2.7 System Theory Modeling and Controls

Year 10 Projects and Participants			
Project Number	Project Title	Participants	Institution
Y10.FS2.1	Distributed Control Methods for Intelligent Power Management of Multi-SST FREEDM System	Chakraborty, Husain, Montoya, Khan, Milani	NCSU

2.7.1 Intellectual Merit and Impact

FREEDM System is proposed as a reliable and resilient future grid architecture that must also support multiple islanding modes of operation. Robust controllability, flexibility of operation, reliability, and lower operating cost have been the major driving factors in conceiving the power electronics based FREEDM power distribution system. To achieve such performance, modeling and controls play a key role in the FREEDM system. The controls are implemented in a hierarchical manner starting from local power converter controls to primary to secondary, and to tertiary levels. The primary controls are responsible for power sharing among multiple sources, while secondary and tertiary controls are for retaining nominal operation through energy management and economic optimization. The FREEDM system intelligent power management (IPM) controls (voltage and frequency regulation) have been developed in a distributed and autonomous way to meet the fast regulation requirement. The intelligent energy management (IEM) algorithms developed deliver the set-points of intelligent power management (IPM) controllers for energy management of the FREEDM devices. Integration of control with protection allows the FREEDM System in transforming the legacy distribution system with centralized control and decoupled protection to a distributed power and energy managed resilient system.

FREEDM system modeling, control and stability issues are very much similar in microgrids and other networked power electronics systems. Modeling is difficult and tedious as all these power electronic systems are non-linear, hybrid, and multivariable system. The control challenges are immense both due to interaction among the power electronics converters and the intermittency of the renewables. Stability issues exist from the lowest level to the highest level as the control loops' timescales increases from 1ms to few seconds and the corresponding instability oscillation frequency decreases from kHz to Hz. As the power electronic converters are actively controlled units, they introduce highly nonlinear and time varying dynamics and the interaction among different units may lead to instability in interconnected systems. A system with multiple power electronics converters 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 demand and desire is to make these intelligent power electronic converters plug-and-play type, and in a network, the control algorithms at different levels are to provide for automated and robust power, energy and fault management. FREEDM SMC developed models and control algorithms advance the technology for all networked power electronic systems.

The major achievements for the SMC thrust are:

- The formulation and implementation of an energy pricing method for the FREEDM system.
- The development of a Large Scale System Simulation (LSSS) test bed.
- Implementing robustness in the control systems design.
- Implementing distributed control of the FREEDM system, and testing of that control on a large system.
- An end-to-end comprehensive mathematical FREEDM system model built into the LSSS testbed.

- Defining feasibility bounds through physical and switching parameters' analytical relationships.
- Developed power sharing methodology among neighboring SSTs using node currents or voltages.
- A structure and platform for distributed IPM controller for multi-SST FREEDM system.
- A predictive current control method for local controllers verified with passivity based stability analysis.

2.7.2 Technical Approach

The primary objective of the SMC thrust has been to produce a framework for the design and analysis of all necessary controls in the system, including stability, and power, energy and fault managements. In addition, fundamental power and energy management control algorithms have been developed in the SMC thrust. The SMC thrust researchers focused on building up the large scale system simulation (LSSS) testbed in the early years of the center, and then improving it over the years while developing the power, energy and fault management algorithms for the FREEDM power distribution system. System feasibility and stability analysis became the critical focus in later years where distributed control algorithms satisfying the power balance requirements in the system were developed. Nonlinear distributed control methods for intelligent power and energy management in a feasible system domain were developed in the final year.

FREEDM system is a non-linear, hybrid, multivariable system, and hence, has its unique challenges for modeling, monitoring, and controls. 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 large FREEDM system involving many fast responding power electronics based devices, and distributed and varying load, generation and storage thus remain a challenge for the system controls. A similar situation exists in general state-of-art microgrid research.

The SMC thrust researchers developed power and energy management control algorithms with both distributed and decentralized schemes. Decentralized schemes make use of the distributed nature of FREEDM's distributed grid intelligence (DGI) in order to facilitate actual implementation, and thus achieve the main benefits of decentralized control. Power and energy management control algorithms developed by the Center over the years are the Incremental Cost Consensus (ICC) Algorithm, volt-var control, Cooperative Distributed Energy Scheduling (CoDES), Master-slave, and Lyapunov based nonlinear power management control. In later years, a comprehensive FREEDM system model that incorporated all the system and switching nonlinearities were developed that enabled system equilibrium point analysis based on fundamental science. Power sharing methods and nonlinear power management controllers for the solid-state transformers based power distribution systems were developed in the final years of the program.

