Control Loop Interaction in Parallel Connected High Frequency Grid Converters

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***Abstract* – Recent progress in power electronic converters has increased the number of distributed energy sources to the grid. These converters act as a source of harmonics which connected with other loads affect the stability of power grid. Parallel operation of converters is common in power grid depends on the power sharing needs and current rating of power semiconductor devices. Though, these connections improves power handling capability of grid, the dynamic interaction between converters can affect stability of system. This paper addresses the stability issues in parallel connected, high frequency voltage controlled converters with an output LC filter. Studies on interactions between control loops verifies that, harmonic instability introduced by parallel converters can't be stabilized by traditional PI controllers in real power control loop. A new damping algorithm is introduced to suppress these harmonic oscillations caused by the interaction of controllers in grid connected converters.**

***Index Terms* – Grid Converter, Parallel Connection, Harmonics, Controller Interaction, Active Power, High Frequency, SVPWM.**

I. Introduction

Power quality requirements are very stringent in grid connected system around the world. Parallel connection of voltage source converters are adopted in grid connected system to incorporate with the power handling capability of the power semiconductor devices and output filter requirements [1]-[2]. Moreover, converters can be switched ON /OFF according to the load demand. An LC or LCL filter is connected at the output of the converter to eliminate the switching frequency harmonics. These filters can induce series or parallel resonances in the system, which can be mostly eliminated by damping methods. Passive damping method is commonly used to mitigate these resonance effects, but it can cause additional losses in the system. In order to overcome this, some authors proposed active damping solutions, where virtual resistor or capacitor voltage feedback in current controlled converters [3]. These damping techniques compensates for individual converter instability issues.

In parallel connected systems, harmonic interaction between converters and their controllers can develop sustained oscillations in the system. Many studies are conducted to analyze the harmonic effects in parallel connected grid converters [4]-[7]. Voltage source converters (VSC) can operate in current controlled mode or voltage controlled mode. Normally an LC filter is utilized in voltage controlled converters, whereas LCL filter can eliminate switching harmonics in current controlled converters. In [8], the harmonic interaction in multiple current controlled and voltage controlled converters are modeled to show the effect of dynamic interaction between the controllers. Direct and quadrature axis based decoupled control is most commonly adopted in current controlled grid converters, whereas in [9], PR controller is utilized for eliminating circulating currents. Small signal analysis was carried out to analyze the stability issues in parallel connected standalone inverters [10] and droop control based frequency and voltage control is utilized in [11] to obtain stable operation of distributed energy resources in micro grid. These studies are carried out at converters switching at few kHz frequencies.

Recent developments in high frequency switching devices like silicon carbide (SiC) MOSFETs and JFETs [12]-[13] leads to operate converters at higher switching frequency with reduced switching losses, which will drastically reduce the size of output filters. Since output capacitors can cause resonance with cable inductances, the reduction in capacitor value will reduce the harmonic oscillations due to output capacitor [14]. The stability issues caused by circulating currents due to the interaction of controllers are still present at high frequency operation. Harmonic interaction and resonance effects in high frequency converters will fall in the range of 2- 9 kHz, due to the reduction in filter size at high frequency. Mostly, the harmonic effects in voltage and current are studied up to 2 kHz, it has to be extended till 9kHz, which is the lower limit of EMI [15]. The type of pulse width modulation schemes used in grid connected VSCs can also reduce the harmonic effects in converters. Even though, sinusoidal PWM is the traditional method utilized in converters, a third harmonic injection based PWM methods and space vector PWM [16], [17] can effectively reduce the harmonics in addition to better DC link voltage utilization.

In this paper, stability issues in parallel grid connected converters are analyzed by connecting two voltage controlled VSCs to the point of common coupling (PCC). The controller of each converter operated with outer real power controller with inner state feedback linear quadratic regulator based voltage and current control [18], [19]]. Closed loop Space Vector PWM (SVPWM) is adopted as PWM scheme for each converter [20]. The dynamic interaction between PI control based real power loops in both converters results in unnecessary oscillations in grid connected systems. A damping factor is introduced in the real power loop to eliminate sustained oscillations present in the active power feeding to the grid. Part II describes the individual control implementation of grid connected voltage controlled converters. The harmonic effects due to dynamic interaction between controllers is modeled and analyzed in section III. The proposed method is validated with the help of simulation software PSCAD and corresponding results are described in part IV. Conclusion of the paper is given in section V. The parameters chosen for simulation are illustrated in section VI.

