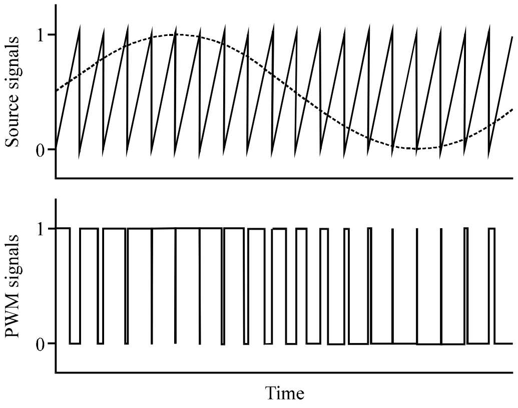

Fig. 4: PWM in the VSC

and off. In the state space representation of the system, the converter is represented as a first order time delay approximation.

GRID SYNCHRONIZATION

The phase angle of the voltage vector is important and basic information for the VSC and injection of current needs to be synchronized with the grid voltages (Blaabjerg *et al*., 2006). The phase locked loop is the most extendedly used technique for grid synchronization and will be given most attention and used for grid synchronization in this thesis. A number of different techniques for grid synchronization exist and by Ljokelsoy (2008) and Suul *et al.* (2009), they were divided into the following main categories:

Zero Crossing Method, filtering techniques, phase locked loop based and adoptive notch filter based techniques.

The Zero Crossing Method provides simplicity but with low dynamic performance (Houldsworth and Grant, 1984). The filtering techniques consist of both d-q-filter algorithms. The adoptive notch filter-based techniques are frequency based and don't have a voltage controlled oscillator in their structures (Ljokelsoy, 2008). A good synchronization technique must track the phase and frequency variation of the utility signals and reject harmonics, disturbances and other types of pollution that exists in the grid signals (Ljokelsoy, 2008).

The Synchronous Reference Frame Phase Locked Loop (SRF-PLL): Control of power factor is a common goal for several different applications of the VSC and detecting the phase angle is a critical part of achieving this.

In (Kwon *et al*., 1998b) the most common control structure, the PI controller in dq-reference frame, the transformation of the current into DC-quantities is dependent on the angle of the d-q axis which should be synchronized with the voltage vector. The PLL should therefore be designed to detect the correct angle of the voltage vector and lock the d-q axis to this angle so that the current and voltage are synchronized to the grid.

The PLL should be able to phase-lock the utility voltages as quickly as possible and provide low distortion output under different operating conditions such as line notching, voltage unbalance, line dips and frequency variations (Kaura and Blasko, 1997).

PLL with notch filter: To suppress the oscillation from the opposite reference frame, the two synchronous rotating reference frame voltage measurements can be filtered in the grid synchronization. The bode plot is achieved in Fig. 5. A low-pass filter of 100 Hz will reduce the band width of the control system and may cause stability problems. Therefore, a notch filter is introduced by Kazmierkowski and Tunia (1994). A notch filter is a band-stop filter with a narrow stop band. Since, it is reducing the gain only at twice the fundamental frequency signals it is not affecting the band width of the control system.

Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL): By adding the Decoupling algorithm in the voltages that are used for synchronization are independent of the opposite sequence. Chang *et al.* (1994) propose a method for removing the oscillations in the two reference frame by a decoupling of the positive and negative sequence (Chang *et al*., 1994). The decoupling is based on decoupling of positive and negative sequence (Fig. 6).

Voltage drop in the grid: The grid is operating around its nominal value most of the time. However, it can happen that the voltage in the grid experience drop in it value for a short period of time and the converter must be able to handle such conditions. This is especially, the case in renewable energy applications where there are grid code requirements for 'low voltage ride through' capabilities (Pan and Chang, 1994). Hence, this study is investigating the operation of the converter under different types of drop in the grid voltage.

Switching frequency in hysteresis current controllers in a three phase voltage drop: A drop in the grid voltage is a case that will influence the average switching frequency of the hysteresis controllers. Limit cycle in the phase current hysteresis current controller is likely to occur under such conditions. The hysteresis controllers have

