Y9.FS2.1: Distributed Control Methods for Intelligent Power Management with Moving Equilibria

Project Leader: Dr. Iqbal Husain

Faculty Members: Dr. Aranya Chakrabortty (NCSU)

Graduate Students: Alireza Milani (NCSU), Md Tanvir A. Khan (NCSU), M. A. Awal (NCSU)

1. Project Goals

The objective of this project is to develop a comprehensive state-variable model of the FREEDM system followed by controller designs for feasibility, stability and dynamic performance analysis. The specific goals for this year are to:

- Incorporate component dynamics into the LSSS testbed following IEEE 34 bus
- Implement power sharing methods in multi-SST testbed
- Develop decentralized controller for multi-SST system
- Stability analysis of multi-SST FREEDM system

2. Role in Support of Strategic Plan

The role of this SMC project is to produce a convincing framework for the design and analysis of all necessary controls in the system, including feasibility, stability, power, energy, and fault managements, followed by validation of these control algorithms in a scalable testbed environment. The FREEDM system consists of two parallel operating control loops - namely, Intelligent Power Management (IPM) and Intelligent Energy Management (IEM). IPM controllers (for voltage and frequency regulation) is implemented in a distributed manner given the small time constants of the power electronics components in the system. The IEM algorithms serve as the set-points for the FREEDM devices for energy management. Integration of control with protection allows the FREEDM System to transform the legacy distribution system with centralized control and decoupled protection to a resilient distributed power and energy managed system.

3. Fundamental Research, Educational, or Technological Advancement Barriers and Methodologies Used to Address Them

The FREEDM system is an engineered, non-linear, hybrid, multivariable system, and hence, has its challenges for identifying suitable analysis techniques. Much of the existing autonomous and distributed control in power systems relies on temporal and spatial decoupling among the phenomena being controlled. A FREEDM system is bound to be affected by the faster switching surge dynamics to slower frequency control both qualitatively (novel dynamics) and quantitatively (many more components). The stability analysis of a large FREEDM system involving many fast responding power electronic based devices, and distributed and varying loads, generation and storage thus remains a challenge for the system controls research. A similar situation exists in microgrid research.

The fundamental research carried out in this project is to produce a convincing framework for the design and analysis of all necessary controls in the system, including stability, power, energy, and fault management. In the FREEDM controls framework, each controller has a local component and a global component. The local controller is designed for faster response time without communications to address IPM functionalities, while the global controller operates under specified communications requirements to address IEM requirements.

4. Achievements in Previous Three Years with an Emphasis on the Current Year

The research in controls in previous years was focused on developing the local controls for power management of FREEDM devices, such as the SSTs and DESDs, and energy and fault management algorithms on simulated FREEDM systems. A Year 7 task completed collecting the local controllers developed in prior years into a platform based controls framework, and developing a comprehensive FREEDM system model. This SMC thrust project focused on performing the feasibility and stability analysis based on the comprehensive model, feasible operation bounds and power sharing methods in Year 7 and Year 8. The developed model from earlier years was then implemented in a large scale system simulation (LSSS) testbed to verify the feasible operation bounds. Power sharing methods developed in Year 8 are demonstrated in a scaled version of LSSS testbed with 9 SSTs. Decentralized controller design approach is also developed as part of the stability analysis based on the results from feasibility study in Year 9. In addition, a predictive current control method using impedance model based passivity techniques have been developed for a stable local controller.

4.1 Dynamic Modeling of the FREEDM System

The 70^{th}-order nonlinear differential-algebraic state-space model of a single-SST FREEDM power distribution system developed in the Year 7 is used to derive analytical relationships between physical parameters and a feasible operational range [1]. This 70^{th} order model includes the dynamic model of SST (front-end rectifier, DAB and inverter), distributed generation systems (solar and wind) and distributed storage system. In order to capture the effect of the grid frequency on the rectifier output voltage, the dynamic model of the rectifier stage has been modified from previously developed model [2]. In the updated model, the phase angle of the grid voltage enters the rectifier dynamic model through bounded trigonometric functions which results in a second harmonic oscillation superimposed on top of the desired DC values for each state. The feasibility analysis is based on the fundamental frequency component of the signals.

