Accurate Measurement of Converter Sequence Impedance by Active Cancellation of Coupling over Frequency

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***Abstract*—Impedance-based analysis plays important role in assessing the stability and dynamics of grid-connected inverters and related systems. Measuring the inverter impedance is, however, not straightforward due to the load effect caused by the power grid. The power grid interacts with the inverter and produces additional (mirrored) frequency harmonics thus distorting the impedance measurements when applying conventional measurement techniques. This paper proposes an active-power filtering method to minimize the undesired load effect caused by the power grid in the measured impedance. Applying the method, the inverter output impedance can be reliably measured under non-ideal grid conditions.**

***Index Terms*—mirrored frequency response, grid-connected, stability, power electronics, impedance measurement**

I. INTRODUCTION

The increased use of inverter-connected resources has started to affect the dynamics of the power grid. Interactions between the inverters and the power grid have been a topic of extensive research in recent years [1], [2]. One issue studied is the harmonic resonance between the inverter and the grid, which may lead to instability and disruption of the inverter operation. A method to assess the stability of these systems is to apply the impedance-based stability criterion [3]. The method requires information of the inverter output impedance and the grid impedance.

Direct measurement of impedance is desirable for practical applications, for example, as a way to certify impedance responses provided by manufacturers for system analysis. Impedance measurement is possible for wind turbines and PV inverters and similar devices, and is being pursued by the industry. Recent studies have presented a number of methods for measuring the inverter output impedance [4], [5]. In the methods, an external current or voltage perturbation is placed on top of the nominal grid current(s) and voltage(s), the resulting responses in the inverter current(s) and voltage(s) are measured, and Fourier techniques are applied to extract the corresponding frequency components in both the currents and voltages. In most studies, however, only low-power devices have been applied, and the effect of real power grid has been neglected.

One of the practical issues in the stability analysis is the load effect of the power grid. In simulation the issue of grid-connected systems can be avoided by using ideal source, but in direct measurement the load effect must be considered. The inverter produces additional (mirrored) frequency harmonics and strongly interacts with the power grid which distorts the measured inverter output impedance. If the power rating of the device under test is much smaller than that of the source, the source impedance is relatively low compared to the measured input impedance and the effect may be ignored. For turbines and PV inverters the source impedance is usually significant and cannot be ignored. The limited bandwidth of the power sources limit the possibility to reduce their output impedance.

In a typical frequency-response measurement of a grid-connected inverter, a perturbation at a frequency of f_p generally produces a response at the same frequency. However, in practice, the perturbation at f_p also causes a response at $2f_1 - f_\mathrm{p}$, where f_1 is the fundamental frequency. The latter response is known as transfer admittance, which modifies the inverter output impedance when the effect of the power grid is considered.

The undesired effect of the mirrored harmonic can be removed by compensating the grid impedance to zero at the mirrored harmonic frequency. This can be achieved by either mitigating the induced voltage to zero with a series-active power filter (APF) or by using a shunt APF to prevent the mirrored harmonic current flowing towards the power grid. The use of shunt APF allows easier implementation but requires an additional voltage perturbation source for the measurement.

This paper reports preliminary work in which a shunt and a series APF are applied for measuring the output impedance of a grid-connected inverter. The APF detects and compensates the inverter mirrored harmonic from affecting the measurements. The proposed method makes it possible to mitigate the undesired effect of the power grid, therefore yielding more