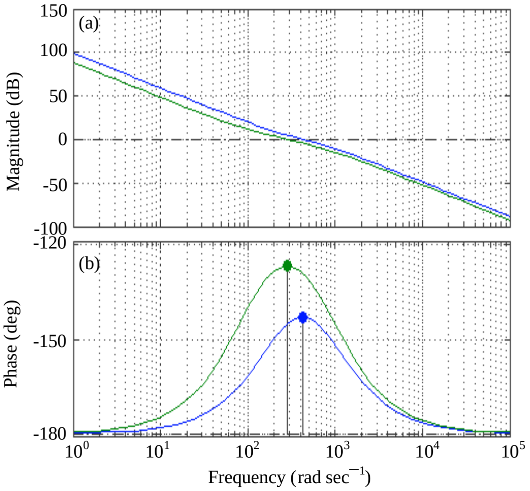

Fig. 5: a, b) Bode plot of notch filter

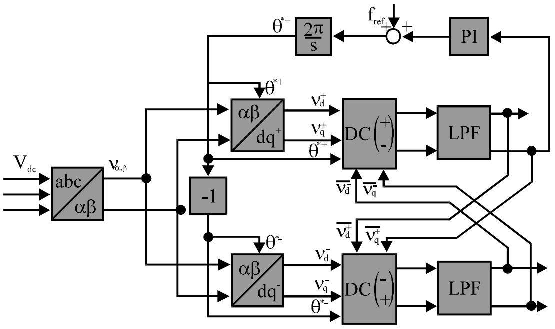

Fig. 6: The DDSRF-PLL

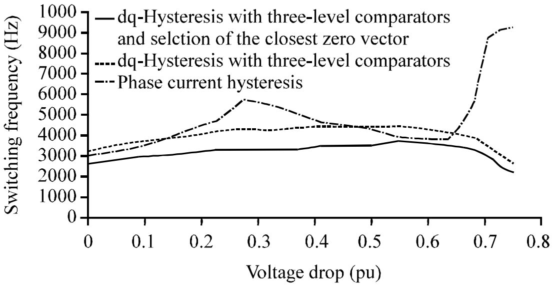

Fig. 7: Switching frequency in hysteresis controllers

therefore been compared with simulations based on the average switching frequency as a function of the grid voltage drop (Blaabjerg *et al*., 2006). The comparison is in Fig. 7.

The two versions of the three level dq-hysteresis controller shows also an increase in switching frequency that has a global peak placed at a voltage drop from 20-70% depending on the current reference. This increase comes also from the increased slope of the current (Aldabas *et al*., 2006).

The d-q hysteresis controller with selection of zero-voltage vector has a lower switching frequency than the two other hysteresis controllers for all the cases and under every condition.

When the grid voltage has a drop to low values, the switching frequency of the d-q hysteresis controllers goes down, on the basis of that it is now utilizing the zero voltage vector that decreases the slope of the current error (Gaubert *et al*., 2003).

Evaluation of current control structures with conventional PLL in a three phase voltage drop in a weak grid: The system is exposed to a perturbation of a three phase voltage drop in the grid from 1.0-0.7 per unit. During the fault, the VSC is operating in generator mode with d-axis current reference at 1.0 per unit and the q-axis current reference is kept at 0 per unit. The grid inductance, including the transformer impedance is 0.2 per unit and the grid resistance is 0.025 per unit in the weak grid thevenin equivalent.

The system is simulated for the PI controller, the PR controller, the phase current hysteresis controller and the hysteresis controller in the d-q-reference frame all with a conventional SRF-PLL (Shin *et al*., 2004).

The resulting response of the current is shown in Fig. 8. The blue plot shows the response when the PLL is tuned and the red plot shows the response when the PLL is tuned five times slower. During a voltage drop in a weak grid, there are two factors that influence the point of synchronization. The three phase drop in the grid gives a change in the d-axis voltage. Additionally, will the change in voltage lead to a transient in the current.

Voltage drop in a stiff grid: The current control structures that are designed to handle an asymmetrical voltage drop. The dual PI controller with notch filter, the DDSRF PI controller, the PR controller with a DDSRF-PLL, the phase current hysteresis controller with a DDSRF-PLL and the d-q-hysteresis controller with a DDSRF-PLL will hence be further investigated. During a voltage drop in a weak grid there are as said two factors that influence the measured voltage used for synchronization (Tilli and Tonielli, 1998).

The change in the grid voltage and the operation of the converter. To give a base for understanding the dynamics and stability-limits for the current controllers in a weak grid, the current response to a voltage drop in a stiff grid is analyzed.

This will isolate the influence the change in the grid voltage plays for the synchronization from the operation of the converter, since the operation of the converter is