4.2 Large Scale System Simulation Testbed

A large scale system simulation (LSSS) testbed has been built based on the IEEE 34 bus distribution system in a PSCAD platform [3]. The LSSS testbed in Fig. 1 has 26 nodes where each node has one or more SSTs in different phases. In this LSSS testbed, only PV DRER is considered. Simulation analysis has been carried out to evaluate the feasibility conditions proposed in Year 8. It has been found out that the feeder which is farthest from the grid suffers infeasibility due to voltage loss in the network. As the voltage level decreases at distant nodes, the maximum current that can be drawn by the DAB stage exceeds the limits forcing the SST to enter an infeasible operating region. Initially, the simulation analysis is carried out for the nearest (2), middle (7c) and farthest (19) feeders from the point of common coupling (PCC). The rectifier output voltage for the mid-network feeder (7c) shows higher levels of dynamic variations due to the load changes in the DRERs and DESDs. Although the rectifier input voltage decreases, the net load for the SST at (7c) is still within the feasibility bound, and hence, it does not fail [4]. The results for the farthest feeder 19 shows that the input voltage keeps decreasing, and at 2.5 secs the operation fails when the voltage reaches a level that is lower than that required to maintain feasible operation as shown in Fig. 1a. The failure at feeder 19 is due to the violation of feasibility constraint as the net load in the system (~20 kW/ 50 amps) is more than the system can handle (~10.2 kW/ 25.5 amps) with the reduced input voltage. To study the effect of parameter values on system feasibility, the rectifier filter resistance has been reduced by one-third to increase the feasibility range (~30 kW/ 80 amps) with the same voltage level. It is found that with the same input voltage and load as previous case and reduced filter resistance value, rectifier and DAB output voltages are regulated and the system is within the feasibility range as shown in Figures 2b and 2c. The findings demonstrate that appropriate parameter selection can ensure wider feasibility range for such distribution system networks which is aligned with the findings in the surface plots and feasibility criteria from Year 7 and Year 8 [1].

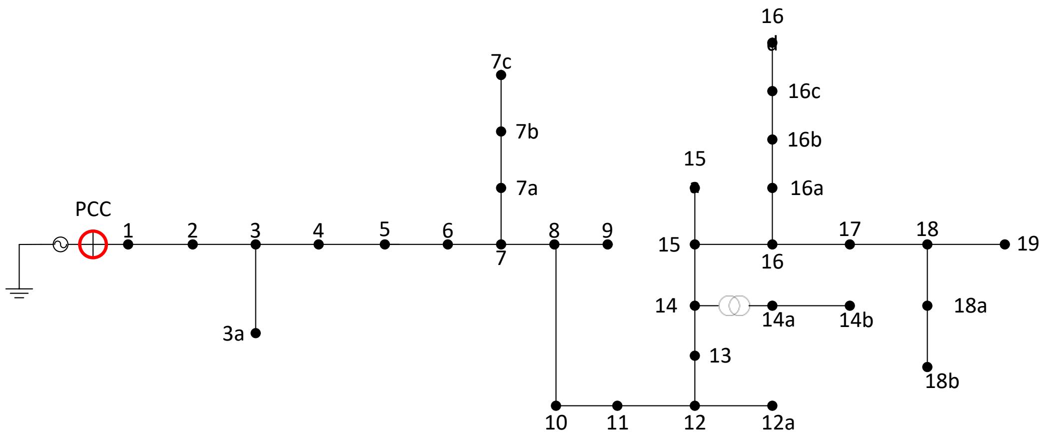
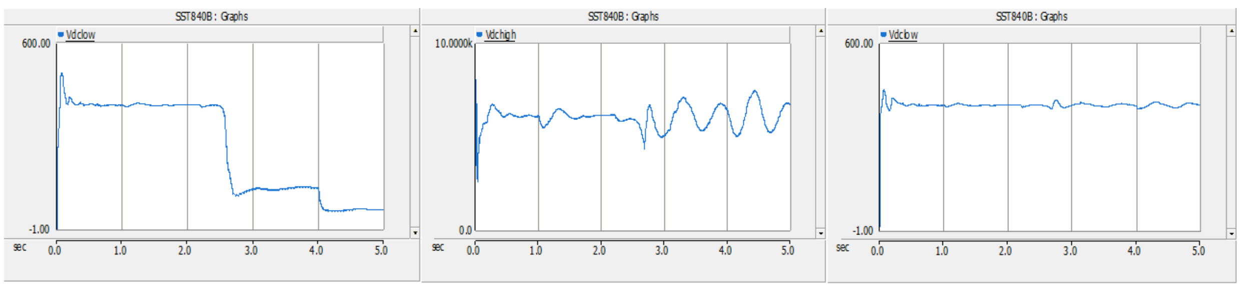


Fig. 1. LSSS testbed.



