Mode Adaptive Inverter Control for Snchronization, is Landing and Grid Connected Modes in abc Frame

Dr. Md. Shibli Rahmani

Associate Professor, Department of Physics, R.B.S College, Andour, Mohiuddin Nagar(R.S), Samastipur, Bihar, Pin-846502, India
Email: *rahmani.shibli[at]gmail.com*

Abstract: ***AC to DC inverters interfacing renewable energy sources operates in different modes to supply power to the grid or a microgrid. We propose a mode adaptive controller which synchronizes an incoming inverter, shares power in islanded mode and supplies power to the grid in its presence. The proposed controller is in abc frame. Index Terms Mode Adaptive Control, Inverter, abc frame.***

Keywords: quantum operator, Yoga-Practice, normal state, Samadhi state

1. Introduction

Future electricity grids will have a higher percentage of renewable energy sources (RES) connected to the grid to meet the load. RES like solar photovoltaic generates DC output voltage and wind generators have variable frequency ac as output voltage. The electricity grid operates at fixed frequency and voltage (nominal values). In order to supply power generated by RES to the grid, inverters are used. Inverter is a controllable device which takes a reference voltage signal and tracks it to give an output matching the reference signal. Inverters are dc to ac converters. Every incoming inverter has to synchronize to the localized grid voltage before they can supply power to a microgrid or to the grid. Two ac sources when connected in parallel to share load have to be synchronized. Synchronization will ensure no circulation of current from one inverter to other. Ac voltage waveform has three characteristic features: amplitude, frequency and phase. Two electric sources are said to be synchronized if they match each other in these characteristic features.

Phase locked loop (PLL) is used for synchronization parameter information to be used in control [1]. Three phase voltages have fundamental frequency component and higher order harmonics. Harmonics, noise, distortion and unbalances in the signal if dominant can affect the response of PLL. The various architectures of PLL are reviewed in [2]. An ideal PLL should be immune to noise, unbalance, harmonics in the signal and provide accurate and fast synchronization [2]. Different version of PLL are implemented for power application in [3], [4], [5], [6], [7], making PLL more robust and providing higher degree of immunity to disturbances. In [3] authors propose Enhanced Mode Adaptive Inverter Control for synchronization, is landing and grid connected PLL which can sustain unbalances in three phases. Authors in [7] describe mathematical model of power flow in a microgrid.

The inverter behaves differently in presence or absence of grid. Grid is a huge collection of sources to meet bulk distributed or lumped load, because of its huge size, they are assumed to have an infinite inertia (or a very large inertia in practical language). Whenever an inverter is connected to a grid, inverter follows grid voltage and transfer power by shifting the phase magnitude to supply active and reactive power [8], [9]. The power control of voltage controlled VSI using phase angle is sensitive to phase errors and large harmonic currents can occur under distortions in grid voltage [8]. However grid voltage distortions are not considered in this work. Parallel connected power sources in absence of grid is said to be islanded. In absence of a grid, multiple or isolated local power sources cannot behave in the same manner as in grid connected, each inverter needs to generate a reference voltage for itself. The reference voltage depends on its capacity. Droop control is very commonly used methodology for power sharing of inverters connected in parallel. Droop control does not require any information about the state of other converters connected in parallel [10]. Droop control assumes linear relationship between active power and frequency (P-f) and reactive power and voltage magnitude (Q-V) for an inductive microgrid [11].

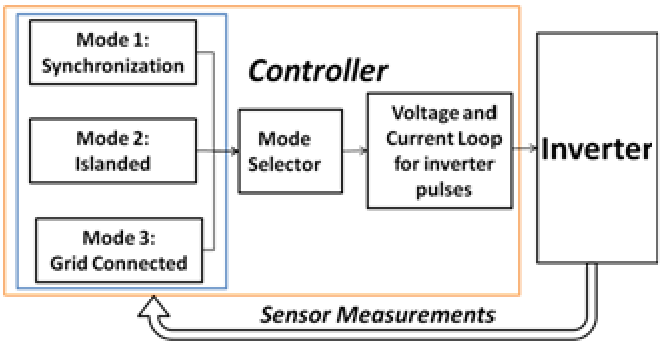

Figure 1: Proposed Mode Adaptive Control

In summary the reference voltage for inverter control can be generated in three deferent ways i.e. synchronization, droop control or grid connected mode, a mode selector will decide which reference voltage should be tracked using inner loops of voltage and current control. We propose a mode adaptive structure of inverter control selected according to its mode of operation. Figure 1 shows the control structure of proposed mode adaptive control. Depending on which mode inverter is operating in i.e. synchronization, islanded or grid connected, the reference voltage is selected to be tracked by outer voltage loop and inner current loop of inverter control. This Paper proposes a control strategy based on mode adaptive control to operate parallel connected inverter interfaced DG sources in islanded and grid connected modes. Simulation results of the proposed strategy verify the stable operation of system under unequal filter parameters. The paper is organized as follows, synchronization and its implementation is outlined in section II, Theoretical analysis of droop control is discussed in section III, the grid connected mode of operation is described in section IV, the simulation parameters are described in section V and conclusion in section VI.

