Active Compensation of Unbalanced Load Currents in Grid Connected Voltage Source Converters

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***Abstract*—For a 2-level 3-phase voltage source converter connected to the grid, it should be capable of supporting the grid with maximum possible active and reactive power during balanced and unbalanced load condition. This paper discusses about the unbalanced current injection algorithm from a VSC to keep the grid currents balanced and sinusoidal in case of asymmetrical loading conditions. Positive and negative sequence synchronous reference frame control have been used to filter the unbalanced component in the grid currents and to compensate it from the converter. A case study with unbalanced reactive load has been simulated to verify the algorithm and the effect of compensation. The compensation reduces the asymmetry in PCC voltage and grid currents, and makes it close to sinusoidal shape to keep it within a standard limit of unbalance in grid power quality.**

***Index Terms*—Voltage Source converter, Positive and negative sequence control, DC link voltage control**

I. INTRODUCTION

In recent days, many renewable sources like wind and solar power are being integrated to the grid using voltage source converters (VSC). As the number of such VSCs connected to the grid are increasing, the grid code associated with it has also changed significantly [1]. This increasing trend of grid integration of VSCs should fulfill the requirements regarding low voltage ride through, grid support during transient faults, steady state unbalanced cases and voltage sag. According to [2], up to 5% of unbalance in grid voltage is allowed as a measure of voltage quality.

The incidences of grid faults and highly unbalanced loads give rise to unbalanced voltage at point of common coupling (PCC). Under such unbalanced conditions, the current injected into the grid can differ from its pure sinusoidal shape. The interaction between such currents and unbalanced voltage may lead to uncontrolled oscillation in active and reactive power delivered to the grid system. The smooth operation of VSCs under such scenarios are also challenging. However, such unbalances can be eliminated by injecting the unbalanced component of the currents from the VSCs connected to the network [1]. It is also evident that due to fast sampling and control mechanism available in the modern converters, it is also possible to compensate for lower order harmonic current along with unbalanced current components in the grid. The unbalanced current injection from the VSCs under unbalanced voltage conditions also helps attenuating power oscillations, maximizing the instantaneous power delivery and balancing the grid voltage at PCC.

In this paper, a case with highly unbalanced reactive load connected to the PCC has been investigated through a Simulink model. An unbalanced load connected to the PCC leads to the unbalanced grid current, which is not desirable and, therefore, the unbalanced component of the grid current has been compensated from the converter.The simulation model consists of a 2-level, 3-phase, 690 V, 50 Hz Voltage Source Converter connected to the grid. In this simulation, the transients due to capacitor switching and load connection have been ignored as the main focus is on improving the steady state performance.

II. CONTROL OF VOLTAGE SOURCE CONVERTER

A. Modelling of VSC

The schematic of a typical 2-level 3-phase VSC connected to a grid through an LCL filter is shown in Fig. 1. The modelling of a two-level VSC can be carried out in stationary reference frame or in synchronous reference frame (SRF). As the transformation of 3-ph quantities to SRF produces dc quantities and can be controlled using PI controller, it has been preferred in this paper.

Neglecting the small loss in the converter and the passive filter, the active power output can be expressed based on power balance on DC side and AC side. And, the per unit equation for it can be written as,

$$p = u_{dc} \cdot i_{dc} = u_{ac,cap} \cdot i_d = u_d \cdot i_d \tag{1}$$

where, u_d and i_d are the ac side voltage and current in synchronous reference frame.

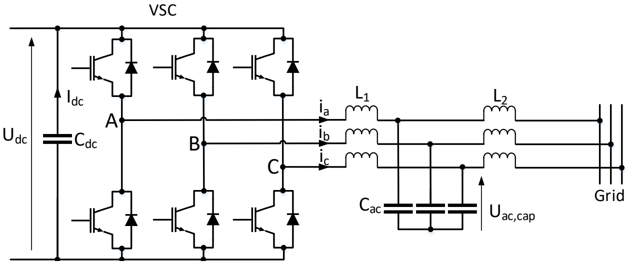

Fig. 1. 2-level 3-phase VSC with LCL filter.

In this case, the AC side capacitor is considered as PCC. The ac current in SRF i.e., (i_d) and the dc current (i_{dc}) are related with a constant ratio of the capacitors on both sides.