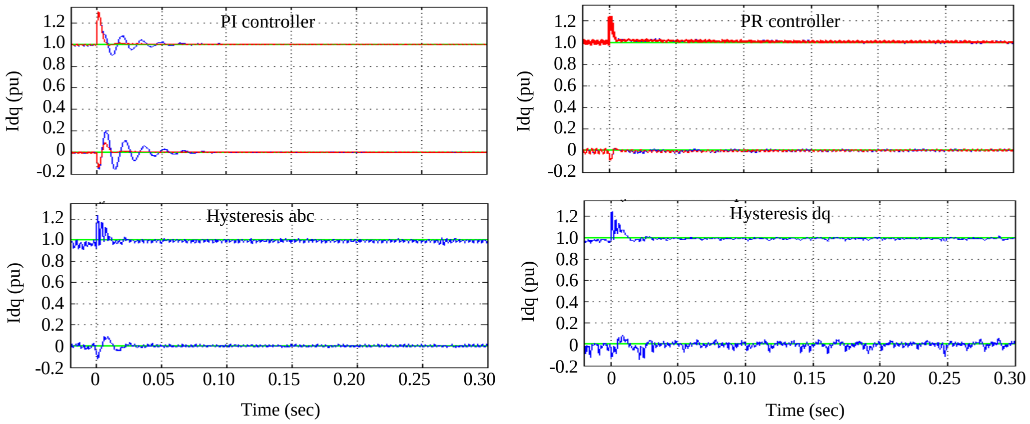

Fig. 8: Current controllers, voltage drop type A when connected to a weak grid controller with a DDSRF-PLL

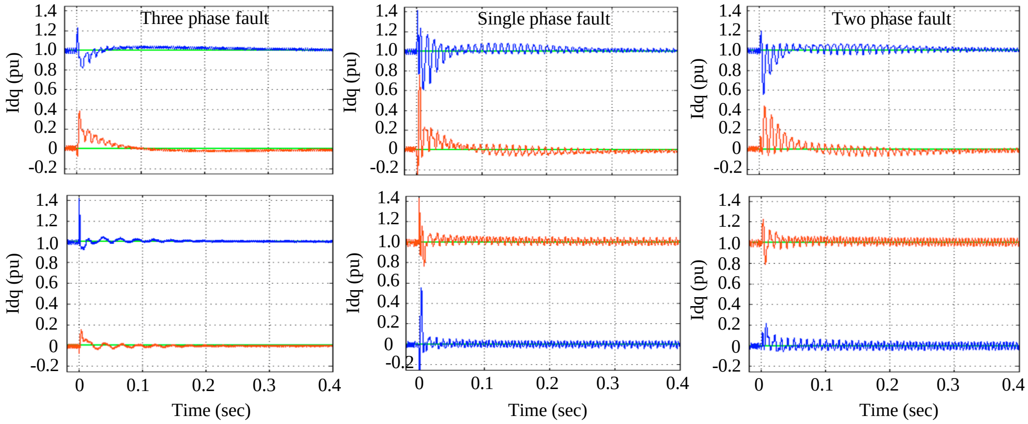

Fig. 9: Current response to voltage drop. The first row shows the dual PI controller with notch filter and the second row shows the dual PI DDSRF controller

not affecting the measured voltage in the stiff grid. The system is simulated and analyzed for three types of grid faults.

Voltage drop in a weak grid: To investigate the influence a weak grid plays for control of current during a voltage drop, the same cases as simulated for the stiff grid. The weak grid is represented with an inductance including the transformer inductance, of 0.2 per unit and a resistance of 0.025 per unit in the thevenin equivalent. The current response for the investigated control structures are shown in Fig. 9.

The first row shows the result of the dual PI controller with a notch filter and notch filter PLL and the second row shows the response of the DDSRF-PI controller and DDSRF-PLL. The first row shows the response for the PR controller with a DDSRF-PLL and the second row shows the Hysteresis controllers with a DDSRF-PLL.

CONCLUSION

The research presented in this thesis is an initial study of the influence that a weak grid has on the response and stability of current controllers for a voltage source converter. Different control structures have been evaluated by comparison based on different simulation cases. The operation of the converter for the simulated cases does not necessarily represent the preferred performance but it show trends that indicate a general behaviour during different type of converter-operation under various grid conditions.

It is verified that a weak grid, represented by a large grid inductance can make the system become unstable and that the interaction between the PLL and the current controllers plays a significant role in provoking such instability mechanisms. This is particularly, the case for the PI controller in the synchronous reference frame. This interaction will be even more evident for the dual PI controllers where the PLL interacts with the PI controller in both the negative sequence and the positive sequence rotating reference frames. The dual PI controllers will at the same time have a slower current response, since it is controlling the current in the two reference frames that transiently interact with each other.

The interaction between the PLL and the current controllers implemented in the stationary reference frame is appearing indirectly thorough the transformation of the current references into the stationary coordinates. Also, the three level hysteresis controller implemented in the synchronous rotating reference frame will be influenced indirectly. These oscillations have to be removed and the simulations show that this can be achieved by both a Decoupling algorithm and a notch-filter under stiff symmetrical and asymmetrical grid conditions.

The current controllers with a DDSRF-PLL has a short transient period compared to the current controller with a notch filter but the weak and asymmetrical grid conditions results in an oscillating steady state where the interaction between the two reference frame are not totally removed by the DDSRF-PLL.

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