Mode 1: Synchronization

PLL keeps the output signal synchronized in frequency and phase with reference to the input signal. The most common synchronization solution to a time-varying signal is described by the block diagram shown in Figure 2. Input signal shown in the figure is the voltage signal and the output is the phase of the input signal.

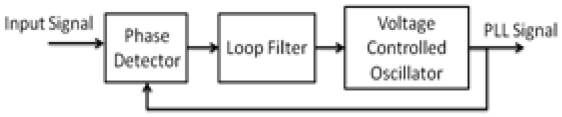

Figure 2: Conventional Phase Locked Loop [1], [2]

Phase detector and voltage controlled oscillator are nonlinear devices [4]. The output of a phase detector is the phase difference between two oscillatory input signals. The phase error is passed through a low pass loop filter. The output of filter is input to VCO. The VCO produces an output signal which follows the input signal. The PLL locks the phase and hence the frequency. PLLs have been extensively used in diversified applications.

Grid Synchronization has been a critical component to connecting large number of converters into the grid. The concern here is the stability of the system during unbalances, harmonics and drastic frequency fluctuations. In order to synchronize the grid with the voltage converters:

- Phase of the grid and DC-AC inverter has to be zero
- The frequency of the grid and incoming inverter has to be same
- The output voltage magnitude of inverter has to be equal to the grid/ microgrid voltage magnitude

When the above three conditions are met the two sources are called synchronized, under this state the inverter is connected to the grid, it will be seamless with almost no transient surges in circulating currents. Circulating currents are an unwanted scenario when power flow is not from the converter to the load but from one/multiple converters among themselves. A PLL assists interconnecting multiple power sources to share common loads. The attributed power sharing of an inverter does not happen because of PLL but of other power sharing algorithms like droop or communication based power sharing technologies. The seamless transformation of synchronization to power sharing mode is highly necessary for stable power supply. Another approach may be coming up with a hybrid control which uses a synchronization signal as well as power sharing signal without any mode transfer. Several modifications of conventional PLL were observed because:

- Conventional PLL may fail under large harmonic conditions; Positive sequence extraction before PLL will provide only the fundamental component of input waveform to be tracked hence the possibility of the PLL being stuck at a non-fundamental component of the input signal [3].
- Unbalances may also fail the output of conventional PLL; unbalanced voltages are commonly caused by load unbalances
- In some of the simulation it is observed that conventional PLL only keeps a track of the phase and frequency, however for seamless connection of two power sources their voltage magnitudes should also be similar. At times because of unequal voltages the system fails (power oscillations begin and its oscillations become unstable and grow larger and larger with time). Various PLL architectures are available in literature which considers magnitude tracking loop in addition to conventional or modified PLL.

Conventional 3-phPLL is highly sensitive to grid voltage unbalances. Thus, use of symmetrical components is suggested in extended 3-ph PLL [3].The elimination of negative and zero sequence will turn an unbalanced system into a balanced 3 phase system. Use of fundamental component will nullify the effect of harmonics. For the simulation evaluation the system is balanced and harmonics are not considered and we implement Synchronous Frame PLL as described in [2].

2.1. Simulation Based Implementation Mode 1

Synchronization with power sharing simulations of parallel voltage source converters is conducted in Matlab Simulink. Mathematical Model

$$q = 2/3 \times a - 1/3 \times b - 1/3 \times c \qquad (1)$$

$$d = -1/\mathrm{sqrt}(3) \times b - 1/\mathrm{sqrt}(3) \times b \qquad (2)$$

$$qe = q \times \cos(\theta) - d \times \sin(\theta) \qquad (3)$$

$$de = q \times \sin(\theta) + d \times \cos(\theta) \qquad (4)$$

The qe-component of the reference signal in equation 3 is forced to zero as a measure of system synchronization, which results in reference being locked to utility voltage vector phase angle [2]. The output of PI regulator is omega. The omega is used to generate the sine and cosine terms which is used in the control loop to generate reference voltage signals to be tracked by inverter controller.

