Grid Inductance Estimation by Reactive Power Perturbation for Sensor-less Scheme Based on Virtual Flux

Arkadiusz Kulka, Tore Undeland

Abstract—**Use of renewable energy sources is raising for grid connected systems, for which higher power quality requirements are being issued. Monitoring the grid impedance ensure stable operation of the controller and proper connection and disconnection from the grid. Thus it is vital to know the value of grid or transformer distributed impedance in given time, instead assuming a constant value in controller. To overcome this problem an identification method based on perturbation of reactive power is proposed. The normally inductive character of the grid used together with synchronous frame current controller have cross coupling terms which are used in analysis. This method is suitable for use with virtual flux oriented control. It uses two current sensors and one dc link voltage sensor. Method enables maintain unity power factor not only at PCC but also further into the grid, including lines and transformer leakage inductance**.

Index Terms—**Grid Impedance, Renewably Energy, Virtual Flux, VSC Control**

I. INTRODUCTION

In recent years the penetration of distributed power generation is increasing, as well as the development of power electronics. Often in remote areas it is not possible to connect to a strong grid, the impedance can vary which could lead to different problems. In close presence of inverter, varying impedance could lead to instabilities in high frequency range, caused by LCL filter. The inverter LCL filter resonant frequency should be in the bandwidth of controller and usually is high in order to minimize size of the C and L filter components, thus challenging the control and the grid filter design. Knowing the grid impedance, also improve dynamic response of current controller in case of rapid changes of active power.

Manufactures of inverters for renewable energy are obligate to deliver unity power factor at PCC. For example in wind industry usually the low voltage turbine output (690V) is connected to step-up transformer and then to medium/high voltage line. So the unity power factor must be maintained at the high voltage side of the transformer. The best would be if we could include the inductance of the transformer into control, so the PCC is not any more at the grid filter, but at secondary side of transformer.

It is beneficial to estimate the leakage inductance of the transformer (4...6%) and include in control algorithms. We assume that we know the parameters of the used LCL filter which is inserter between inverter and transformer. Having knowledge that the converter will be connected directly to the transformer we can try to minimize or even remove the grid side filter inductor L_2.

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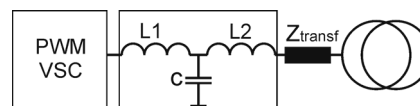

Fig.1. Inductances on the path from converter to infinite bus

Usually the grid side L_2 inductor is introduced to minimize the influence of the grid impedance for a resonant frequency variation, thus inserting L_2 ensures that resonant frequency never goes beyond controller bandwidth. Having only LC filter and stiff grid, could lead to out of bandwidth uncontrollable resonances which would cause inverter trip. Normally increasing L_2 would decrease the resonant frequency difference between grid connected and disconnected mode. In this letter we will focus mostly on estimation of inductances as they dominant, have large influence and difficult to estimate by steady state methods, involving active power. The resistive part of grid impedance is easier to estimate since active power and terminals voltage in steady state can be used.

There are many methods to measure grid impedance by dedicated hardware and software. However the inverter is not such a trivial platform (not dedicated), the DSP has already computational tasks, and the inverter has reduced number of sensors (no grid voltage sensors).

A. Existing Impedance Detection Methods

Various methods can be used for line impedance measurement; normally they employ special hardware devices. Precise acquisition of voltage and current is performed which follows the mathematical calculation to obtain the impedance value.

In literature two kind of method exist: passive and active.

The passive methods based on observation of noncharacteristics harmonics (line voltage and currents). Method depends on existing background distortion of the voltage which very often is undetectable by inverter platform, thus not used in practice.

Active methods usually produce "disturbance" of the network, followed by response acquisition and processing. There are many ways to "disturb" the network, therefore active methods further can be divided into steady-state and transient methods [1][2][3][5][5].

The methods can be also characterized for estimation of impedance for given frequency (50Hz) or calculate impedance characteristics as a function of frequency.