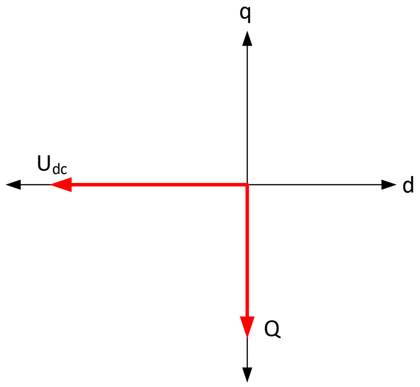

Fig. 2. Alignment of controlled parameters in SRF. DC link voltage is aligned to negative d-axis as the power out of the VSC has been considered positive. And, 90° behind the active power is the reactive power, i.e. negative q-axis is aligned to the positive reactive power out of the VSC.

The change in dc link voltage using (1) can now be formulated as,

$$C_{dc}\frac{du_{dc}}{dt} = i_{dc} = \frac{u_{ac,cap}}{u_{dc}} \cdot i_d \tag{2}$$

The PCC voltage $u_{ac,cap}$ is defined to be oriented along the d-axis, and then a virtual grid flux vector can be assumed to be acting along the q-axis as shown in Fig. 2. With this alignment, the instantaneous active power (p) and reactive power (q) out of the converter is expressed as,

$$\begin{aligned} p &= u_d \cdot i_d \\ q &= u_d \cdot i_q \end{aligned} \tag{3}$$

B. Control Philosophy

As given by (3), the control system consists of two outer controllers to generate the d and q axes current references as shown in Fig. 3, and one inner current controller. The outer controllers, according to the external references, control the dc-link voltage (U_{dc}) and the reactive power (Q). The inner current controller is a hysteresis band controller. The schematic of overall control system is presented in Fig. 4.

The active power required by the converter is only to cover the losses in the passive components and the switching devices, and is very small compared to the capacity of the converter. As there is no source of active power on the dc link, a limit of oscillation of U_{dc} by 10% can be allowed due to oscillatory power caused by the unbalanced load. Hence, the limit for i_d and i_q can be set as,

$$\begin{aligned} i_d &= 0.1 \cdot i_{max} \\ i_q &= \sqrt{i_{max}^2 - i_d^2} \end{aligned} \tag{4}$$

C. Negative Sequence Current Control

A perfectly balanced system produces only positive sequence current. In an unbalanced system, current flowing through the network can be decomposed into positive, negative and zero sequence components. As presented in Fig. 1, the dc link has no connection to the ground, therefore, the zero sequence component of current has no path to flow in case of unbalance due to phase-to-ground fault, and can be disregarded. Hence, the only component that causes the unbalance is negative sequence component of the load current.

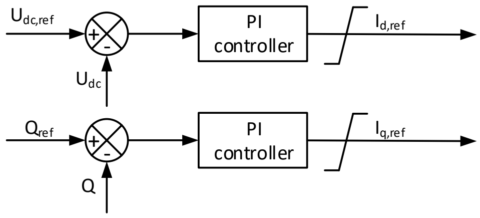

Fig. 3. SRF controller for dc link voltage and reactive power. DC link voltage and reactive power reference is provided by secondary controller.

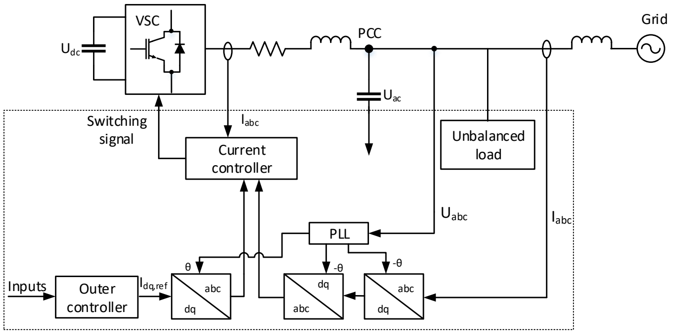

Fig. 4. Schematic of VSC with control blocks.

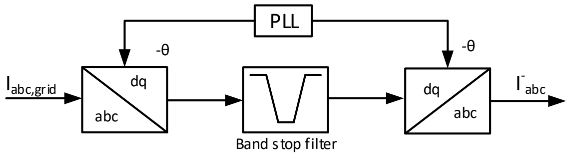

Fig. 5. Schematic of unbalanced current injection algorithm. The measured grid current is transformed to SRF in opposite direction to identify the negative sequence component. the positive sequence component thus oscillates at double frequency and is removed using band stop filter to let only the negative sequence pass through.