(a) Feeder 19 rectifier output voltage change in resistance

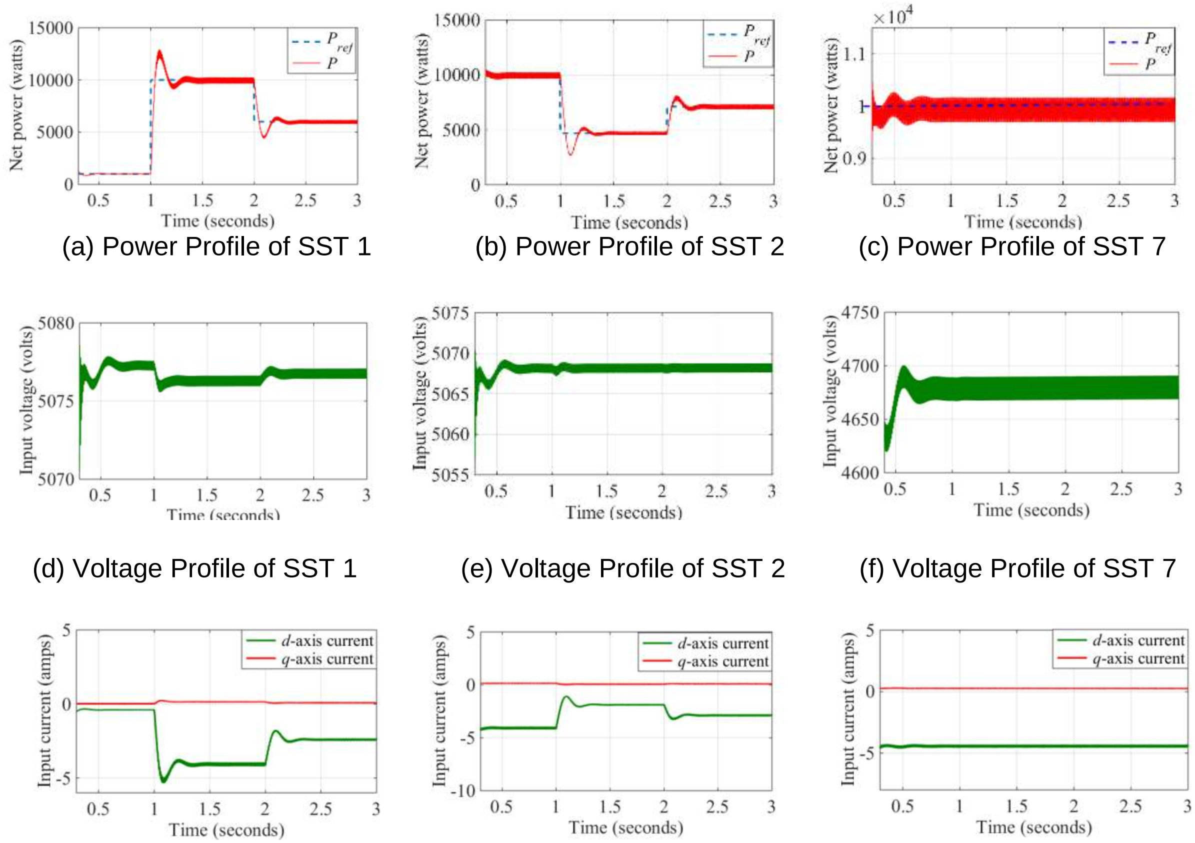
(b) Feeder 19 rectifier output voltage after change in resistance

(c) Feeder 19 DAB output voltage before after change in resistance

Fig. 2. Results from LSSS testbed.