There are some methods [1] which inject high frequency, short duration current signal and based on voltage response the inductance is calculated. Fourier analysis of the voltage is used, which require significant amount of computational power and memory. When filter capacitor is used (LCL filter) the method by injecting short current pulses can be error prone, thus often in those methods only L filter is considered.

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II. PROPOSED METHOD

A transient method technique is used to estimate the line inductance. The principle of operation is to inject reactive current into the grid for short time (3..5 periods, current 0.2..0.5 pu.) using the inverter and obtain the response of d-axis current controller. D-axis current controller should be responsible only for active power. If the d-axis current (i_d) response is significant in amplitude that means that there is wrong value of L in cross coupling of current controller. In other words we will try to find L in cross coupling for which the response of i_d is minimized in amplitude. For the correct value of L the orientation of axes during transient is proper and accordingly d and q axes controllers control the active and reactive power independently. If the value of L is mistaken the orientation of axes is twisted during transient, and reactive controller control some of the active power as well, which e.g. can be observed as a dc-link voltage variation. The dc-link voltage will come back to the commanded level quickly because it is the major task o f the d-axis and dc-link controller.
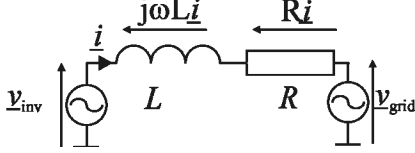
Fig. 2. Simplified representation of interconnection between inverter and voltage source.

Model of PWM converter in stationary coordinates (α/β) is:

$$\begin{bmatrix} v_{inv,\alpha} \\ v_{inv,\beta} \end{bmatrix} = R \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} v_{g,\alpha} \\ v_{g,\beta} \end{bmatrix} \tag{1}$$

The dc-link voltage balance equation:

$$C \frac{du_{DC}}{dt} = \left(i_\alpha S_\alpha + i_\beta S_\beta \right) + i_{DC} \tag{2}$$

After transformation to synchronous reference frame (d/q) the equations are:

$$\begin{bmatrix} v_{inv,d} \\ v_{inv,q} \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega L \begin{bmatrix} -i_q \\ i_d \end{bmatrix} + \begin{bmatrix} v_{g,d} \\ v_{g,q} \end{bmatrix} \tag{3}$$

The active and reactive power is given by

$$p = \text{Re}[\underline{v} \cdot \underline{i}*] = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \tag{4}$$

$$q = \text{Im}[\underline{v} \cdot \underline{i}*] = v_\beta \cdot i_\alpha - v_\alpha \cdot i_\beta \tag{5}$$

Now it is clear that the cross coupling term in the current controller is appearing from model transformation from stationary (1) to synchronous frame (3).

The importance of having a correct grid inductance in the control system is illustrated in Fig. 3. A d-axis current reference step of 0.5p.u. is applied.
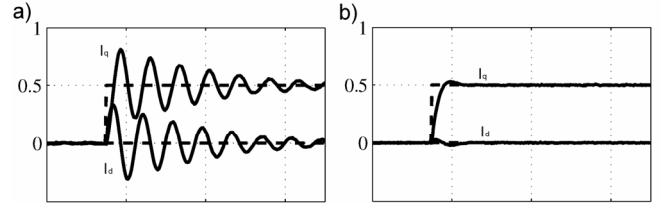
Fig.3.Simulated different responses of i_d and i_q dependent on the cross coupling L value in current controller.

In the first case (Fig 3a) there is over or under compensation of L in cross coupling of current controller. It is an effect that L in controller is not adequate to real inductance and the system is barely stable. In this case the reference angle is distorted and active/reactive current controllers are not controlling proper axes.