It was first introduced in [3] as dual-sequence SRF control where two different current controllers are used, one regulating the dq current references in positive synchronous reference frame, whereas the other in negative synchronous reference frame rotating in opposite direction compared to the former one. As shown in Fig. 5, the measured grid current is transformed to synchronous reference frame with negative PLL angle to filter the negative sequence current. The transformed value in negative sequence SRF constitutes of a dc value superimposed with the positive sequence part of the current with double the frequency of fundamental current (in this case $2 \times 50 = 100\ Hz$). A band-stop filter with cut-off frequency of 100 Hz is implemented to eliminate the oscillating positive sequence component and is transformed back to stationary frame. The cut-off frequency can be made adaptive where the fundamental frequency varies due to power sharing based on frequency droop.

The negative sequence current is added to the current reference generated by two outer controllers. The sum of these currents is passed to the inner hysteresis band controller to generate the switching signals.

D. Unbalanced Current Injection

The impact of unbalanced load and hence the unbalanced current i.e. negative sequence current in this case can be quantified using instantaneous power theory. According to instantaneous power theory [4], the instantaneous power in a network when expressed in terms of positive and negative sequence components consists both constant and oscillatory terms, and can be stated as,

$$\begin{aligned}
\bar{p} =& 3U_+ I_+ \cos(\phi_{u+} - \phi_{i+}) + 3U_- I_- \cos(\phi_{u-} - \phi_{i-}) \\
\bar{q} =& 3U_+ I_+ \sin(\phi_{u+} - \phi_{i+}) - 3U_- I_- \sin(\phi_{u-} - \phi_{i-}) \\
\tilde{p} =& -3U_+ I_- \cos(2\omega t + \phi_{u+} + \phi_{i-}) \\
& -3U_- I_+ \cos(2\omega t + \phi_{u-} + \phi_{i+}) \\
\tilde{q} =& -3U_+ I_- \sin(2\omega t + \phi_{u+} + \phi_{i-}) \\
& +3U_- I_+ \sin(2\omega t + \phi_{u-} + \phi_{i+}) \\
p =& \bar{p} + \tilde{p} \\
q =& \bar{q} + \tilde{q}
\end{aligned} \tag{5}$$

where $\bar{p}$ and $\bar{q}$ denote the average part of active and reactive power, whereas $\tilde{p}$ and $\tilde{q}$ denote the oscillatory part of active power (p) and reactive power (q) respectively. The above expressions for unbalanced grid conditions can also be rewritten as,

$$\begin{aligned}
p &= P_0 + P_{c2}\cos(2\omega t) + P_{s2}\sin(2\omega t) \\
q &= Q_0 + Q_{c2}\cos(2\omega t) + Q_{s2}\sin(2\omega t)
\end{aligned} \tag{6}$$

where P_0 and Q_0 are the average values of the instantaneous active and reactive powers whereas, P_{c2}, P_{s2}, Q_{c2} and Q_{s2} represent the magnitude of the oscillating terms in these instantaneous powers [5], [6]. From (5) & (6), it can be noted that the oscillatory active and reactive power components has the double frequency as in the case of single phase instantaneous power. As it is convenient to design and tune the controllers with DC quantities, power flow in a converter is mostly calculated using voltage and current magnitudes in synchronous reference frame. Hence, the magnitude of the above power quantities can be calculated as,

$$\begin{aligned}
P_0 =& \frac{3}{2}(u_d^+ i_d^+ + u_q^+ i_q^+ + u_d^- i_d^- + u_q^- i_q^-) \\
P_{c2} =& \frac{3}{2}(u_d^- i_d^+ + u_q^- i_q^+ + u_d^+ i_d^- + u_q^+ i_q^-) \\
P_{s2} =& \frac{3}{2}(u_q^- i_d^+ - u_d^- i_q^+ - u_q^+ i_d^- + u_d^+ i_q^-) \\
Q_0 =& \frac{3}{2}(u_q^+ i_d^+ - u_d^+ i_q^+ + u_q^- i_d^- - u_d^- i_q^-) \\
Q_{c2} =& \frac{3}{2}(u_q^- i_d^+ - u_d^- i_q^+ + u_q^+ i_d^- - u_d^+ i_q^-) \\
Q_{s2} =& \frac{3}{2}(-u_d^- i_d^+ - u_d^- i_q^+ + u_d^+ i_d^- + u_q^+ i_q^-)
\end{aligned} \tag{7}$$

where superscripts “+” and “-” denote the positive and negative sequence components.