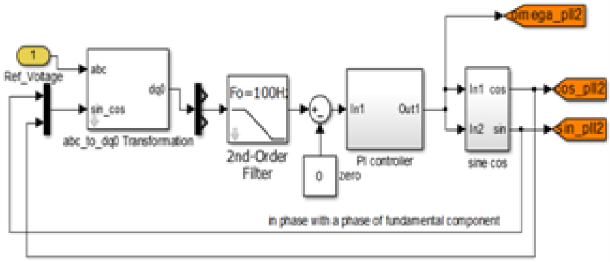

Figure 3: Phase Locked Loop Implemented in Simulink

Figure 3 shows the PLL used for synchronization. The use of low pass filter will ensure the elimination of higher order harmonics. An oscillator is used to generate reference sine and cosine terms to be used for generation of reference voltage shown in Figure 8.

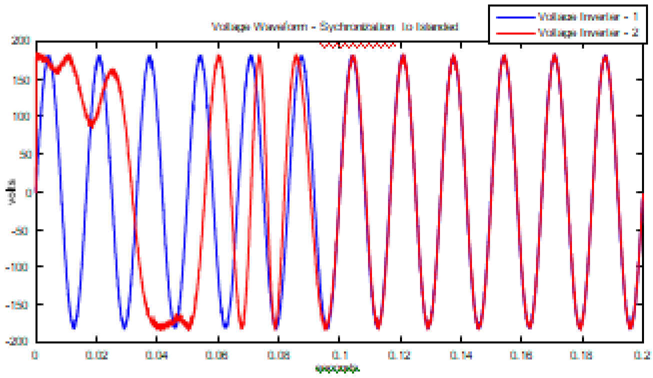

Figure 4: Inverter 1 and 2 voltage signals

Inverter 2 follows inverter 1 using PLL shown in figure 3. The inverter 1 is connected to the load and incoming inverter needs to synchronize to share electric load. At time 0 a command is sent to inverter 2 to begin synchronizing. The input to PLL for inverter 2 uses the local voltage and not the output voltage of inverter 1. Figure 4 shows the inverter voltages. It is observed that inverter 2 completely tracks inverter 1 voltage signal within 0.1 second. The inverter reference voltage used by PLL to track the desired inverter is a locally available signal and not of the other inverter and hence no communication is needed. It should be noted that often inverters in a distributed system are located at different locations making the information related to other converters difficult. Our control uses the voltage signal just beyond the breaker separating the inverter with the microgrid.

3. Mode 2: Droop Control

Parallel control of inverters is crucial for power sharing among inverters. The inverters should share power harmoniously maintaining the power quality and there should be no circulating ideally among converters. The challenging aspect of RES interfaced by an inverter in a microgrid is to share power proportionally. RES are intermittent in nature and generate power according to solar irradiance for solar PV or wind speed for wind turbines. Power output of RES is very dynamic, it is essential to proportionally sharing power among all power sources in a microgrid.

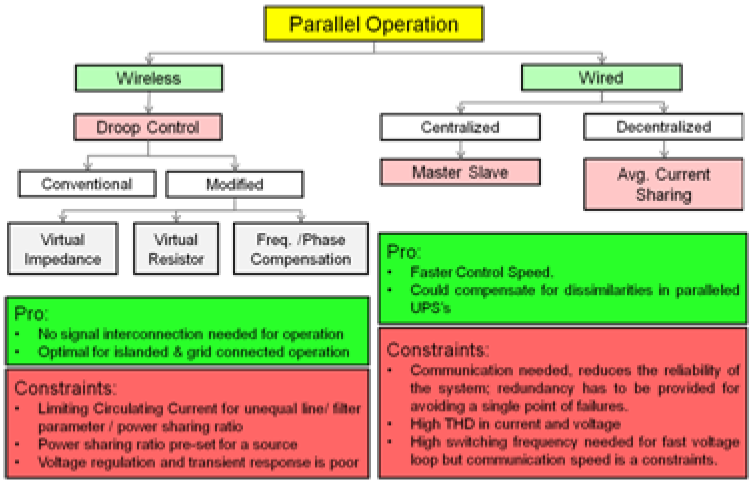

Figure 5: Comparison of Parallel Control Mechanisms

The parallel operation of power electronic converters can be done in multiple ways listed in figure 5. Figure 5 classifies power sharing algorithms elaborately defining pros and cons of the methodology. For medium voltage and high voltage line which are highly inductive in nature, droop control uses voltage and frequency as control inputs which enable DGs to share the load as per droop constants without any communication network. Active (P) and Reactive power (Q) flow into line is described in [10]. Conventional droop assumes