The second case (Fig 3b) present correct response, without overshoot, which mean that the inductance used in the cross coupling is the estimate of infinite grid inductance.
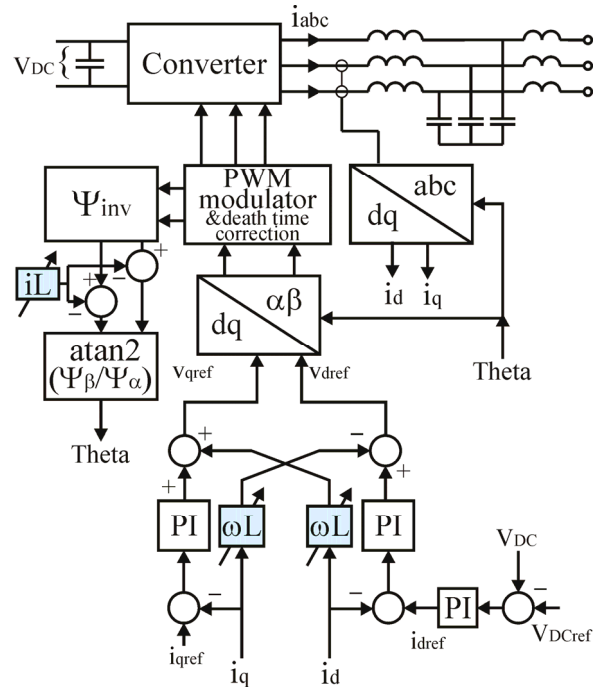
Fig.4. Block diagram of the control

A. Current regulator

Using converter model of equations (3) to design the current regulator

$$L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_{inv,d} \\ v_{inv,q} \end{bmatrix} - \begin{bmatrix} v_{g,d} \\ v_{g,q} \end{bmatrix} - R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega L \begin{bmatrix} -i_q \\ i_d \end{bmatrix} \tag{6}$$

The problem with the voltage capacitor feed-forward is that we do not measure this value; in case of constant amplitude signal the PI-regulator will compensate it quickly in steady state. In case where the amplitude of voltage is changing rapidly then the feed forward would speed up the setting time (supporting the integrators). It has been observed, that when capacitor voltage is unbalanced then the feed forward term (in synchronous frame) is distorted. The distortion is usually 100Hz oscillations from negative sequence, from where the unbalance comes from. In this situation the single frame controller is not capable of rejecting of that signal and

the output current is distorted, thus in unbalance case the voltage feed forward is not giving any beneficial.

The last expression in (6) is the cross coupling term $-\omega L i_q$ and $\omega L i_d$. If we supply the capacitor voltage feed forward term and $i\omega L$ term then our controller would be able to keep track under steady state and transient. Since the resistance R and the inductance L are the same for both, d and q axes, the time constant of the current regulator can be the same. This is done by using two independent PI regulators.

In our case when we change the direction of i_q but with much higher or lower amplitude we introduce disturbance to our controller which is not able to reject it during the transients. This introduces distortion in d axis which is analyzed later.

B. DC-bus regulator

The task of dc-bus regulator is to keep the dc voltage as close or equal to a given reference value. The input to the regulator is the voltage difference and the output is the active current reference. The amount of the current needed to charge/discharge the capacitor to the desired reference value can be found by looking at the energy equations of the dc bus capacitor.

The used time constant for the dc-bur regulator based on equations

$$T_i = 8\left(T_{DSP} + T_{PWM}\right) \qquad K_p = \frac{3V_{dc,ref}C_{DC}}{16\left(T_{DSP} + T_{PWM}\right)}$$

C. Virtual Flux Oriented Control

Important part in impedance estimation is the derivation of synchronization angle for synchronous coordinates. The well known virtual flux approach is used for angle reference (instead PLL based on measured voltage). The idea is to estimate output voltage of the inverter from measured DC link voltage and duty cycles of modulator D_a, D_b, D_c (8)(9). The integration of the estimated voltage vector lead to virtual flux vector of inverter. The grid flux is a converter flux and flux coming from inductive part of our filter, transformer or grid.

$$\underline{\Psi}_{grid} = \int\left(\underline{v}_{inv} - L\frac{d\underline{i}}{dt}\right)dt = \underline{\Psi}_{inv} - L\cdot\underline{i} \qquad (7)$$

The virtual flux grid vector is 90 degree delayed from real grid voltage vector. Based on this angle the synchronization is performed.