III. SIMULATION RESULTS

The VSC and the control blocks are simulated in Simulink as shown in Fig. 4. The outer controller blocks and the measurements are carried out in digital environment and the interrupt runs at 9 kHz. An unbalanced capacitive load is connected at the PCC of the grid connected VSC. The parameters involved in the simulation is presented in Table I.

The events in the simulation model are as follows:

i) at $t = 0.15$ s, a step change of 100 V applied to the dc link voltage reference $U_{dc,ref}$
ii) at $t = 0.25$ s, a dc load of 270 kW connected to the dc link
iii) at $t = 0.30$ s, unbalanced capacitive load is connected to the PCC, and
iv) at $t = 0.50$ s, unbalanced capacitive load is disconnected from the PCC.

The unbalance current injection is active all the time during the simulation and it injects the negative sequence current whenever it is detected by the transformation block. The transient due to inrush current during connection of capacitor (at $t = 0.30$ s) has not been considered as it can be eliminated by implementing a proper method of capacitor switching.

TABLE I
PARAMETERS USED IN SIMULINK MODEL

Nominal Voltage	U_n	690 V
Nominal Current	I_n	800 A
Frequency	f	50 Hz
LCL Filter	L_1	83 µH
	C_{ac}	996 µF
	L_2	50 µH
Unbalanced Load	Z_1	$(0.002 - j0.80)$ Ω
	Z_2	$(0.002 - j1.59)$ Ω
	Z_3	$(0.002 - j3.18)$ Ω

A. Positive and Negative Sequence Current

The reactive load which is connected to the circuit at time instant $t = 0.30$ s is highly capacitive and consists a very small resistance, but equal in all phases i.e. the load does not dissipate energy except in the small resistance. Therefore, the positive sequence component of the grid current remains same at a value of 622.5 A (as shown in Fig. 6) whereas the negative sequence component reaches to 138 A. The compensation for the negative sequence current from the converter improves it to 35.6 A as shown in Fig. 7. The percentage reduction in negative sequence current with respect to positive sequence current is from 22.2 % to 5.7 %.

B. Positive and Negative Sequence Voltage

As it can be observed from (5), only the elimination of both negative sequence voltage at PCC and the negative sequence grid current can lead to zero oscillating power. In this

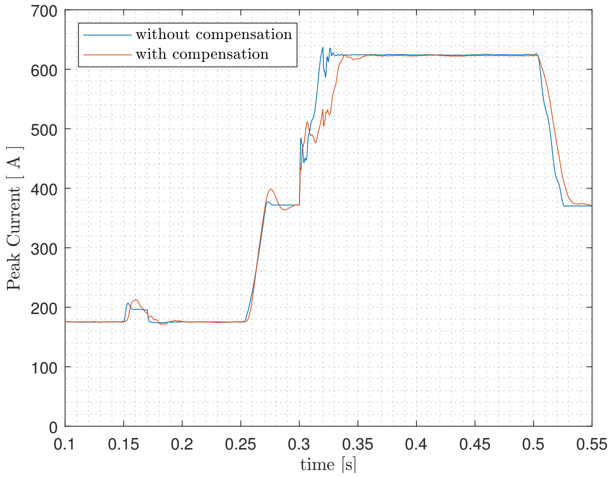

Fig. 6. Positive sequence component of grid current. The first rise in the current at $t = 0.25s$ is due to the dc load and the second rise at $t = 0.30s$ is due to the capacitive unbalanced load. As the load is highly reactive, the positive sequence current has not been affected and therefore, has not been compensated by the VSC.