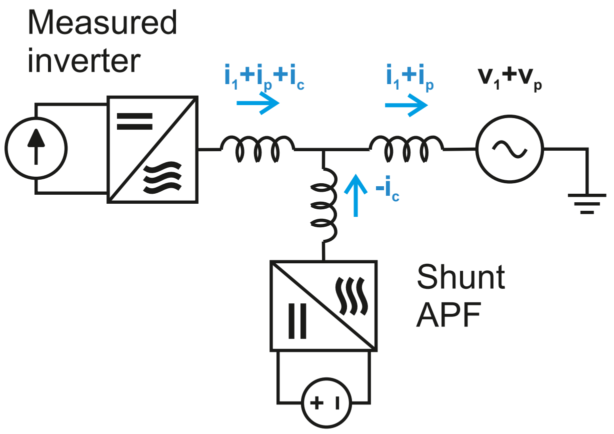

Fig. 1. Shunt APF layout of for the compensation of the mirrored harmonic

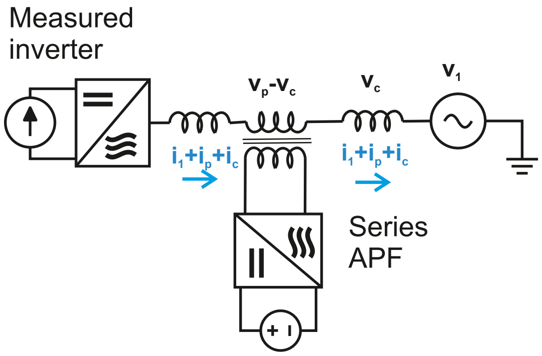

Fig. 2. Series APF layout of for the compensation of the mirrored harmonic

accurately the inverter output impedance.

The rest of the paper is organized as follows. Section II reviews the sequence domain impedance measurement. Section III presents the impedance measurement method and the coupling over frequency. Section IV presents the active power filter design. Section V shows the simulation results when the measurement compensation is applied. Finally, Section VI draws conclusions

II. SEQUENCE IMPEDANCE MEASUREMENT

The stability assessment of a three-phase inverter can be performed by transforming the currents and voltages into either sequence domain or dq-domain. The dq-domain analysis requires knowledge of the exact phase angle of each device compared to the point of common coupling, which makes the analysis of multiple devices more complicated. In sequence domain the measurements can be used to analyze the system regardless of the relative placement of the different devices.

For the analysis of a three-phase system the electrical variables in the AC-system are transformed into sequence domain, containing positive, negative and zero components. The sequence domain currents and voltages can be calculated from phase domain by applying Fourier transform to each phase and then using the transformation matrix $T_\text{abc-to-pn0}$, given as

$$T_\text{abc-to-pn0} = \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \tag{1}$$

In the sequence domain the system has positive and negative domain impedance. In a balanced system, the zero sequence components can be ignored. The positive and negative sequence are coupled through the nonlinear response of the inverter components. This phenomenon can be shown through multiharmonic linearization, where the system is linearized including the coupling over frequency [6]. When the system is perturbed and analyzed at f$_p, thefrequenciesofinterestare$f$_\text{p}$ and $2f_1 - f_\text{p}$. The sequence domain impedance can then be expressed as

$$\begin{bmatrix} Y_\text{p}(s) \\ Y_\text{c}(s) \end{bmatrix} = \begin{bmatrix} I(s)/V(s) \\ I(2f_1 - s)/V(s) \end{bmatrix} \tag{2}$$

where the linear positive sequence admittance is $Y_\text{p}(s)$ and corresponding nonlinear transfer admittance is $Y_\text{c}(s)$. The sequence domain currents and voltages can be calculated as

$$v_\text{pn0}(s) = T_\text{abc-to-pn0} * v_\text{abc}(s) \tag{3}$$

$$i_\text{pn0}(s) = T_\text{abc-to-pn0} * i_\text{abc}(s) \tag{4}$$

where $a = e^{2/3\pi i}$. By measuring and calculating the sequence-domain admittances and corresponding the transfer admittances the system stability can be analyzed.

III. COUPLING OVER FREQUENCY AND COMPENSATION

The multiharmonic linearization was used to analyze the effect of the mirrored harmonic in [7]. The work applied the method to a two-level voltage source inverter, and showed that the mirrored harmonic frequency response is caused by the PLL and DC-bus dynamics.