$$v_{conv,\alpha} = U_{DC}\frac{2}{3}\left(D_A - \frac{1}{2}(D_B + D_C)\right) \qquad (8)$$

$$v_{conv,\beta} = U_{DC}\frac{1}{\sqrt{3}}\left(D_B - D_C\right) \qquad (9)$$

And the grid flux components are calculated from:

$$\Psi_{G,\alpha} = \int\left(v_{conv,\alpha} - L\frac{di_\alpha}{dt}\right)dt \qquad (10)$$

$$\Psi_{G,\beta} = \int\left(v_{conv,\beta} - L\frac{di_\beta}{dt}\right)dt \qquad (11)$$

The grid voltage vector position is:

$$\varphi_G = arctg(\Psi_{G,\beta} / \Psi_{G,\alpha}) + \pi/2$$

The inductance L substituted in the flux model will be responsible for orientation angle of the controller. Also at the point for that distributed inductance (in our string of series inductances) the commanded reference current $i_q=0$ will be corresponding to unity power factor.
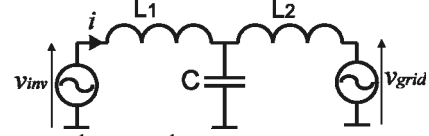

Fig.5 Reference voltages and current

In classic controller design, only the two inductances of the filter L_1 and L_2 are included (ideal grid), so this is the minimum value which should be included in control. In reality there is some grid inductance, which knowledge of it enables us to change it in control. Because here we estimate the grid distributed inductance we know the maximum value of L for which we can tune our controller. Changing L in cross coupling of current controller from minimum to maximum of above mentioned value, accordingly move our point of PCC with unity power from inverter terminal to infinite bus.

Similar situation happen with our virtual flux orientation, adding more L, mimics as we were moving the point of synchronization "inside" the grid.

Because flux based orientation has embedded flux term (iL in Eq. 7) dependent on inductance and current, it will behave better during transients than voltage sensed PLL, which has no information about the L grid.

Also the given angle for flux based orientation is insensitive during reactive power transients; it will influence only voltage at PCC. It is easy to analyze on Fig.3, when we change reactive current C - D, it will correspond to voltage c-d which is in phase with grid voltage.
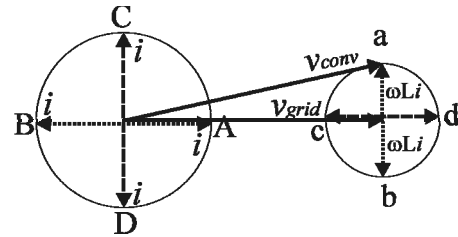

Fig.6. Vector diagram of current, grid voltage and inverter voltage

When we change active power from flow A - B then we see that during transient it will be angle error, but with good estimation of L it is compensated.

D. Realization of Reactive Perturbation Method.

Proposed by author method is based on commanding reference reactive current (*iqref*) in order to see the response of active (*id*) current. During three cycles (60ms) of commanding capacitive reactive current the variation in i_d is recorded, then switching to inductive character instantly the procedure to find variation of i_d is repeated. For easier calculation we assume that there is no current delivered to the dc-link.

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Experiments shows that the step level don't have to be large, it is sufficient to make steps of i_{qref}=0.3p.u. With every disturbance of i_q we made change (e.g. step increase) of the p.u. value of inductance in cross coupling (cc) term.

For better illustration a sweep procedure is performed, the sweeping parameter L in a cross coupling is changed from 0.6 to 4.0 p.u. in a 0.2 p.u. step. One unit of L is equal to the known LCL filter inductance.

During the sweep procedure we watch for the difference of id current (Δid), and for point where is minimum variation occur, we can assume that estimated infinite bus inductance.
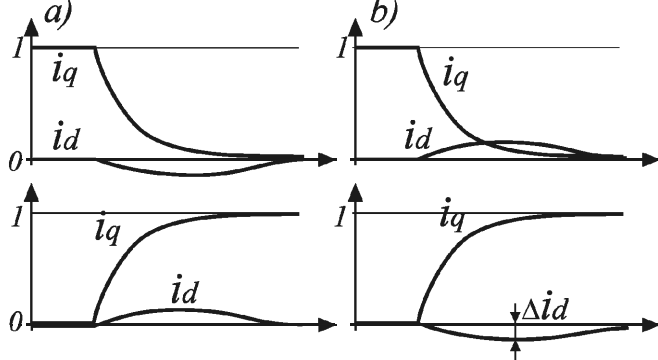
Fig.7. Responses of the i_d current for i_q steps from 0 →1 and 1→0
a) Under compensation of L b) Overcompensation of L

It is also important to have L in flux model set to 1 p.u., which in our case is equal to inductance of LCL filter.