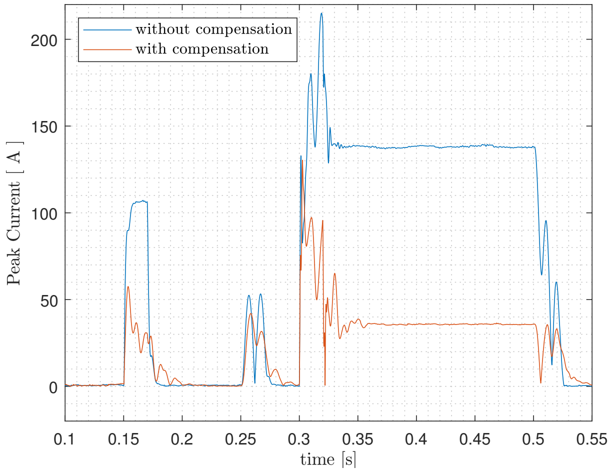

Fig. 7. Negative sequence component of grid current. Step change in dc link voltage and dc load connections at $t = 0.15s$ and $0.25s$ respectively give rise to transient negative sequence current. The unbalance capacitive load connection at $t = 0.30s$ causes a very high increment (138 A) in this current (blue color curve). After the compensation from VSC, this current has fallen to 35.6 A (orange color curve).

simulation, the VSC is connected to a relatively strong grid (i.e. the impedance between the PCC and the grid is very low); therefore, the unbalance current caused by the unbalanced load connected at PCC has not much effect on the voltage. The positive sequence component of the voltage remains intact as displayed in Fig. 8 and, therefore, no compensation current needed to improve this part. The negative sequence component of the voltage has also relative low amplitude and is 1.55 V which reduces to 0.4 V when the compensation for negative sequence current is enabled as shown in Fig. 9. The voltage will differ significantly according to the grid impedance i.e. higher the grid impedance, higher will be the impact of unbalanced load on the PCC voltage.

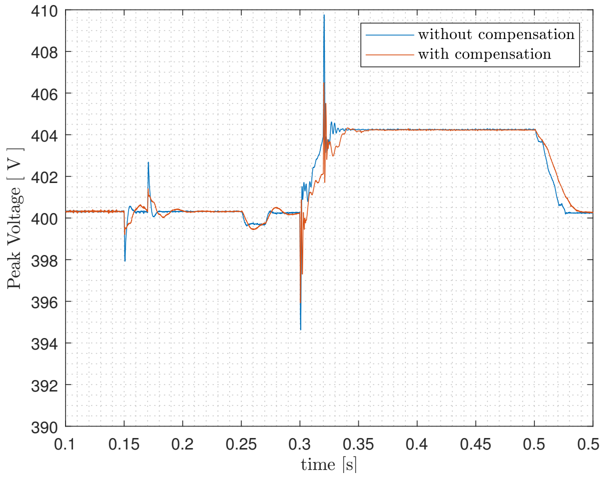

Fig. 8. Positive Sequence Component of PCC Voltage. The connection of capacitive load at $t = 0.30s$ give rise to huge inrush current and lead to voltage spikes. An appropriate capacitor switching method can resolve this problem. The capacitive load has increased the PCC voltage from 400.2 V to 404.4 V.

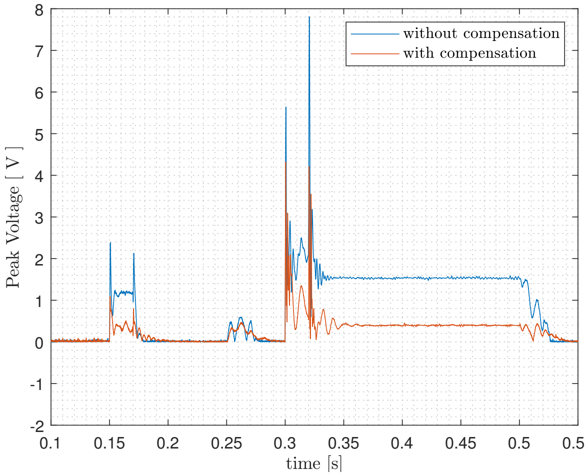

Fig. 9. Negative Sequence Component of PCC Voltage. As the VSC is tightly coupled to the grid (i.e. with low inductance between PCC and grid), the negative sequence component of PCC voltage has gone up only by 1.55 V. The compensation from VSC has drawn it back to 0.4 V.