4.3 Power Sharing in Multi-SST FREEDM System

When multiple SST systems are connected together, a power flow solution is required to find the input current (and input node voltage) of each SST maintaining the feasibility constraints of the system. Besides maintaining the constraint at each time interval from the energy management controller (IEM), feasibility has to be maintained when there is a change in the load of any of the SSTs in between the time intervals of IEM command. Two different methods were proposed in Year 8 based on power sharing among neighboring SSTs to maintain feasibility. In Year 9, the proposed power sharing methods are validated using simulations on a radial 9-bus distribution feeder model containing a total of 9 SSTs, one at each bus. The tie-line impedances of this model are based on the IEEE 34-bus distribution system model. The SST models are considered to be identical to each other, and their parameters are based on the GEN-II SST model. In order to verify the power sharing methods, the load connected to SST 1 is varied. The simulation starts with a nominal load of 1 KW at time t = 0. At time t = 1 sec, the load is increased from 1 kW to 10 kW. At t = 2 sec, the load is reduced from 10 kW to 6 kW. Simulation results of method 2 are shown in Fig. 3 for three different SSTs, namely SST 1, 2, and 7. Figures 3a, 3b, and 3c show the net power flowing through the SSTs while figures 3g, 3h, and 3i show the input current of the SSTs. The figures show that for each change in the load, other SSTs adjust their input power by changing their storage output to keep the system in the feasible zone of operation. Figures 3d, 3e, and 3f show the input voltage of the SSTs. As it was expected, using method 2, the input voltage of SST 2 and SST 7 remain constant. Since in method 2, the change in power only effects the input current of the impacted SST and its immediate neighbors, the input current of SST 7 has remained constant while the input current of SST 1 and SST 2 have changed. Both the developed methods are successful in maintaining the system to converge to feasible equilibria following the load perturbations [5]. The superimposed oscillations on the steady-state DC values in all the plots are within the permissible limit of 1%-5%.



(a) Power Profile of SST 1 (b) Power Profile of SST 2 (c) Power Profile of SST 7

(d) Voltage Profile of SST 1 (e) Voltage Profile of SST 2 (f) Voltage Profile of SST 7

(g) Current Profile of SST 1 (h) Current Profile of SST 2 (i) Current Profile of SST 7

Fig. 3. Simulation results for the power sharing method 2 applied to a nine-SST FREEDM system

4.4 Decentralized Controller Design for Stability Analysis

A controller structure using the Lyapunov function has been developed to stabilize a multi-SST power distribution system. Only the front-end rectifier stage of the SSTs are considered for designing the controller. First, the dynamic model of the rectifier stage has been updated by moving the equilibrium of the system to zero. By defining the Lyapunov function as the sum of total energy of the passive elements of each SST system, in order to have a negative Lyapunov function derivative, the following inequality must be satisfied:

$$\sum_{i=1}^{n} u_{1i}(x_{3i}^{*}z_{1i} - x_{1i}^{*}z_{3i}) + u_{2i}(x_{3i}^{*}z_{2i} - x_{2i}^{*}z_{3i}) - \frac{2}{R_{Li}}z_{3i}^{2} \leq 0 \tag{1}$$

In the inequality above, $z_{ki}, x_{ki}^{*}, R_{Li}, u_{1i}$ and u_{2i} represent k^{th} state of the i^{th} SST moved to zero, desired value of the k^{th} state of the i^{th} SST, load of the i^{th} SST, input *d*-axis and *q*-axis controllers of the i^{th} SST moved to zero, respectively. By assigning the controllers to be as shown in (2) and (3) and some math manipulations, it can be shown that the Lyapunov function derivative will be negative if some inequalities based on power and current rating of the SST on α_{1i} and α_{2i} are satisfied. These conditions are given in (4), (5) and (6). Moreover, using La Salle's principle results in all of the states of the system in the z-domain (z_{ki}) to go to zero in the steady state which subsequently means that each state will go to its desired steady state value. We are currently exploring means of implementing this controller on top of nominal PI controllers to maintain both regulation and stability.