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II. GRID CONNECTED CONVERTERS - INDIVIDUAL OPERATION

An equivalent circuit of grid connected converter connected to grid through a feeder is depicted in Fig. (1).

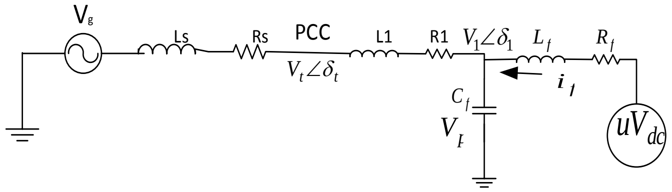


Figure 1 Single Line diagram of Grid Connected Converter

where, uV_{dc} is the converter voltage, L_s and R_s corresponds to grid inductance and resistance, L_1, R_1 represents the feeder inductance and resistance of the converter and L_f, C_f are filter parameters. Assuming the feeder is highly inductive, average real power can be defined as given in equation (1).

$$P = \frac{VV_t}{X}\sin(\delta - \delta_t) \quad (1)$$

$V_t\angle\delta_t$ is the voltage at point of common coupling (PCC) and X is the equivalent impedance. Assuming the angle difference is small, the power is proportional to the angle $(\delta - \delta_t)$. Normally grid voltage V_g is considered as $V_g\angle 0$. Considering the negligible drop across feeder impedance, magnitude of voltage at filter capacitor is assumed as network voltage. Thus, active power feeding to the grid can be controlled by controlling the voltage angle.

A. *Closed Loop Control of Converter I*

Fig. 2 represents the closed loop control diagram for voltage controlled grid connected converter.

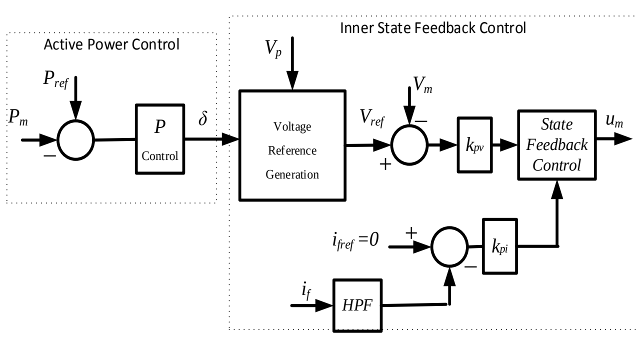


Figure 2 Closed Loop Control of Grid Converter

The control loop consists of two loops, outer active power control and inner state feedback control. The measured instantaneous power is passed through a low pass filter to obtain the average value, and it is compared with the reference power to be supplied to the grid. The error is then passed through a controller to generate the required voltage angle. The output of this converter gives angle δ, which is used to find out the desired voltage reference in state feedback control. A PI or PID controller is used to track the actual power to the amount of power feeding to the grid. The detailed study with PI and PID controller is explained in Part II. Three phase converter with an output LC filter is depicted in Fig. 3, where $S_1 - S_6$ represents the switching pulses, L_f, R_f and C_f corresponds to filter inductance, converter losses and output capacitance.