C. Active and Reactive Power

The grid supplies 270 kW in normal condition to the load connected to the DC side of the converter. The steady state active power is approximately 280 kW as shown in Fig. 10 which includes the losses in the converter and passive filter components. From $t = 0.30\ s$ to $t = 0.50\ s$, the unbalanced load is connected and the peak-to-peak variation in active power without compensation for negative sequence current is 270 kW (from -150 kW to -420 kW). The peak-to-peak variation decreases to 56 kW (from -254 kW to -310 kW) with compensation i.e. a reduction in oscillation from 96.4 % to 20.1%.

Similarly, the peak-to-peak variation in reactive power is 235 kVAr (from 330 kVAr to 565 kVAr) without compensation when the unbalanced capacitive load is introduced. As it can be observed from the Fig. 11, the same variation shrinks to 85 kVAr (from 403 kVAr to 488 kVAr) after the negative sequence component caused by the load is delivered from the converter.

In both active and reactive power, the amplitude of oscillatory part has reduced.

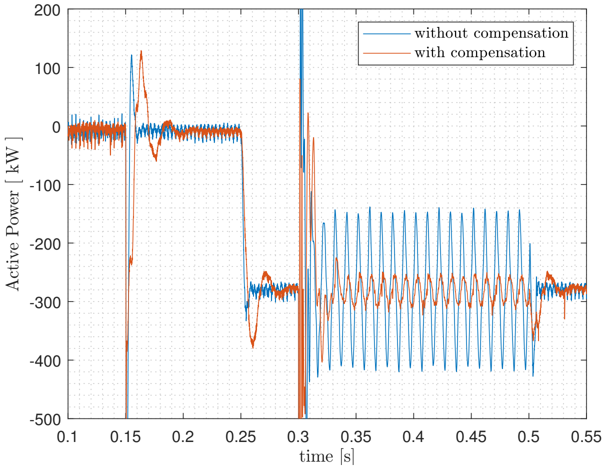

Fig. 10. Effect of Compensation on Active Power. Due to aggressive tuning of dc-link controller loop, a step change in dc-link voltage reference at $t = 0.15s$ leads to a large power towards the converter. The dc load connected at $t = 0.25s$ is of 270 kW. The unbalanced reactive load connected at $t = 0.30s$ has a very small resistance and therefore, the constant part of the power remains at that value. The unbalanced load causes an oscillation of another 270 kW which reduces to 56 kW after enabling the compensation for negative sequence current from the VSC.

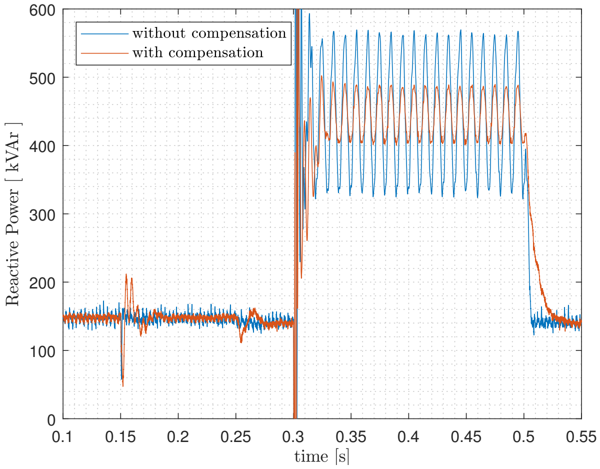

Fig. 11. Effect of Compensation on Reactive Power. Until $t = 0.30s$, the VSC is delivering 146 kVAr to the grid which is from the filter capacitor (part of LCL filter). After the connection of unbalanced capacitive load at $t = 0.30s$, the constant part of reactive power has increased to 450 kVAr and the oscillatory part to 235 kVAr. The compensation from VSC reduces the oscillatory part to 85 kVAr.

As expressed in (6), both the active and reactive power consists of double frequency oscillatory components due to the negative sequence component of the current. The theoretical calculation for active power (constant and oscillatory parts) according to (5) is compared in the Table II. The results also verifies the accuracy of simulation model. The simulation results for the oscillatory power terms are higher than the calculated values because of the loss in the grid side impedance, which is not included in the calculation.

TABLE II

THEORETICAL CALCULATION OF POWER TERMS. THE TABLE SUMMARIZES THE AMPLITUDE AND PHASE OF POSITIVE AND NEGATIVE COMPONENTS OF PCC VOLTAGE AND GRID CURRENT. USING (5), THE CONSTANT AND OSCILLATORY PART OF THE INSTANTANEOUS POWER IS CALCULATED FOR BOTH WITH AND WITHOUT COMPENSATION FROM VSC. THE CALCULATION MATCHES CLOSELY TO THE SIMULATED VALUE EXCEPT FOR THE OSCILLATORY PART WHICH IS DUE TO GRID IMPEDANCE.