After detecting the L_{inf} with sweep procedure, we can see how many times it is greater than our LCL filter inductance. Laboratory experiments shows that in case of stiff grid the detected infinite bus inductance is around 1.0..1.1 p.u. of our LCL filter.

In case of emulating weak grid by connection of two transformers in series with converter, the test shows around 2.5 p.u. (so the grid inductance is 1.5 times higher than our LCL filter).

Experiment shows that the best accuracy is when there is no active current; the method is well suited for start up procedures of inverter.

It is possible also to estimate when active current is applied (online identification during normal operation), but then the added extra reactive current, must not exceed limits of the converter transistors.

Experiment shows that 3 periods per step is far enough to detect the max and min of the i_d. In the shown results 17 steps were applied, each step L=0.2 p.u.
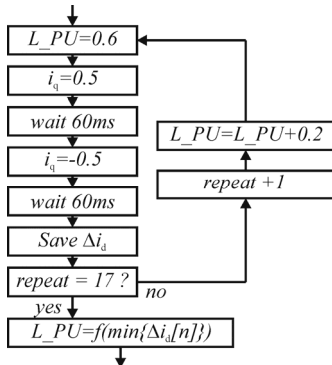

Fig.8. Algorithm used for the sweep test

The implementation for laboratory experiment assumes wide spectrum of swept inductance, the total detection time is

*3 periods x 2 sides x 17 steps *20ms = 2 sek*

E. Possible improvements in detection time

The algorithm can be easily improved in detection time, based not only on minimum Δ_{id} as so far, but also on direction of i_d. This would minimize number of steps to just few. The algorithm would divide the range to half, and then dependent on sigh of i_d go for next left or right half. So the rough estimation would take short time, while more exact would require more iteration and time. Many others possibilities exist.

III. EXPERIMET\NTAL RESULTS

The system was tested in the laboratory on a 20kW converter using a Texas Instrument TMS320F2812 processor. The LC filter uses 800μH inductor and 25μF capacitor connected in delta. The system was rated for 230V line to line voltage and 30A of current, the switching frequency was 10kHz. The dc-link voltage reference was kept constant at 1.4 p.u. or 455V. The commanded reference reactive current during experiment was set to ±0.7 p.u. There were two cases of grid inductance condition, first the converter was connected with series with 3mH inductor, emulating weak grid (3.8mH), second case the converter was connected directly to the grid, only LC filter was used (0.8mH). For easier analysis of the figures we will call strong (0.8mH) and weak (3.8mH) conditions respectively.

FFCCL is abbreviation for feed forward cross coupling L in current regulator (the highlighted ωL block in Fig.4). The CCKP and CCKI are abbreviations for current controller proportional and integral gain respectively.
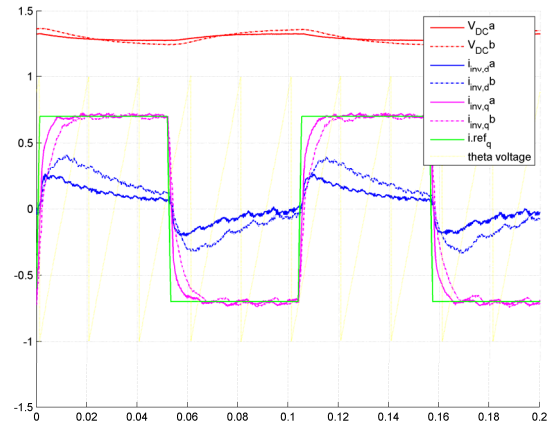