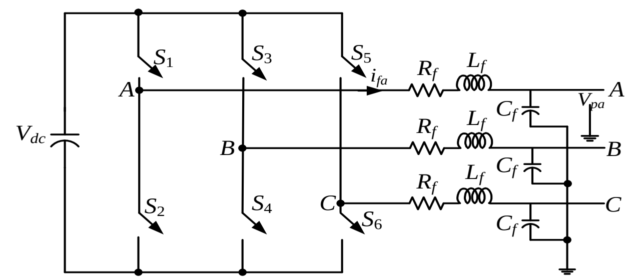


Figure 3 Three Phase VSC with output LC filter

Desired value of three phase reference voltages at the PCC can be defined as,

$$\begin{aligned} v_{Pa}^{*} &= |V_P|\sin(\omega t + \delta) \\ v_{Pb}^{*} &= |V_P|\sin(\omega t + \delta - 120^\circ) \\ v_{Pc}^{*} &= |V_P|\sin(\omega t + \delta + 120^\circ) \end{aligned} \quad (2)$$

where, $|V_P|$ is a pre-specified network voltage magnitude, δ is an angle that maintains the power flow from VSC to the grid and ω is the rated frequency. One line diagram of converter with output LC filter is illustrated in Fig. (4).

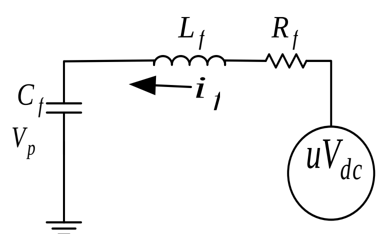


Figure 4 Per Phase Equivalent of converter with output filter

State space equation for converter I can be written as given in equation (3) and state variables x_i is defined in equation (4), where i_f is the current through filter inductor and V_p is filter capacitor voltage.

$$\dot{x}_i = A_i x_i + B_{1i} u_i \quad (3)$$

$$x_i^T = [\mathrm{i}_f \ V_p] \quad (4)$$

The output capacitor voltage v_p and the inductor current i_f are the states used in linear quadratic regulator based state feedback proportional control. As these technique accounts the filter characteristics, the effect of phase shift generated by the use of passive LC filters have been included in control algorithm. Since it is hard to define the reference value of i_f , modified reference value of i'_f is set as zero. In order to eliminate the mismatch in measured value of current, it is passed through a high pass filter (HPF), as i_f contains only low frequency components. The reference value of voltage and current are then compared with measured values, to obtain the error signal. The state feedback control is defined as given in (5).

$$u_c = k(x_{ref} - x) \quad (5)$$

Where, state feedback gain matrix, $k = [k_1 \;\; k_2]$ and $x_{ref} - x$ is the error signal. The filter capacitor voltage reference v_P^* is compared with the measured value v_p and corresponding voltage and current errors are fed to a linear quadratic regulator based state feedback control. The resultant output of state feedback control is then utilized to obtain the modulating signal used for PWM generation.

B. PWM Generation

The modulating signal generated by the control loop is utilized for generating the switching signals (S_1-S_6) for three phase converter. As the harmonics generated by the converter depends upon the type of PWM scheme, a closed loop space vector modulation SVPWM [20] which can effectively utilizes the DC link voltage is selected for converter switching pulse generation. The modulating signal generated by closed loop SVPWM is capable of utilizing 15% more DC link voltage compared with traditional sinusoidal PWM. Moreover, lower harmonic distortion due to the inherent addition of third harmonic signal to sinusoidal waveform in SVPWM enhances its suitability to grid connected applications.

III. CONTROLLER INTERACTION IN PARALLEL CONNECTED VSCS

A three phase network, where two parallel voltage controlled converters are connected to the grid through feeder is depicted in Fig. 4.

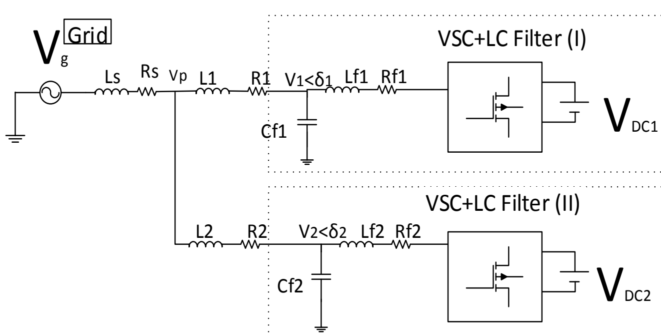


Figure 5 One line Diagram of Grid Connected VSCs

A constant DC Link voltage is assumed for converters. L_s and R_s corresponds to grid inductance and resistance. L_1, R_1 and L_2, R_2 represents the feeder impedance for converter 1 and 2 respectively. An LC filter is utilized at the output of converter to get rid of switching frequency harmonics L_f and C_f corresponds to filter inductance and capacitance for different converters.