Power and energy management control algorithms developed were incorporated into the DGI/RSC to study and analyze the integration and interaction of distributed control algorithm in the DGI/RSC platform. The algorithms were evaluated in HIL and GEH testbeds to analyze the effect of packet loss on the distributed control algorithm, to analyze the effect of different sampling rate using MATLAB/Simulink based simulator, to assess the performance of synchronous and asynchronous distributed control algorithms, and to quantify the effect of packet routing on the performance of distributed control algorithms.

Failure modes for the FREEDM energy and power management controls have also been identified and rank ordered to the probability of occurrence. The probability of occurrence was estimated from statistical System Average Interruption Duration Indices (SAIDI), System Average Interruption Frequency Indices (SAIFI), discussion with the designers of the solid state transformer and conferral with power electronic experts, conferral with power system communication experts, and rank ordering the geographic extent of subsystems.

2.7.3 Unique Approaches:

2.7.3.1 Comprehensive System Modeling and Coupling with LSSS Testbed

The SMC thrust developed a physics based comprehensive state-space based dynamic model of the FREEDM system considering the nonlinear dynamic characteristics of its components that comprises of multiple solid-state transformers (SSTs), and load, generation, and storage connected to each SST in a distributed network. A physics based 70th-order state-space average model is first developed considering the physical and controller properties of a single-SST FREEDM system along with its distribution components [1]. This fundamental model is then extended to build a multi-SST FREEDM system for feasibility and dynamics behavior analysis of the entire system, which is essential to ensure system power balance. The full average model with multiple SSTs has been incorporated in an IEEE 34 bus distribution testbed for a scaled analysis of the system. The end-to-end comprehensive mathematical model has been developed capturing all the nonlinear, and sometimes non-smooth, dynamic phenomena triggered by different types of switching command, and disturbances within a FREEDM system. This representative system is shown in Fig. 1 where each of the DC and AC microgrids comprise of load, generation and storage. For system level studies, reduced-order models have been developed applying model reduction techniques to reduce the complexity and order of the model; the reduced order models were validated against high-fidelity simulation models and experimental results. The reduced-order models include both large signal state space models as well as linearized models at operation points for small signal analysis. The feasibility analysis of single and multiple SST based FREEDM power distribution system lends itself to IPM controller development and system stability analysis has been carried out. Analytical relationships between physical parameters and feasible operational range were developed based on the model. The models are based on the *dq* representations of the variables of both the three-phase as well as the single-phase segments of the system. The fundamental research carried out provides a convincing framework for the design and analysis of all necessary controls in the system, including stability, and power, energy and fault managements.

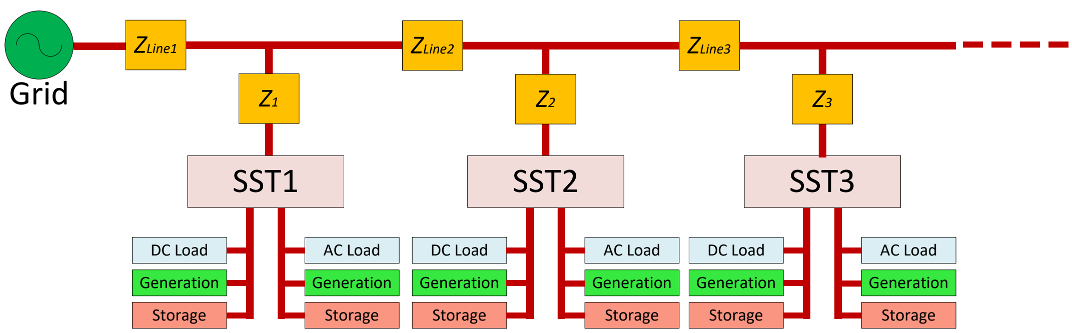

Fig. 1: Grid connected multi-SST FREEDM power distribution system.

The large scale system simulation (LSSS) testbed whose development started at the fundamental plane in the early years of the center was later used by the SMC thrust to validate and evaluate their state-space model of the SST based FREEDM power distribution system in a scalable platform. The nonlinear fundamental dynamics model of the SST with the energy cell have been incorporated into the LSSS model built in the PSCAD platform to address scalability and evaluate the FREEDM system feasibility constraints, dynamic stability, and controller performance. The testbed has 40 single-phase SSTs placed in different phase nodes of the feeders as shown in Fig. 2. Each node of the network consists of the average model of SST with energy cells as shown in node 810. The system distributed generator, energy storage, and SSTs are based on the average models. In this LSSS testbed, only PV DRER is considered. The LSSS testbed enhanced with the SST and energy cell dynamics serves as the high fidelity model to verify the feasibility bound obtained from the theoretical analysis. It has been found out that the feeder, which is farthest from the grid, suffers infeasibility due to voltage drops in the network [2]. 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.