The mirrored harmonic current causes a voltage response with the grid impedance. The voltage response of the grid causes again a current response from the inverter through the transfer admittance changing the current and voltage ratio at the original perturbation frequency. The mirrored harmonic frequency response has a major effect to the output admittance of the inverter below the frequency $2f_1$ in non-ideal grid conditions. For the stability analysis the admittance containing the effect of the mirrored harmonic is required. The actual output admittance can be calculated by [2]

$$Y(s) = Y_\text{p}(s) - \frac{Y_\text{c}(s)Y_\text{c}^*(s - j2\omega_1)}{Y_\text{g}(s - j2\omega_1) + Y_\text{p}^*(s - j2\omega_1)} \tag{5}$$

where Y_p is the positive sequence admittance, Y_c is the transfer admittance, Y_g is the grid admittance, ω_1 is the grid angular velocity, and $*$ denotes complex conjugate. The ideal measurements are made by either compensating the mirrored harmonic current out of the current flowing to the grid or by mitigating the voltage induced by the mirrored harmonic from the measurement point. As the grid admittance at the mirrored harmonic frequency increases towards infinity, latter term on

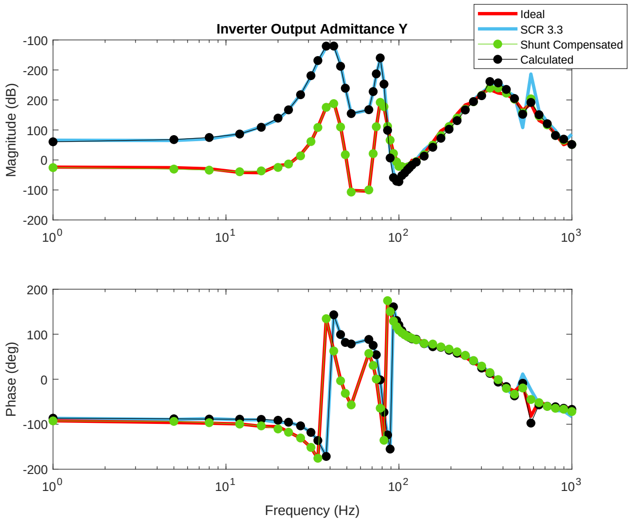

Fig. 3. Measurement of the ideal inverter output admittance in non-ideal conditions. The ideal output admittance (red), the output admittance in nonideal grid (blue), the compensated admittance measurement (green) and the output admittance calculated from the compensated measurements (black).

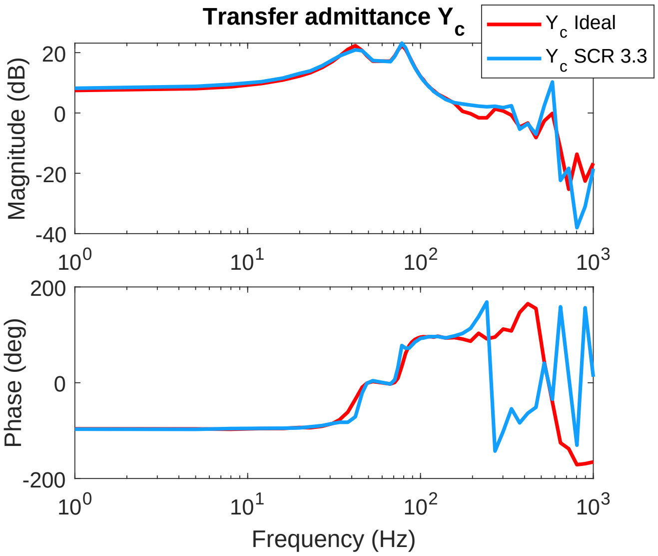

Fig. 4. Inverter output transfer admittance Y_{c} measurement. The output admittance in nonideal grid (blue), the ideal output admittance (red).

the right-hand side in (1) becomes zero and the measurement can be performed as in an ideal grid connection. The real output admittance can be calculated by (1) when the ideal terms $Y_{\mathrm{p}}(f_{\mathrm{p}})$, $Y_{\mathrm{c}}(f_{\mathrm{p}})$, $Y_{\mathrm{p}}(2f_1-f_{\mathrm{p}})$, $Y_{\mathrm{c}}(2f_1-f_{\mathrm{p}})$ and the grid admittance $Y_{\mathrm{g}}(2f_1-f_{\mathrm{p}})$ are known.