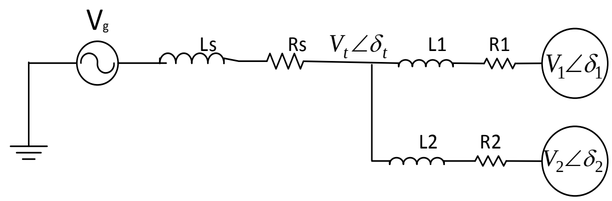


Figure 6 Single Phase Equivalent Circuit

The real power delivered by the converters to grid can be written as mentioned in Equation (6).

$$P_1 = V_1 V_t \sin(\delta_1 - \delta_t)$$
$$P_2 = V_2 V_t \sin(\delta_2 - \delta_t) \quad (6)$$

The outer loop system transfer function can be written as

$$\frac{k}{s+\alpha} = \frac{k}{s+\frac{R1}{L1}} \quad (7)$$

Step response of this system with PI and PID controller is shown in Fig. (7). Results verify that both PI and PID controller have satisfactory response for outer loop control of VSC. Note that the effect of controller interaction is not incorporated in this case.

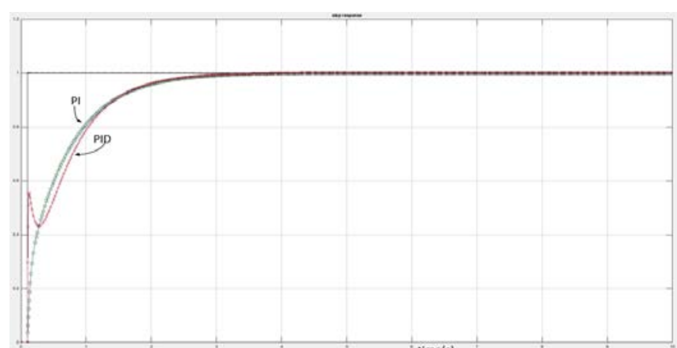


Figure 7 Step Response of VSC Real Power with PI and PID

The interaction between the controllers can be modelled by feeding back a part of converter 1 real power to converter 2 and vice versa as given in equation (8). In reality the interconnection of controller algorithm is difficult due to excessive communication requirements. In addition, it creates delay in converter fast switching operation. During parallel operation this may lead to sustained oscillations which cause unstable condition.

$$P_1 + x_2 P_2 = V_1 V_t \sin(\delta_1 - \delta_t)$$
$$P_2 + x_1 P_1 = V_2 V_t \sin(\delta_2 - \delta_t) \quad (8)$$

Since the angle difference $\delta_1 - \delta_t$ and $\delta_2 - \delta_t$ are very small, $\sin(\delta_1 - \delta_t) \cong (\delta_1 - \delta_t)$, $\sin(\delta_2 - \delta_t) \cong (\delta_2 - \delta_t)$. Also assuming the angle at PCC $\delta_t \cong 0$, real power can be rewritten as

$$P_1 \propto (\delta_1 - x_2 P_2)$$
$$P_2 \propto (\delta_2 - x_1 P_1) \quad (9)$$

This strategy is explained in Fig. (8), where $\frac{k}{s+\alpha}$ is the system transfer function. A part of converter 2 real power is fed back to converter 1 real power. As the controller is the mirror image of system, the same factor is subtracted inside the controller. This factor is treated as a disturbance signal inside the controller. PI or PID control can be used as real power control as shown in Fig. (9). Similar strategy has been applied to converter 2, where a part of converter 1 power is used as disturbance signal.