In the FREEDM controls framework, each controller will have: (1) Local Controller, and (2) Global Controller. The local controllers for the FREEDM system components are designed for speed of response and use faster feedback control loops for instantaneous power balancing functions; the local component is without communications. The contextual global controller is enabled by communications that operates with specified communications requirements (expressed for example in Mb/s). The requirements for load voltage control and local generation by power electronic circuits including the SST using the local controllers is well understood, but system modeling with wide separation of time constants among the subsystems is the more challenging aspect. Designing the global controllers satisfying system stability requirements is the challenging part.

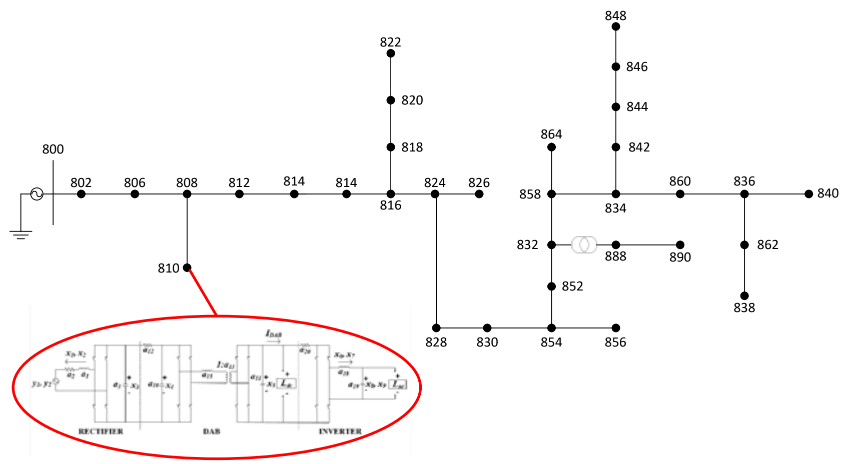

Fig. 2: LSSS testbed with FREEDM dynamic model incorporated at 40 nodes.

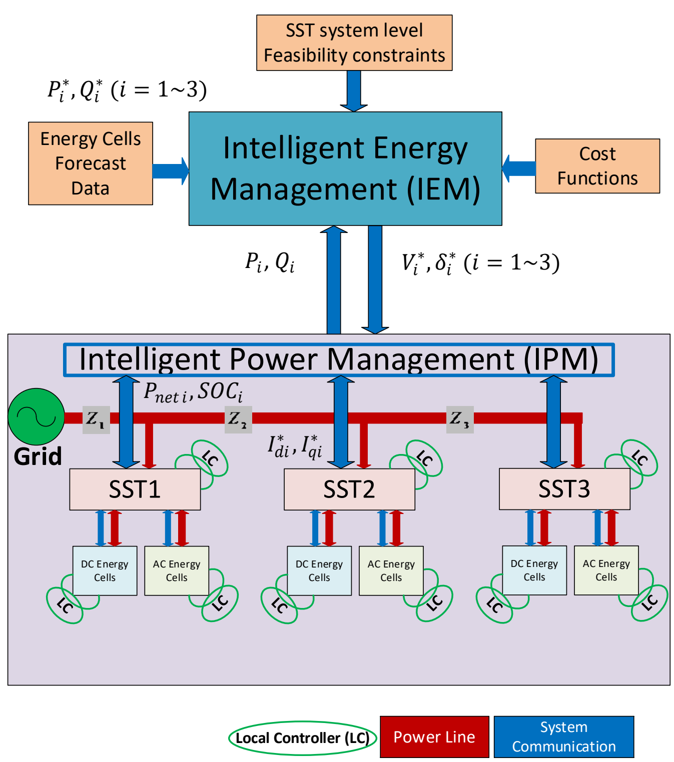

Fig. 3: Controller interactions in a FREEDM system.

In the control hierarchy for the FREEDM system, shown in Fig. 3, global controllers in the IEM layers provide the power reference commands, while local controllers in each FREEDM system will maintain the voltage and frequency at its desired level. An example scenario of IPM and IEM interaction with respect to load changes is shown in Fig. 3. The IPM layer is responsible for regulating the input current of each SST system such that the system operates within feasible and stable regions in the grid-connected mode. In the islanded mode, a master SST will be responsible for maintaining the high-voltage bus while the other slave SSTs will operate in the current controlled mode. The IEM layer is responsible for providing set-points based on the distributed renewable energy resources (DRER) and distributed energy storage devices (DESD) available in the system, weather forecast data, economic constraints, and feedback from power levels of energy cells in the system. The responsibility of the IPM layer is to establish the IEM requests respecting the physical constraints and dynamics, and at times overriding IEM commands, to ensure system feasibility and stability.