Fig.9. Weak grid, FFCCL=1p.u. i_d variation visible due to inductance mismatch between grid and controller (underestimation). The solid lines (a) CCKP=0.6, CCKI=5, the dotted (b) CCKP=0.3, CCKI=1
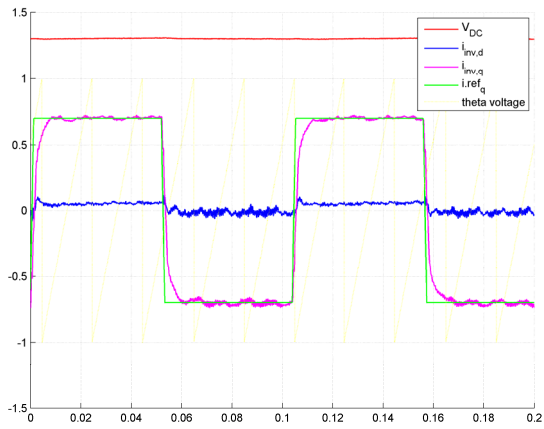
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Fig.10. Weak grid, FFCCL=4p.u., CCKP=0.6, CCKI=5. Match between grid and controller. Even for weak grid the i_q variations are minimized.
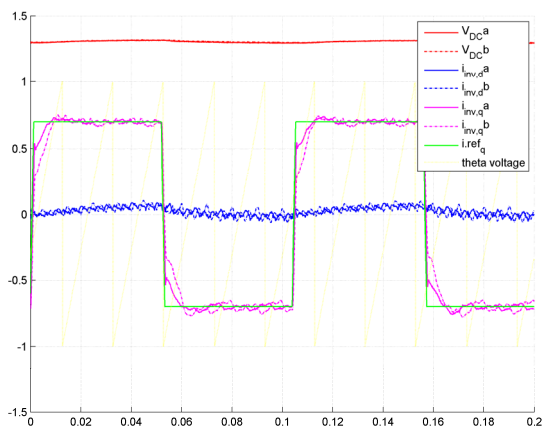

Fig.11. Strong grid, FFCCL=1p.u., i_d variation minimized due to inductance match. The solid lines (a) CCKP=0.6, CCKI=5, the dotted (b) CCKP=0.3, CCKI=1
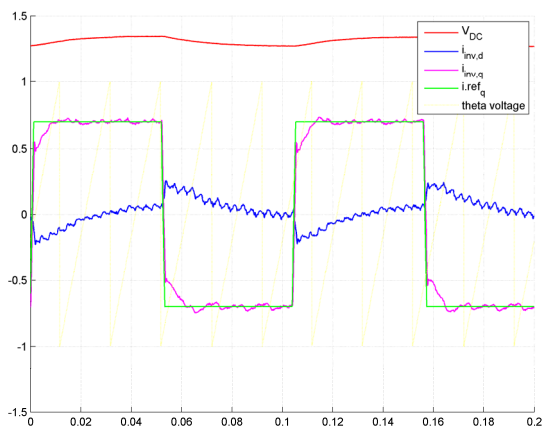

Fig.12. Strong grid, FFCCL=4p.u. i_d variation exist due to inductance mismatch (overestimation), CCKP=0.6, CCKI=5
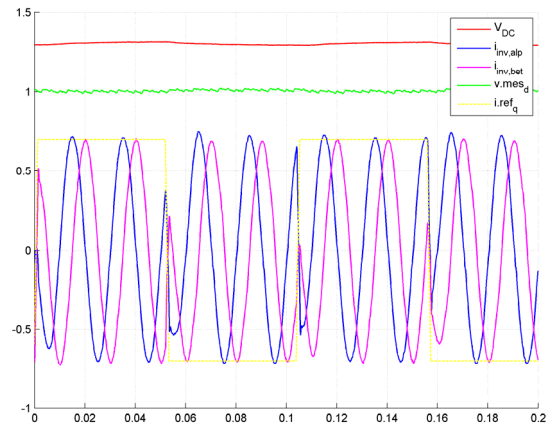

Fig.13. Transition of the inverter current (in alpha beta plane) during pure inductive and capacitive mode of operation. The current controller was used without feed forward voltage as shown on Fig. 4. Even without feed forward voltage support, the speed of current changing direction by 180 degree is significant.