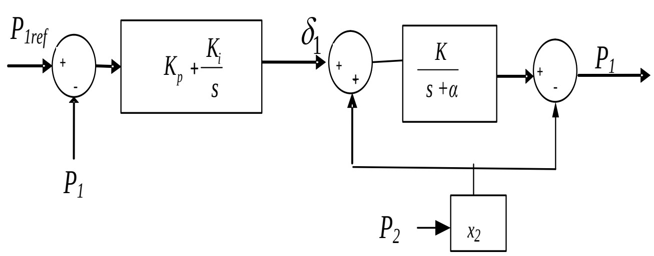


Figure 8 Outer Loop Real Power- Closed loop operation

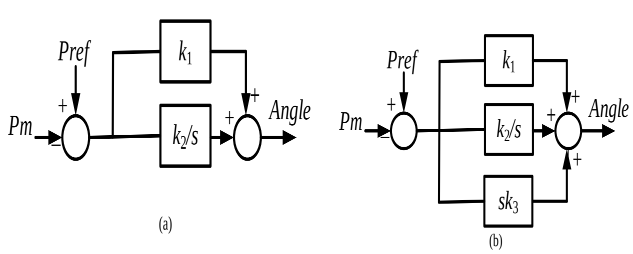


Figure 9 (a) PI Control (b) PID Control

The step response of above mentioned system with PI and PID control is illustrated in Fig. (10).

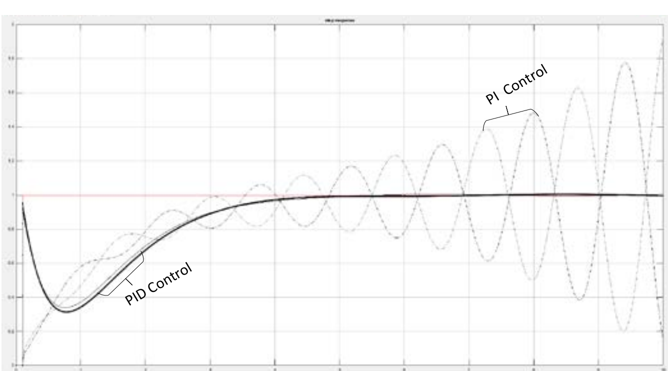


Figure 10 Step Response of parallel connected VSC Real Power with PI and PID

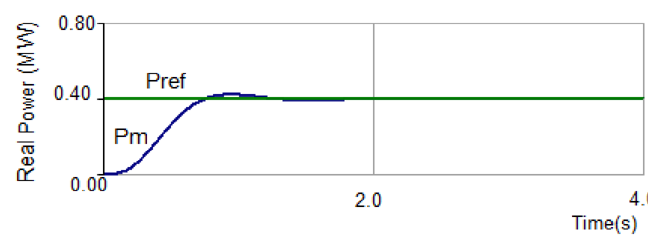
As seen from the response with PI control, sustained oscillations in P1 and P2 leads to unstable operation of the system. Even though the PI control work for individual operation, the interaction between the control loops may lead to unstable operation. These unnecessary oscillations can be damped out by introducing a damping factor to the system. Here a PID control is proposed to damp down the resonance oscillation caused by the interaction of the parallel converter. Moreover, it limits the peak overshoot and steady state error to an acceptable range. A compromise between peak overshoot and settling time is inevitable for active power loop in parallel operation of converter.

IV. Simulation Study

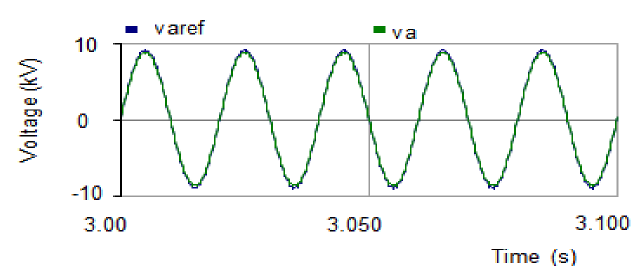
In this section, simulation studies are conducted using PSCAD for grid connected converters to demonstrate the interaction between control loops of each converter when connected in parallel. Three different case studies and corresponding results are presented. The data chosen for grid and converters are given in Table I.