Figs. 1 and 2 show the basic layout of the compensation devices. Either a shunt or series APF can be used to compensate the effects of the mirrored harmonic. Fig. 3 shows the impedance measurement and the difference in the inverter output admittance Y, when the grid impedance increases. The compensation removes the load effect from measurement and the ideal impedance measurements can be used to calculate the real output admittance. The transfer admittance is shown in Fig 4. Applying the APF makes it possible to measure the inverter output impedance as if it were connected to an ideal power grid with minimal distortions. This allows the use of single measurements of output admittance Y_{p} and transfer admittance Y_{c} to be used for stability analysis in any point of connection as long as the grid impedance is known.

IV. MEASUREMENT COMPENSATOR DESIGN

The goal of the APF is to act as a zero impedance sink for the mirrored harmonic current and preventing the voltage response from the grid impedance affecting the measurements. Fig. 5 shows how the spectrum of the inverter output voltage and the grid current frequency spectrums change when the compensation is applied. The design of the APF is a basic selective compensation device [8]. Fig. 6 shows a layout of the shunt APF control and reference detection. The series implementation has the same control layout, except it uses the grid voltage instead of the inverter output current for its reference generation. The measurements are transformed to the dq-domain at the frequency of the mirrored harmonic response. The dq-domain measurements are then filtered by a fifth-order Butterworth-lowpass filter and the remaining DC signal includes only the mirrored harmonic response. The DC signal is then transformed back to phase domain and used as a reference signal for the APF controller.

Using a shunt APF design, the APF detects the inverter mirrored harmonic current response $i_{\mathrm{inv}}(2f_1-f_{\mathrm{p}})$ and the shunt APF is used as a current sink drawing that current in. The grid side admittance $Y_{\mathrm{g}(j2\omega_1-s)}$ increases towards infinity. The injected current negates the current at the point of common coupling.

The series APF design uses the grid voltage measurement to detect the induced voltage response. With the series APF the mirrored harmonic current flow is allowed to flow to power grid but the induced voltage response is negated from the point of common coupling. The injected voltage is same amplitude as the grid side mirrored harmonic voltage response with 180 degrees phase shift. The admittance of the grid at the mirrored harmonic is frequency is sensed as infinity by the inverter under testing.

The APF itself does not require a PLL, but the mirrored harmonic signal detection must be made at the correct frequency. A MSOGI-FLL based frequency locked is used for detecting the exact grid frequency [9]. The MSOGI-FLL is tuned to reject the perturbation signal to make it possible to inject the perturbation voltage without distorting the frequency tracking. The PLL bandwidth is tuned by assessing how near the fundamental frequency the measurement is made. The power source of the APF needs to have high enough bandwidth for the DC-bus voltage control of the APF to appear as stiff DC-voltage source to avoid the measurement device causing additional harmonics.

The APF appears to operate at open-loop as the current measurements are made from the inverter side with the shunt