$$Z \approx X\,, \quad (5)$$

$$\sin(\text{power angle}) \approx \text{power angle}(\phi), \quad (6)$$

$$\text{Impedance angle}(\theta) = 90\text{deg} \qquad (7)$$

which simplifies power sharing equations to

$$\text{Active Power, } P \cong E \times V/X \times \phi \qquad (8)$$

$$\text{Reactive Power, } Q \cong V/X \times (E - V) \qquad (9)$$

For low voltage distribution network, resistance (R) cannot be neglected as impedance is resistive in nature, applying reverse droop strategy considering Z approximately equal to R, equations for reverse droop can be derived. Further simplification leads to:

$$\omega_{(}ref) = \omega^{*} - m_{1} \times P \qquad (10)$$

$$V_{(}ref) = V^{*} - n_{1} \times Q \qquad (11)$$

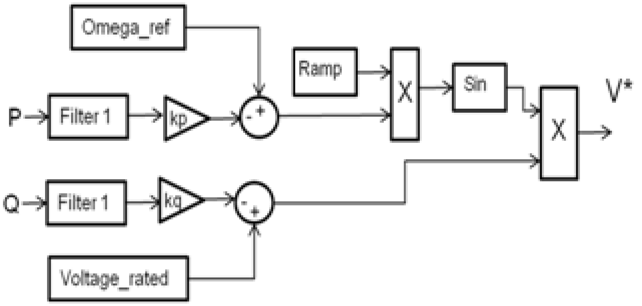

Figure 6: Droop Controller

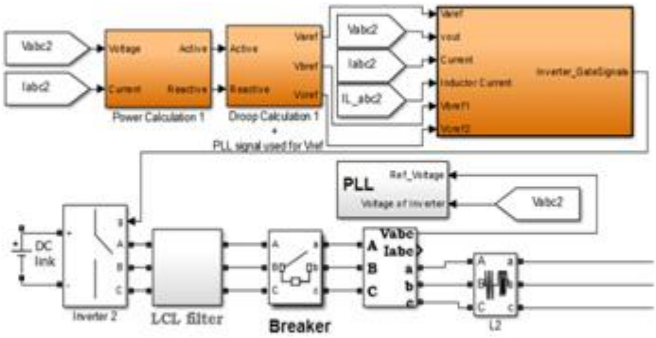

Figure 7: Inverter plus Controller Schematic

Figure7 shows inverter control used in simulations. The control structure is modular and can be used for n-inverters connected in parallel. The control operation of each inverter is independent of remote signals. The PLL reference uses the accessible voltage signal before the breaker. Figure 8 shows the mode adaptive controller. As discussed earlier the power sharing i.e. droop control and synchronization uses different methodology for voltage reference generation. Inverter 1 is online and at no load, inverter 2 starts tracking localized microgrid voltage. A load is connected to the microgrid, initially whole load is fed by inverter 1 and then inverter 2 after synchronization is connected to the microgrid. Once inverter 1 and 2 are connected in parallel we expect them to share power. Figure 10 shows the current waveform of inverter 1 and 2, within