A. Case-1: Converter I connected to grid

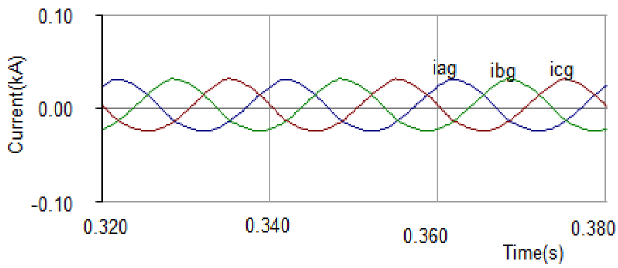
In this example, converter 1 is switched at a frequency of 100 kHz and the output filter values are reduced accordingly. Due to the decreased value of 2uF filter capacitor, the interaction with cable inductances is found to be negligible in high frequency converters. Control algorithm described in section 2 is used for the closed loop operation. Here, a PI controller is used to regulate the real power. It is clear from Fig. 10(a) that, real power is following the reference value and feeding 400kW to the grid. At t=1.2s, the controller acquired steady state and the maximum overshoot and the steady state error falls in the acceptable limit. Inner loop voltage and current controller are operating well within the defined limit and corresponding waveforms for phase-a converter voltage and three phase currents are illustrated in Fig. (10). Even though the resonance frequency is falling in the range of 2-9 kHz, the harmonics are not dominant in this range, giving a grid voltage and current THD of 0.56% and 2.5 % respectively.



(a)



(b)

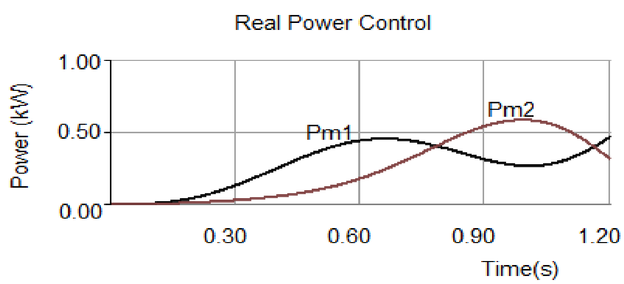


(c)

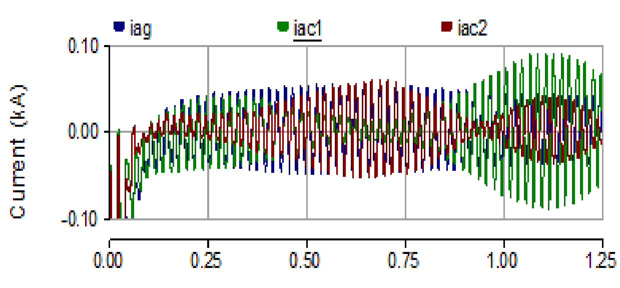
Figure 10 Converter I connected to Grid (a) Real Power (b) Phase-a Voltage Control (c) Grid Currents

B. Case-2: Converter 1 & 2 with independent PI controller

Each converter is controlled by independent controller. Outer loop utilizes PI control to regulate the real power supply to grid. Even though, controller is following the reference value until steady state, oscillations around required power makes the system unstable as depicted in Fig. (12.a). Filters used for measuring real power, increased the system order and delay, which in turn make the closed loop complex and uncontrollable by PI. The circulating currents in converter are shown in Fig. (12.b), clearly reveals that a constant current flowing to grid, but the current circulating through converters are responsible for oscillations in the parallel system. Even though, the converter currents are oscillatory in nature, the grid current distortion was found to be 3.8%.



(a)

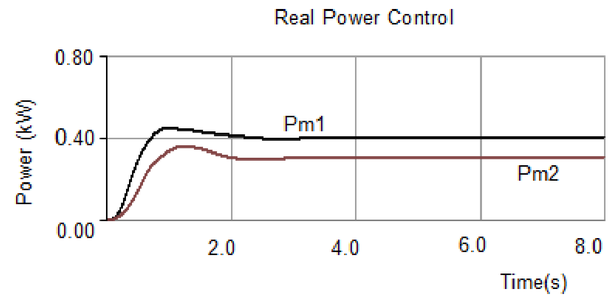


(b)