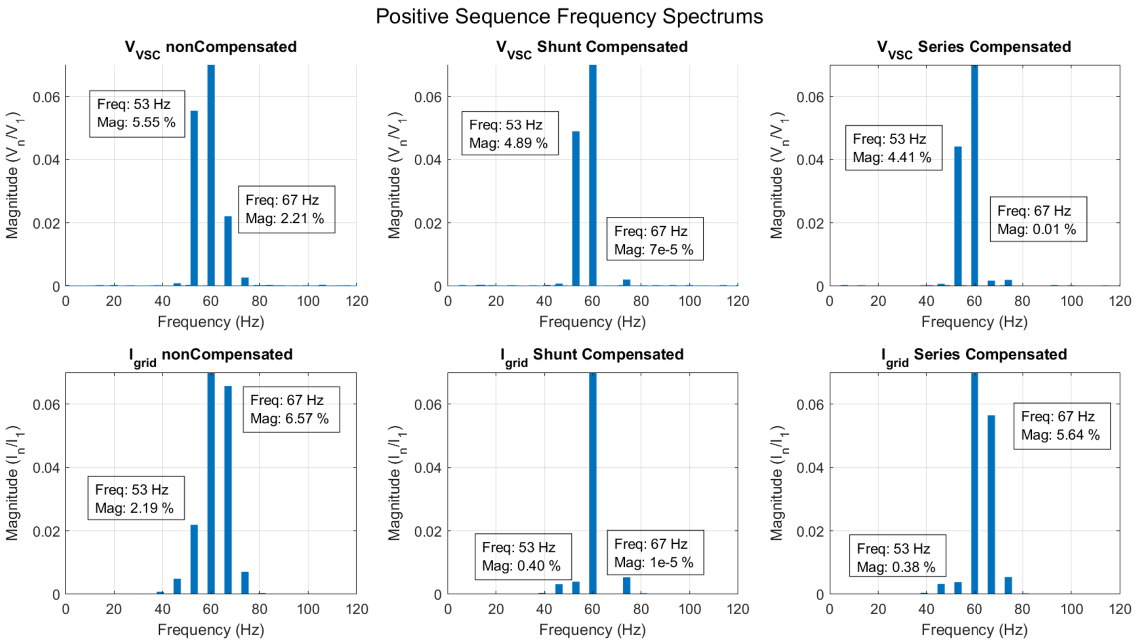

Fig. 5. Non-compensated and compensated current and voltage frequency spectrums with 53 Hz perturbation.

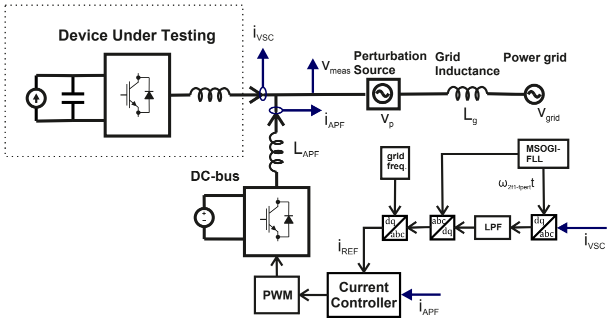

Fig. 6. Detection of the mirrored harmonic current response and mitigating it

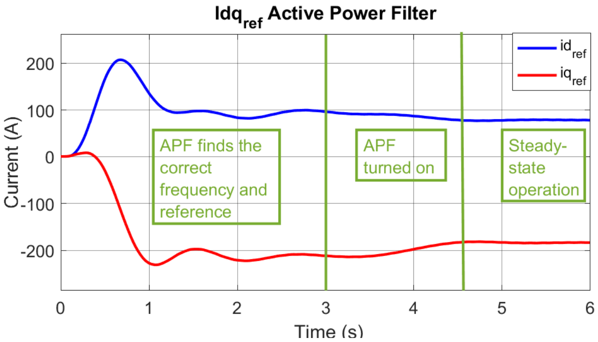

Fig. 7. Shunt active power filter mirrored harmonic current detection with 53 Hz perturbation

APF design and the voltage measurements are made from the grid side with the series APF design. However, there is a hidden feedback which must be analyzed. The measured inverter impedance is not infinite, and the source impedance is not zero, which means the injected current will be split to both branches and may cause stability issues when using the APF.

The series APF design allows integrating the voltage perturbation source, but with the shunt APF design the perturbation injection must be made with something else. With high powered devices where this measurement technique is required, the perturbation is created with additional equipment as the variable frequency drive used for creating the grid voltage during testing usually does not have fast enough control bandwidth.

V. SIMULATION EXPERIMENT AND ADMITTANCE MEASUREMENT

The inverter admittance measurement applying the APF is tested in a simulation with a 3 MW inverter. The inverter measurements are considered in an ideal condition and in a strong grid (SCR=3.3). Table 1 shows the test scenario parameters.