A. The Sweep Test Results.

For the sweep test the same converter and DSP is used. The inductor in the LC filter is changed to 1200μH and 18μF capacitor connected in delta. The dc-link voltage reference was kept constant at 1.5 p.u. or 488V for rest of experiments. The commanded reference reactive current during experiment was set to ±0.8 p.u. for better visualization of the curves.

There were two cases of grid inductance condition, first the converter was connected directly to the grid, only LC filter was used (1.2mH = 1p.u.).

The second case (emulating weak grid) is when between converter and grid two isolation transformers are inserted.

Because LC filter is used which could lead to oscillation and tripping of converter, active damping function is used. The active damping function is based on Lead-Lag compensator [8] and is directly implemented in c language software like the rest of the control.

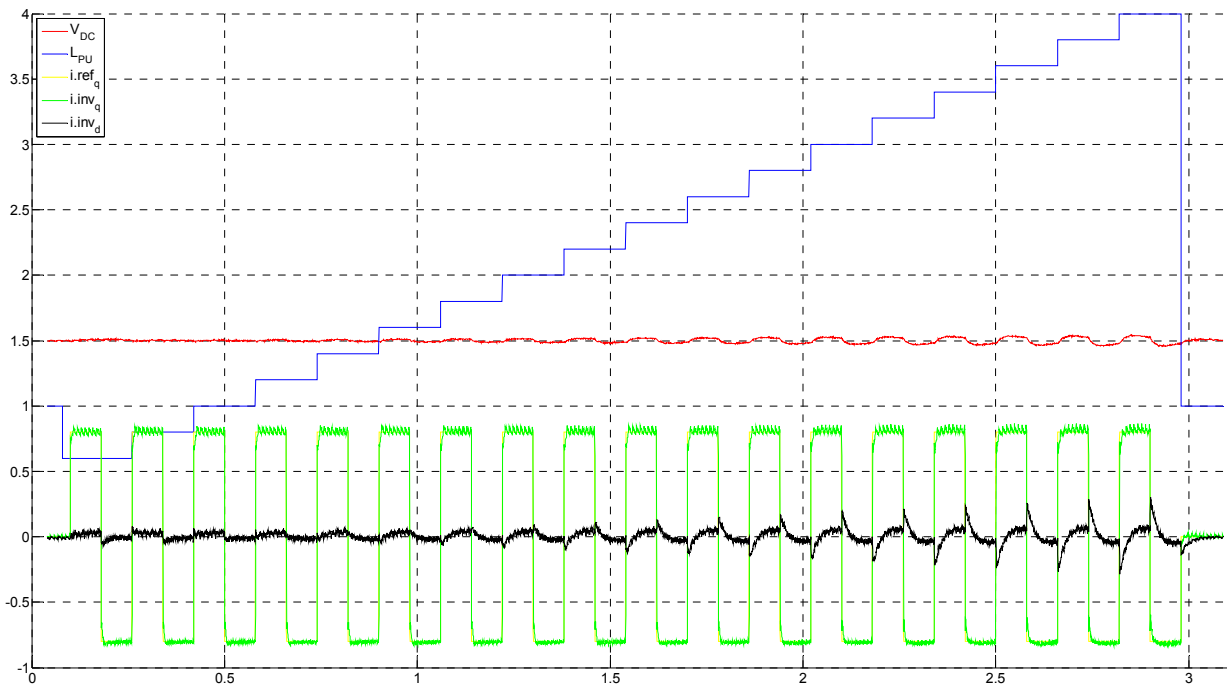The sweep test visualizes the process of changing L in current controller of cross coupling term