$$u_{1i} = -\alpha_{1i}(x_{3i}^* z_{1i} - x_{1i}^* z_{3i}) = -\alpha_{1i}(x_{3i}^* x_{1i} - x_{1i}^* x_{3i}) \quad (2)$$

$$u_{2i} = -\alpha_{2i}(x_{3i}^* z_{2i} - x_{2i}^* z_{3i}) = -\alpha_{2i}(x_{3i}^* x_{2i} - x_{2i}^* x_{3i}) \quad (3)$$

$$\alpha_{1i} \geq \frac{x_{1i}^{*^2} - a_{2i}}{x_{3i}^{*^2}} \quad (4)$$

$$\alpha_{2i} \geq \frac{x_{2i}^{*^2} - a_{2i}}{x_{3i}^{*^2}} \quad (5)$$

$$\frac{-2}{R_{Li}} \leq (\alpha_{1i} + \alpha_{2i})a_{2i} \quad (6)$$

4.5 Impedance Based Stability Analysis and Local Controller Design

The system stability among multiple grid-tied solid state transformers is evaluated using frequency domain passivity theory. Then a predictive current control (PCC) has been developed to stabilize such interconnected power electronic converters. This local controller for the power converter achieves stability irrespective of grid impedance variation, and is suitable for SSTs as well as for any other similar grid-tied converters such as PV converters in a legacy power distribution grid. The network retains stability if all units employ the predictive controller which has been demonstrated via frequency domain analysis and system simulation of a system with two power electronic converters, although the analysis is scalable to multiple number of power electronic units.

Fig. 4 shows a system of two grid tied generic power converters. Fig. 5 shows one possible choice for converter side current control where $F_c(s)$ denotes a linear controller which can be of proportional-integral (PI) or proportional-resonant (PR) type and the capacitor voltage is used as a feedforward signal through a filter $H_F(s)$. With this choice of controller, the converter side inductor current is given as

$$i_{L\_n} = \frac{e^{-sT_d}F_c(s)}{sL_{1\_n} + e^{-sT_d}F_c(s)} \times i_{ref} + \frac{1 - e^{-sT_d}H_F(s)}{sL_{1\_n} + e^{-sT_d}F_c(s)} \times v_{c\_n} = T_i(s) \times i_{ref} + Y(s) \times v_{c\_n} \quad (7)$$

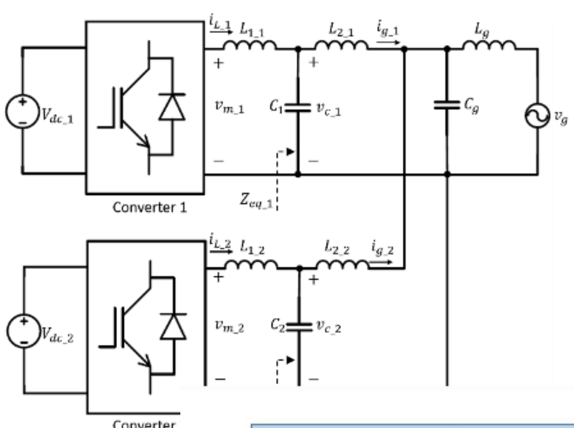


Fig. 4. System of two grid tied power electronic converters. The tie-line impedance for each converter is lumped with the grid side inductor of the LCL filter.