Parameters	Without compensation	With compensation
U_+	404.2 V	404.2 V
ϕ_{u+}	-0.53°	-0.53°
U_-	1.55 V	0.4 V
ϕ_{u-}	-162°	174°
I_+	623 A	623 A
ϕ_{i+}	-122.4°	-122.4°
I_-	138 A	35.6 A
ϕ_{i-}	108°	84°
$\bar{p}$	281.8 kW	281.8 kW
$\tilde{p}$	239 kW	62 kW
$\bar{q}$	452.8 kVAr	453.3 kVAr
$\tilde{q}$	234.4 kVAr	60 kVAr

D. Converter and Grid Currents

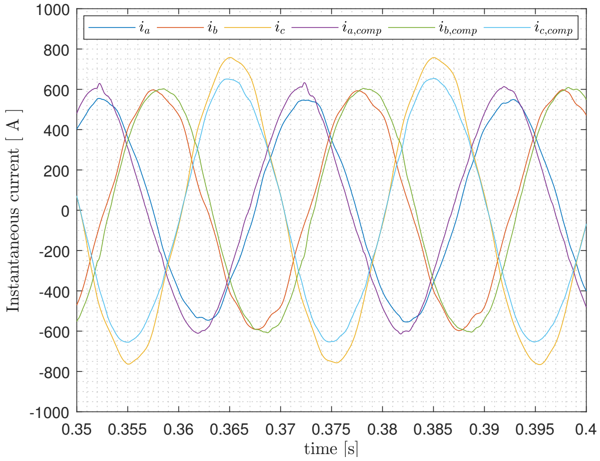

Fig. 12. Instantaneous Grid Currents when load is connected. The subscript “comp” in the legend are for the case with compensation for negative sequence current from VSC. The currents for compensated case (magenta, green and cyan) are well balanced compared to the uncompensated case (blue, red and yellow).

The instantaneous waveform of the grid current and the converter current are presented in Fig. 12 and Fig. 13 respectively. The subscripts “comp” in the legends present the currents with the compensation for negative sequence current activated. It can be observed from the shape of current waveforms that the unbalance in the grid currents have clearly been transferred to the converter side when the compensation is activated. The reduction in unbalance can be quantified by the same number as described for reduction in negative sequence current i.e. from 22.2 % to 5.7 %.

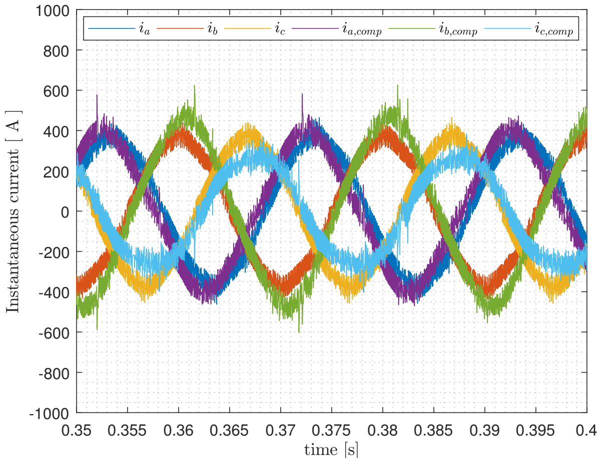

Fig. 13. Converter currents when the load is connected. The current waveforms for the compensated case (magenta, green and cyan) are unbalanced whereas the same for uncompensated case (blue, red and yellow) are balanced i.e. the VSC is delivering the unbalance part of the current caused by the load.

E. DC link Voltage

The controller is tuned to control the dc-link voltage to a reference value. As it can be observed from the Fig. 14, at $t = 0.15\ s$, a step of 100 V has been applied to the voltage reference and the measured voltage settles within 40 ms with an overshoot of 20 %. The overshoot is relatively high (40 %) when the compensation for unbalanced current is activated. This can be controlled using the limit for the unbalanced component that will limit the high current injection during dynamic conditions and the oscillation can be reduced.