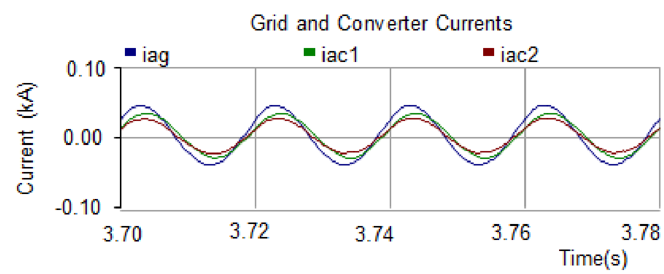
Figure 12 Converter 1 & 2 with Real Power-PI control (a) Real Power (b) Grid and Converter Currents

C. Case-3: Converter 1 & 2 with independent PID controller

Here, a damping factor is introduced in the active power control loop to mitigate the unnecessary oscillations in the real power, which in turn controls the circulating currents. Converter 1 and 2 are supplying 400W and 300W to the grid respectively as depicted in Fig. (13). The maximum overshoot and the steady state error lies in the limits as per grid requirements and grid voltage and current THD is found to be 0.45 % and 3.6% respectively. Amplitude of harmonics present around the resonant frequency of filter is very small and thus eliminates the necessity of individual passive or active damping methods. This in turn reduces the loss in overall system, in addition to reduced losses in highly efficient fast switching power converters.



(a)



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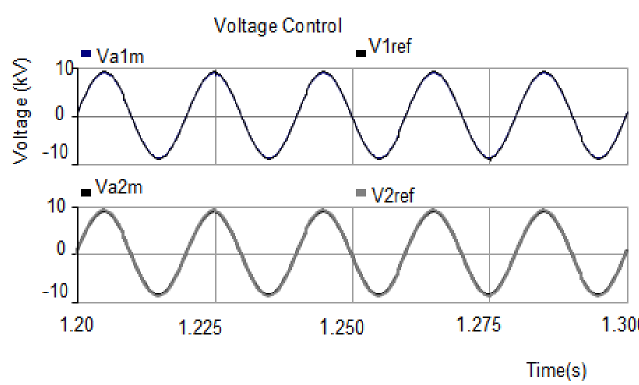

(c)

Figure 13. Converter 1 & 2 with independent PID control (a) Active Power Feeding to Grid (b) Phase a Grid and Converter Currents (c) Phase a Capacitor Voltage Control

V. Conclusions

This paper analyses the stability issues in parallel connected voltage source converters operated in grid feeding mode. It has been clear that the significant reduction in filter size in high frequency converters reduced the harmonic interaction between filters and feeder cables. Controller interaction is still present in high frequency converters, where real power controller of one converter interacts with other converters destabilizes the system, thus results in sustained oscillation in the power and circulating currents. Traditional PI controller is not capable of suppressing this oscillations and simulation studies and results verifies, proposed PID controller is well suitable for eliminating the oscillations in converter real power and makes the grid connected parallel system stable.

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APPENDIX

Table I. Parameters for Parallel converters connected to Grid

System Quantities	**Values**
Grid Voltage	*11kV*
Grid Impedance	R_{f1} = 1.21 Ω, L_{f1} = 38.5 mH
Feeder impedance Converter 1 Converter 2	 R_{f1} = 0.25 Ω, L_{f1} = 12 mH R_{f2} = 0.21 Ω, L_{f2} = 10 mH
Converter 1 Rating	400 kW
Converter 2 Rating	300 kW
Load-1	R_{La}=500 Ω, L_{La} = 320 mH R_{Lb}=500 Ω, L_{Lb} = 320 mH R_{Lc}=500 Ω, L_{Lc} = 320 mH
Switching Frequency	100 kHz
State feedback Control (Voltage- Current)	
Converter 1-Voltage Gain	93
Converter 1-Current Gain	150.5 rad/kWs
Converter 2-Voltage Gain	93 kV/MVAr
Converter 2-Voltage Gain	150.5 kV/MVAr

Table III. PARAMETERS OF Real Power (PID) CONTROLLER

System data	**Value**
Proportional gain (K_P)	0.05
Integral gain (K_I)	0.5
Differentiator gain (K_D)	0.022