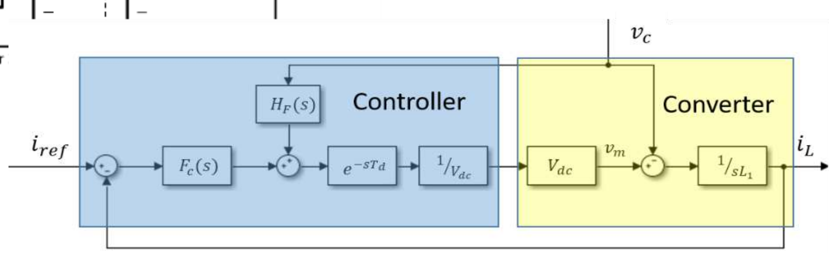
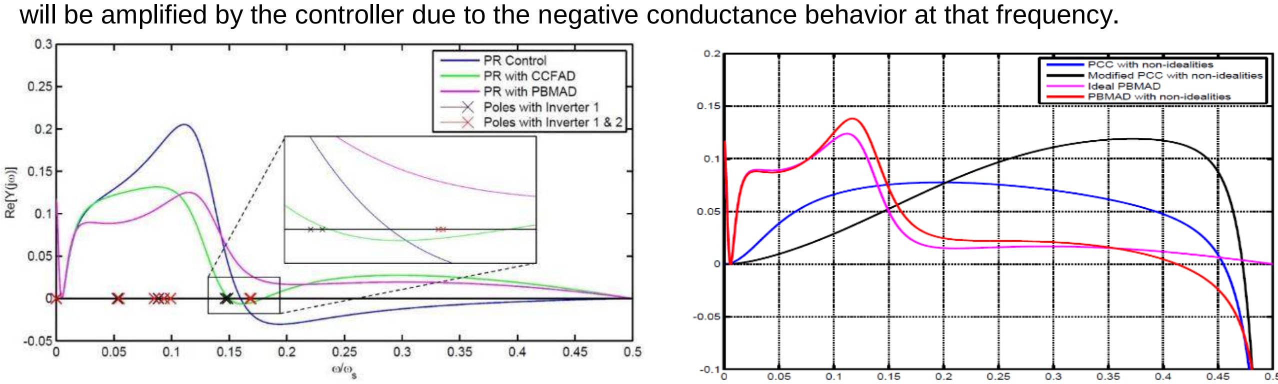


Fig. 5. Equivalent model of power stage with linear controller and voltage feedforward.

$F_c\,(s)$ is designed to give a stable closed loop response $T_i(s)$ and for such a controller the first term in (7) becomes stable. However, the second term containing the output admittance $Y(s)$ interacts with the grid impedance. With infinite resolution sampling for $H_F\,(s)$ and instantaneous control, i.e. zero delay with

$T_d = 0$, the effect of the output admittance could be negated, but for practical systems there is a finite time delay and in most applications $T_d = 1.5T_d$ where T_s is the converter switching period. The output impedance $Y(s)$ is said to be passive in the frequency range of interest if it can be shown that it is stable and has non-negative real part in that particular frequency range. A negative conductance behavior at a range of frequencies signify amplification of disturbance or oscillation at any frequency within that range. The stability of the equivalent system is defined by the poles of $1 + Y(s)Z_{eq}(s) = 0$, where $Z_{eq}(s)$ denotes the equivalent impedance seen by the converter looking into the grid. It is to be noted that the capacitor and the grid side inductor of the converter LCL filter are lumped in $Z_{eq}(s)$. However, if both $Y(s)$ and $Z_{eq}(s)$ are passive in a specific frequency range, frequency domain passivity theory defines the whole system to be stable over that range [6]. Both $Y(s)$ and $Z_{eq}(s)$ to be passive over the entire frequency range is a sufficient condition, but not a necessary one.

Fig. 6(a) shows the position of poles of the whole impedance network and the real part of converter output admittance for ideal implementation of different existing control methods- PR control, PR with capacitor-current-feedback active damping (CCFAD) and a passivity based modified active damping (PBMAD) technique proposed by Harnefors et al. [7]. The frequency axis is normalized with respect to the converter switching frequency ω_s. It is to be noted that due to discrete implementation of controllers, anything beyond Nyquist frequency $\omega_s/2$ does not propagate through the controller, and therefore, output admittance only over $[0, \omega_s/2\,]$ is of interest. For PR and PR with CCFAD the converter output admittance goes into negative conductance region beyond a critical frequency which is determined by the controller delay as $\omega_{critical} = \pi/(2T_d)$. For the single converter case of the system in Fig. 4, the network poles lie close but below the critical frequency resulting in stable operation. Next consider two converters connected to the same point. The passive elements of the second converter add additional poles to the network, and additionally, positions of some of the pre-existing poles shift into the negative conductance region for the existing controller. The network can sustain large oscillations at these frequencies which will be amplified by the controller due to the negative conductance behavior at that frequency.



(a) (b)

Fig. 6 Passivity based impedance analysis: (a) Network pole positions for single and dual converter case and real part of output admittance for different controllers; (b) Converter output admittance for PCC and PMBAD method.