There is no energy source connected to the dc-link, therefore, it cannot deliver active power to balance the losses in the resistive components in the passive filter and the capacitive load caused by the unbalanced current. The oscillation in dc-link voltage between the interval $t = 0.30\ s$ to $t = 0.50\ s$ when the unbalanced load is connected, is due to the aforementioned reason. However, such a small oscillation of $\pm 10\ V$, which equates to 0.9 % of the steady state value of dc link voltage, can be accepted for such applications.

This topology can be further improved with an energy source on the dc-link which will then be capable of contributing to supply for the unbalanced resistive load as well as will keep the dc-link voltage constant.

IV. CONCLUSION

This paper investigates the impact of unbalanced reactive load to the grid current and PCC voltage in a system with grid connected VSC. The method to filter the unbalanced component of the grid current in synchronous reference frame has been implemented in a 690 V, 800 A converter. It is apparent from the simulation results that the method significantly reduces the unbalance in the grid current. The negative sequence component of the grid current reduces from 22.2 % to 5.7 % with respect to the amount of positive sequence component of the current which, consequently, decreases the negative sequence component of the PCC voltage. The method helps to improve the voltage waveform close to sinusoidal to meet the standard limit.

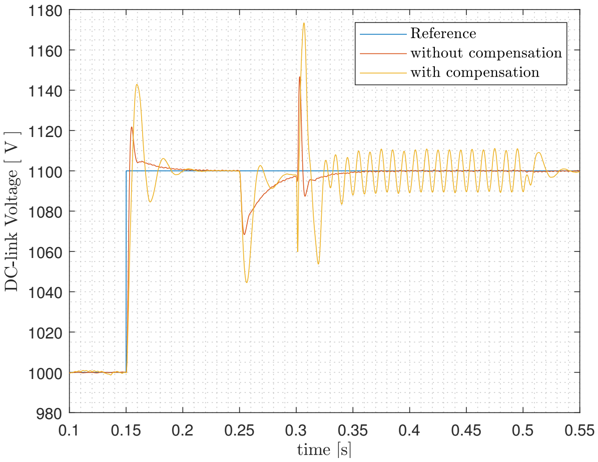

Fig. 14. . DC link voltage at different events. At $t = 0.15s$, the dc-link voltage increases to 1100 V as per the reference in the simulation. The overshoot is 40% and the settling time is 40 ms. After the unbalanced load is connected at $t = 0.30s$, the dc link is oscillating with a peak-to-peak amplitude of 20 V due to the active power consumption in the small resistances of LCL filter. A energy source at dc-link can resolve this.

However, the simulation model can further be improved with an energy source connected to the dc link such that it can compensate for the unbalanced resistive load as well and can keep the dc-link voltage constant. In addition, a proper switching method for capacitor switching can also be implemented to avoid the inrush current during capacitor connection.

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REFERENCES

[1] R. Teodorescu, M. Liserre, and P. Rodriguez, Grid Converters for Photovoltaic and Wind Power Systems. Wiley-IEEE press, 2011. 398 p., 2010.

[2] H. Markiewicz and A. Klajn, "5.4.2 Standard EN 50160 Voltage Characteristics in Public Distribution Systems," Wroclaw University of Technology, p. 16, Jul. 2004.

[3] H.-S. Song and K. Nam, "Dual current control scheme for PWM converter under unbalanced input voltage conditions," IEEE Transactions on Industrial Electronics, vol. 46, no. 5, pp. 953–959, Oct. 1999.

[4] H. Akagi, E. H. Watanabe, and M. Aredes, Instantaneous Power Theory and Applications to Power Conditioning. Wiley-IEEE press, 2007.

[5] P. Rioual, H. Pouliquen, and J. P. Louis, "Regulation of a PWM rectifier in the unbalanced network state," in Proceedings of IEEE Power Electronics Specialist Conference - PESC 93, 1993, pp. 641–647.

[6] P. Rioual, H. Pouliquen, and J.- Louis, "Regulation of a PWM rectifier in the unbalanced network state using a generalized model," IEEE Transactions on Power Electronics, vol. 11, no. 3, pp. 495–502, May 1996.

[7] L. Xu, B. R. Andersen, and P. Cartwright, "VSC transmission operating under unbalanced AC conditions - analysis and control design," IEEE Transactions on Power Delivery, vol. 20, no. 1, pp. 427–434, Jan. 2005.