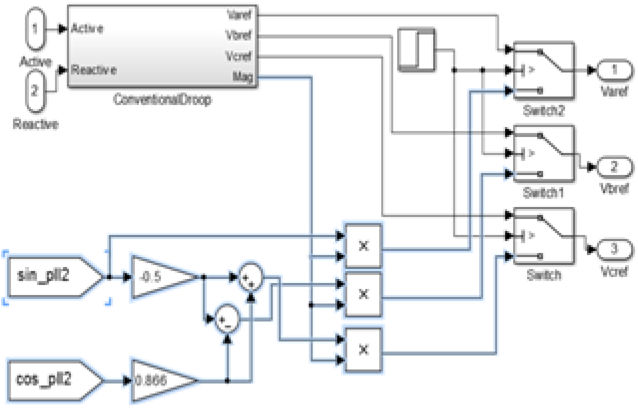

Figure 8: Mode Adaptive Controller for synchronization and droop control

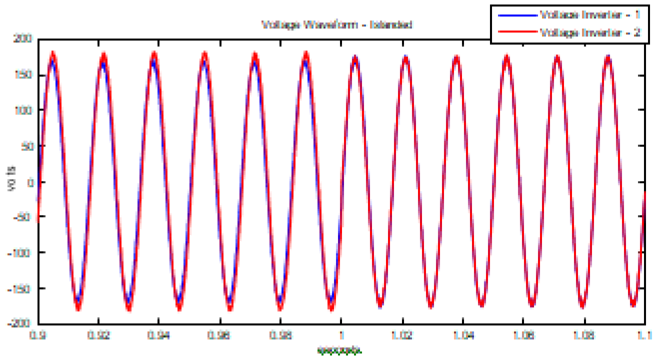

Figure 9: Inverter 1 and 2 voltage waveforms of Phase A

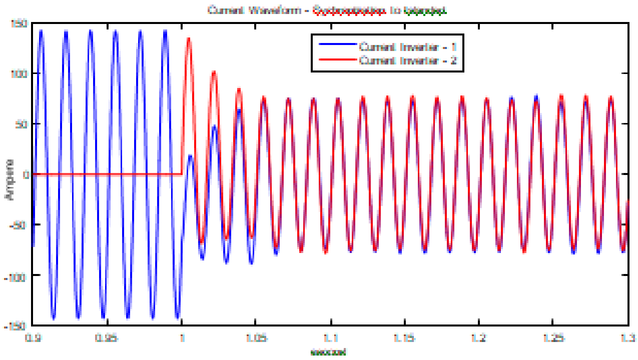

Figure 10: Inverter 1 and 2 current waveforms of Phase A

0.1 seconds of the incoming inverter the currents are shared proportionally. Figure 9, 10 and 11 shows the simulation results. Figure 9 shows the voltage and current of inverter 1 and2 for phase A. Figure 10 and 11 shows the active and reactive power shared by inverter 1 and 2. It should be noted that the LC filter components of Inverter 1 and 2 are different by 10

Figure 11: Active Power Sharing waveforms of inverter 1 and 2

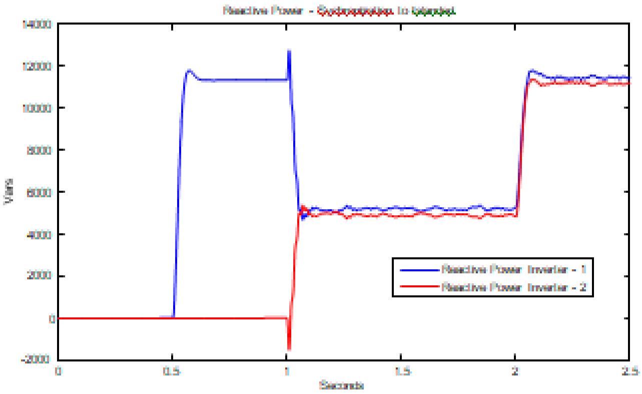

Figure 12: Reactive Power Sharing of inverter 1 and 2

	Inverter 1	Inverter 2
Inductor of Filter	110 e-6	100 e--6
Capacitor of Filter	149.6 e-6	136 e--6

The power sharing between inverters are stable as depicted in Figure 10 and 11. Table 1 shows the evaluation of droop based islanded control in presence of LC Filter mismatch (10

4. Mode 3: Grid Connected Control

When the grid is present and the inverters need to supply power, they do not need droop control for power sharing. The grid connected inverters follow the grid voltage for power sharing. The inverter behaves differently in presence or absence of grid. Grid is a huge collection of sources to meet bulk distributed or lumped load, because of its huge size, they are assumed to have an infinite inertia. Whenever an inverter is connected to a grid, inverter follows grid voltage and transfer power by shifting the phase magnitude to supply active and reactive power [8, 9].

Conceptually the grid connected mode is similar to the synchronization mode, the difference is for grid connected mode the inverter control tracks the grid voltage and for synchronization the control tracks the voltage at the breaker separating the inverter and the rest of the power system. The power supplied during grid supplied during grid connected mode depends on parameter the delta theta and voltage. Parameter delta theta added to grid frequency (rad/sec) measured by PLL, this controls the power supplied by the inverter and the voltage magnitude to be tracked by control w.r.t. to grid voltage.