The simulation tests are made with Simulink. The active power filter and the measured inverter are modeled as switching mode devices. The voltage perturbation is made with sine wave perturbation. With the shunt APF the perturbation is made with additional perturbation source modeled as an ideal voltage source. The series APF design allows performing the voltage perturbation with the APF. Tables 2 and 3 show the parameters used for the shunt and series APFs. The DC-

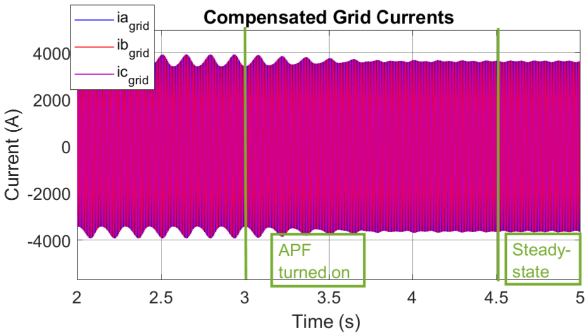

Fig. 8. The shunt APF compensates the mirrored harmonic from the current flowing towards the power grid

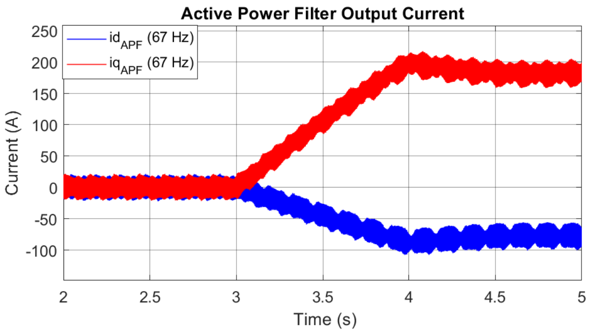

Fig. 9. The current injected by the shunt APF in dq-frame synchronized to the mirrored harmonic frequency.

voltage side is assumed to be from a fast operating outside power source, which appears as a stiff voltage source. The series APF is connected to the grid line with a 1:1 ratio ideal transformer. For future application of the method the transformer must be designed to be able pass high frequency signals without distorting them while also being able withstand the large currents flowing to the power grid.

TABLE I

SIMULATION PARAMETERS

Parameter	Symbol	Value
Inverter Apparent Power	S_{inv}	3 MVA
Inverter Switching Frequency	f_{sw}	3 kHz
Inverter DC-voltage	V_{DC}	1500 V
Grid Voltage	V_{ll}	690 V
Grid Frequence	f_{g}	60 Hz
Grid Inductance SCR 3.3	L_{g}	0.126 mH

TABLE II

SHUNT ACTIVE POWER FILTER PARAMETERS

Parameter	Symbol	Value
APF Apparent Power	S_{apf}	300 kVA
APF Switching Frequency	f_{sw}	20 kHz
Inverter DC-voltage	V_{DC}	1500 V
APF filter inductor	L_{apf}	0.58 mH

TABLE III

SERIES ACTIVE POWER FILTER PARAMETERS

Parameter	Symbol	Value
APF Apparent Power	S_{apf}	300 kVA
APF Switching Frequency	f_{sw}	100 kHz
Inverter DC-voltage	V_{DC}	200 V
APF filter inductor	L_{apf}	1.46 uH
APF filter capacitor	L_{apf}	5 uF

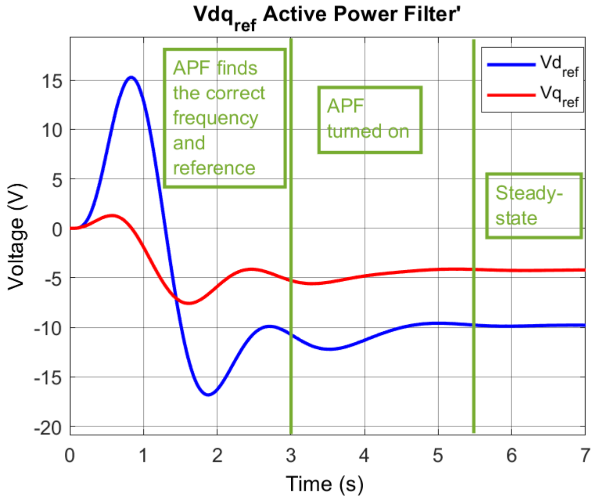

Fig. 10. Series active power filter mirrored harmonic voltage response detection from the grid voltage