The impedance analysis for the developed predictive current controllers is shown in Fig. 6(b) along with the admittance plot for PBMAD with non-idealities, i.e. bandwidth limitation imposed by voltage and current sensors, noise filters, and anti-aliasing filters, which was neglected in the analysis of [7]. The proposed PCC and modified PCC methods significantly extend the passive output admittance-frequency range compared to PMBAD. Figs. 7 and 8 show the results for the converter side inductor current and grid side inductor current for the passivity based PCC method and the PR control with capacitor-current-feedback active damping (CCFAD), respectively with two converters. Both methods showed stability with one converter but the CCFAD fails when the second converter is added as shown in Fig. 8. Overall the PCC method and the modified PCC method have been developed both of which show superior performance over all other existing controllers as seen in Fig. 6(b). The experimental validation of the concept will be carried out in the GEH testbed.

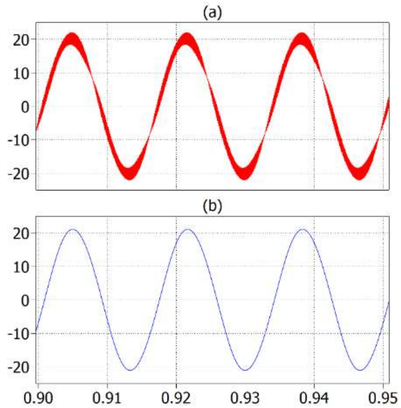


Fig. 7 Simulated waveforms using PCC method for two inverters connected to the grid: (a) converter side inductor current, (b) grid side inductor current.

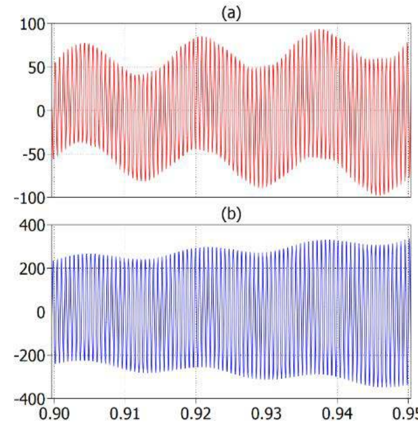


Fig. 8 Simulated waveforms using PR based control with CCFAD method for two inverters connected to the grid: (a) converter side inductor current, (b) grid side inductor current.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

With respect to fundamental controls research outside the ERC, the activities are fairly limited to serve the needs to fulfill the FREEDM vision. There are activities in terms of power electronics controls of microgrid devices or at a much higher systems level such as in Professor Iravani's group at University of Toronto, Canada and Professor Gurrero's group at Aalborg University in Denmark. Prof. Frede Blaabjerg's group, also in Aalborg University has many contributions on the stability analysis on networked power electronic converters. Prof. Santi's group in the University of South Carolina has been researching on stability analysis and controller developed for networked power electronic converters in the context of power systems in more electric ships. However, there is no activity for scaled systems with solid state transformer interfaced microgrids. This provides the FREEDM group a unique opportunity to make fundamental advances in distributed controls for power distribution systems.

6. Milestones and Deliverables

The deliverables from this SMC research task are:

- Dynamic modeling of the FREEDM system
- Large scale system simulation to validate the feasibility study
- Power sharing methods in multi-SST power distribution systems based on IEEE 34 bus
- Decentralized Controller design for a multi-SST power distribution system
- Impedance Based Stability Analysis and Local Controller Design

7. Plans for Next Year and Five Years

The following activities are planned for the next three years in the SMC sub-thrust with respect to fundamental controls activities:

- Contextual Model Development and Controller Design
    - ✓ Developing controllers to maintain both regulation and stability
    - ✓ Implement the proposed controller for multiple SSTs in power distribution network
    - ✓ Verify the proposed controller experimentally in LSSS, HIL and GEH testbeds
    - ✓ Optimal control law and sizing for energy storage system

8. International Collaboration

The NCSU team collaborates with Prof. Romeo Ortega and his PhD students Daniele Zonetti and Rafael Montoya in Centrale-Supelec, France. The controls team in Centrale-Supelec conducted stability analysis using a port-Hamiltonian representation of the FREEDM system. Daniele spent several weeks at NCSU in summer 2015 and in Fall 2016. Several publications resulted from the collaboration [8, 9, 10]. Both Daniele and Rafael finished their PhD in 2016 and Rafael joined FREEDM Center at NCSU to work on the CREDENCE project.

9. References

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