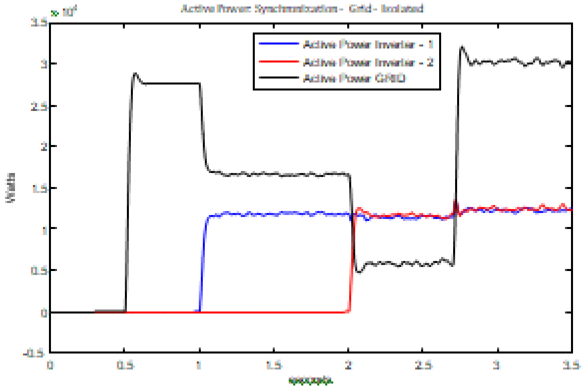

Figure 13: Active Power Sharing of inverter 1 and 2

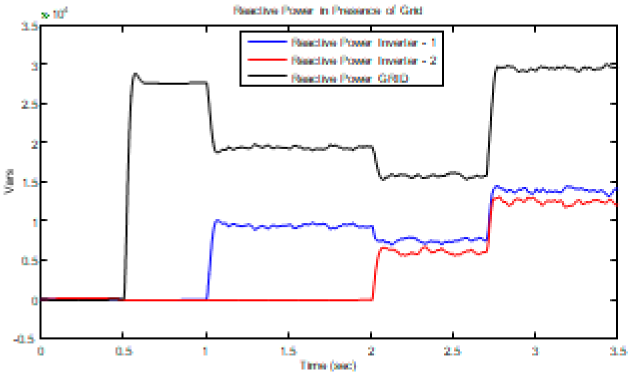

Figure 14: Reactive Power Sharing of inverter 1 and 2

Figure 11 and 12 shows the results of power sharing in presence of grid. Simulation Description: Initially all the grid is connected and till 0.5 sec remains at no load. At 0.5 sec the microgrid load is connected. The whole load is fed by the grid. The grid feeds 27.6 kW of active power and 27.6 kVar of reactive power. Inverter 1 synchronizes and is connected to share load at t=1 sec. Now the grid supplies 16.7 kW and 19.4 kVar and inverter 1 supplies 11.8 kW and 9.4 kVar. At t=2 sec, inverter 2 is also connected to share the load. Now the grid supplies 5.5 kW and 15.86 kVar, inverter 1 supplies 11.6 kW and 7.75 kVar, inverter 2 supplies11.8 kW and 5.71 kVar. At t=2.75 sec an additional load is connected (to understand effect of load changes). Now the grid supplies 32.07 kW and 29.3 kVar, inverter 1 supplies 12.54 kW and 13.66 kVar and inverter 2 supplies 12.34 kW and 12.84 kVar. The stable operation of power aring by inverters and grid is demonstrated.

2. Simulation Model Description

The proposed controller is simulated by using MAT-LAB/SIMULINK for two parallel-inverter system based DG sources with unequal filter parameters and the grid sharing a load.

Parameters	Values
Inverter Rating	25 kVA
Rated RMS Voltage	187.77 Volt (three phase)
Line Impedance	R=4e-3, L=1.9910e-005
LC Filter Inverter1	Rl=0.2,L=0.11e-3, C=149e-6
LC Filter Inverter2	Rl=0.2,L=0.1e-3, C=136e-6
Low Pass 1 (Power Calc)	10 Hz Cut off
Low Pass Filter 2	200 Hz Cut off
DC Link Voltage	400 V

Controller Description: Parallel operation of two inverter system is evaluated for power sharing in presence and absence of external grid.

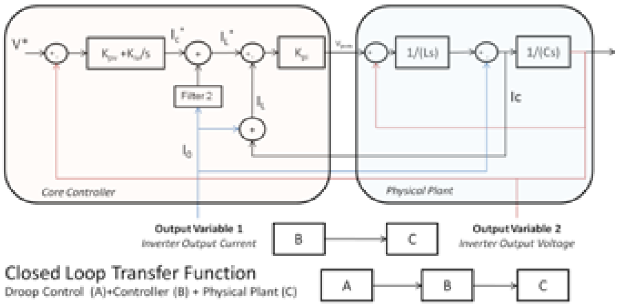

Figure 15: Voltage and Current Loop with the inverter along with Physical Plant

Seamless transition from islanded to grid connected mode and vice versa has been studied in literature and can be evaluated as future work. Detailed transfer function analysis as shown in figure13 [12]is also an area we wish to extend in future.

3. Conclusion

A mode approach for inverter control is proposed in this paper. The modes are evaluated using simulation and its performance is validated. Mode transitions from synchronization to is landed and synchronization to grid connected
is simulated. Mode adaptive control leads to seamless transition.

4. Acknowledgments

The authors would like to thank.

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