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Fig.15. Laboratory measurement results with strong grid. The smallest variation of dc-link voltage and i_d appear around 1 p.u of L, This means that the grid inductance is nearly zero (which is confirmed, because the supply transformer for the laboratory is very near).
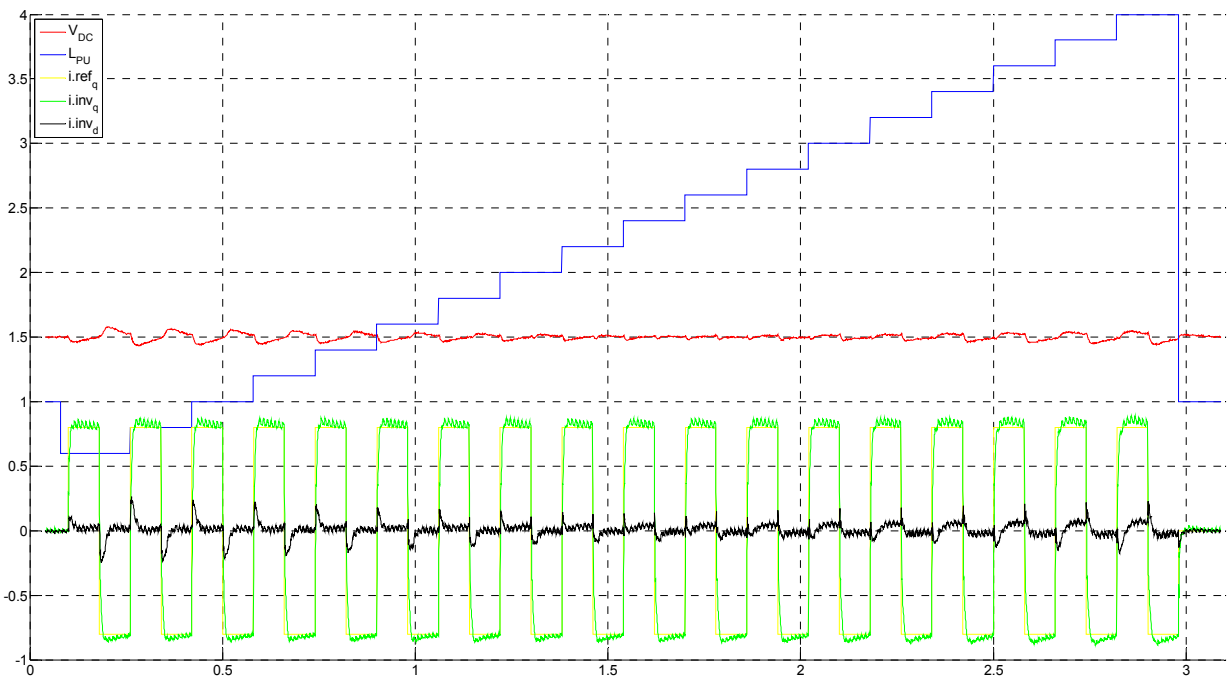

Fig.14. Laboratory measurement results with weak grid. The variation of dc-link voltage and i_d current variation are smallest approximately for inductance (blue line) around 2.4 to 2.6p.u. The total inductance seen from the converter terminals into infinite bus is $(2.5)\cdot(1.2mH_{PU})$=3mH. The only grid inductance is 3mH-1.2mH(filter)=1.8mH.

In above graphs the green line represents the reactive power in synchronous frame, the yellow one is the squared reference reactive power, red line is the dc-link voltage, black is the inverter active current in synchronous frame, blue is the inductance in cross coupling term of current controller.

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III. CONCLUSION

Estimation algorithm of distributed inductance is presented based on virtual flux sensor-less approach. Accuracy of 5% was achieved in laboratory setup. Stability and dynamic performance of controller is improved. Important feature is that algorithm does not require any extra hardware changes in inverter (cost), all features can be implemented only in software. Another property is that algorithm is able to estimate impedance when filter capacitor is used. Removing of voltage sensors brings extra advantages, in author opinion the ac voltage estimation is better and less distorted than measured when only L filter is used (no capacitor, chopped measured voltage due to grid impedance). It is also possible to startup the synchronization with the grid without voltage sensors. In this laboratory setup current sensors are used to detect initial position of the grid voltage angle, by shorting the grid (by IGBT) two times by 100us. Sequence and angle can be calculated based on the current.

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