Figs. 7-9 show the operation of the mirrored harmonic compensation with shunt APF design in the time domain. Fig. 7 shows the tracking of the mirrored harmonic. Fig. 8 shows the mirrored harmonic mitigated from the grid currents and Fig. 9 shows the injected current in the dq-frame. With the combination of a PLL and a low-pass filter, the correct frequency is reached in 5 seconds. The correct reference is reached in the next 5 seconds and then the APF is ramped to the full power within the next 1 second. The APF is capable of acting as a sink for most of the current at the mirrored harmonic and the voltage response at the mirrored harmonic frequency is negligible.

The same operation is shown for the series APF in Figs. 10 and 11. Fig. 10 shows the APF acquiring the correct reference and Fig. 11 shows the injected voltage containing the mirrored harmonic mitigation and perturbation signal for one phase.

Both shunt and series APF implementations are able to compensate the mirrored harmonic out of the measurements and the ideal output impedance and transfer impedance can be measured. The accuracy of the shunt and series compensated measurements are shown in table 4. At low frequencies, where the effect of the transfer impedance Y_c is significant the series APF has worse accuracy than the shunt APF implementation. This is caused by the filter capacitance used in the series APF connection.

At high frequencies, the measurement has an error in the

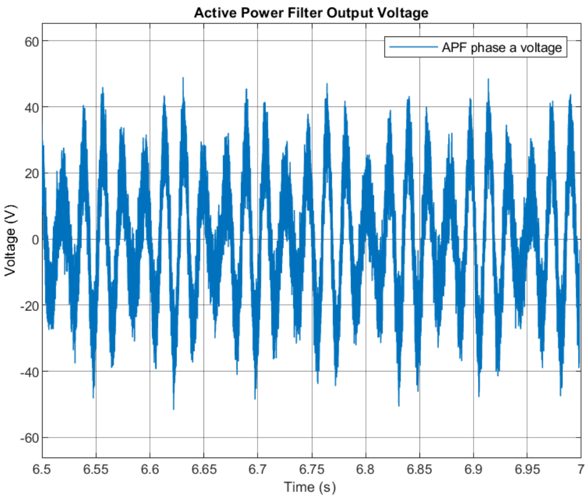

Fig. 11. Series active power filter phase-a voltage

TABLE IV
REAL AND IDEAL IMPEDANCES COMPENSATED AT 35 HZ AND 170 HZ WITH SCR 3.3 GRID IMPEDANCE

Measured Value	Ideal	Shunt Compensation	Series Compensation
35 Hz Y	17.1 dB -143 deg	17.2 dB -151 deg	19.2 dB 150 deg
35 Hz Y_p	6.51 dB 174 deg	6.00 dB 174 deg	7.45 dB 175 deg
35 Hz Y_c	19.4 dB -74 deg	19.4 dB -80 deg	20.4 dB -81 deg
170 Hz Y	4.49 dB 73 deg	3.39 dB 74 deg	4.27 dB 74 deg
170 Hz Y_p	3.67 dB 71 deg	3.4 dB 74 deg	3.40 dB 74 deg
170 Hz Y_c	1.93 dB 92 deg	3.3 dB 105 deg	2.4 dB 104 deg

phase of the transfer admittance Y_c. However, the error in the transfer admittance has small effect in the calculated output impedance at the point of connection at frequencies above the frequency $2f_1$. When calculating the real output impedance, the output admittance of the inverter is significantly larger than the transfer admittance.

VI. CONCLUSION

Recent studies have presented a number of impedance-based methods for stability analysis of grid-connected systems. In most studies, however, only low-power devices have been applied, and the effect of real power grid to the impedance measurements has been neglected.

This paper has presented an active-power filtering method to minimize the undesired load effect of the power grid in the measured inverter impedance. In the method (lisää tähän hieman tiivistä ja ytimekästä tarinaa miten homma toimii). Applying the presented method, the inverter output impedance can be reliably measured under non-ideal grid conditions.

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