2.7.3.2 Pricing and Control in the Next Generation Power Distribution System

Smart grid technologies such as the FREEDM system are gaining acceptance and are being integrated into power distribution systems as a result of public and private investment and funding. However, costs of these technologies appear to be a clear obstacle in the widespread integration and maximal use of these technologies. Method for the utilization of dollar pricing signals has been developed and illustrated for power distribution engineering [3,4,5]. A signal modeled after locational marginal pricing from transmission engineering is proposed to provide pricing data locally in distribution systems. The calculation, utilization, advantages, and shortcomings of the concept are presented. A main conclusion is that the use of a distribution locational marginal price signal fits well with an electronically controlled power distribution system.

2.7.3.3 Cyber security in the Smart Grid

The integration of advanced computing and communication technologies is expected to greatly enhance efficiency and reliability of the FREEDM power distribution system which is the future power systems with renewable energy resources as well as with distributed intelligence and demand response. Along with the silent features of the scaled FREEDM system, cyber security emerges to be a critical issue because millions of electronic devices are inter-connected via communication networks throughout critical power facilities, which has an immediate impact on reliability of such a widespread infrastructure. The FREEDM system is a key enabler for the future smart grid and the FREEDM researchers conducted a comprehensive survey of cyber security issues for the smart grid. Security requirements, network vulnerabilities, attack countermeasures, secure communication protocols and architectures in the smart grid were reviewed in the early years of the FREEDM center activities. A deep understanding of security vulnerabilities and solutions in the smart grid were developed to shed light on research directions for smart grid security [6,7,8]. The initial work led to incorporating security aspects at both the algorithm levels for power, energy and fault management, and in the physical component and system configurations.

2.7.3.4 Real-Time Energy Dispatch

An offline Cooperative Distributed Energy Scheduling (CoDES) control algorithm has been developed to calculate the charging/discharging schedules of the DESDs in a FREEDM system in order to minimize the total electricity bill of the system for a certain time period (e.g., 24 hours) in a distributed manner using day-ahead forecast profile [9,10,11]. The system framework of integration of CoDES and Load Balancing algorithms is shown in Fig. 4. In the CoDES algorithm, each SST is modeled as an agent with an embedded controller which has access to the information of connected local devices. The agents also form a communications network to exchange information with each other. These communication linkages are established by the distributed DGI processes controlling the FREEDM system. By utilizing the primal-dual gradient descent method and consensus algorithm, the CoDES algorithm is able to solve the optimization problem in a distributed fashion as long as the communication network formed by the agents is connected. When the system approaches real-time operation, the actual device status might deviate from the forecast profiles. In order to handle this mismatch, the Load Balancing algorithm is utilized. The two different control time frameworks correspond to the day-ahead and real-time energy market, respectively. The (CoDES) control algorithm has been integrated with the DGI and its performance has been evaluated on the HIL-TB.

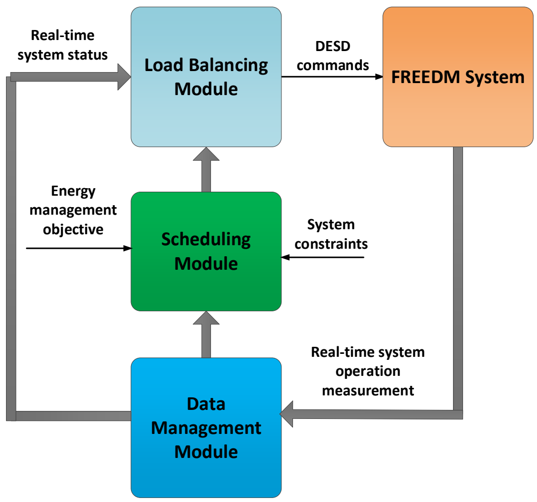

Figure 4 - CoDES real-time operation with DGI Load Balancing algorithm

2.7.4 Scientific Breakthroughs:

2.7.4.1 Equilibrium Point Analysis and Power Sharing Methods for Solid-State Transformer Driven Distribution Systems

The feasible equilibria of operation of distribution level power system models interfaced with solid-state transformers (SST) have been analyzed and presented through a set of analytical relationships [12]. The active and reactive power balances in the SST are realized through control of power electronic converters with appropriate choices for voltage and current setpoints. These setpoints parameterize the nonlinear model of the SST. Therefore, choosing them appropriately in sync with the generation and load profiles in the system is critical for maintaining a feasible equilibrium. These equilibrium sets are derived by first considering a fundamental physics-based model of a single-SST system, and thereafter, by extending them to systems with multiple SSTs connected to a radial distribution feeder. Power sharing methods are developed by which multiple SSTs can share a given change in load by generating an appropriate set of feasible setpoints for their input stage rectifiers. A control architecture has been proposed for executing these load-sharing methods for both instantaneous and predictive load commands. The algorithms were verified by simulations on a representative distribution test system with nine SSTs.

2.7.4.2 Nonlinear Power Management Distributed Controls for Intelligent Power Management with Moving Equilibria

The activity focused on the feasibility analysis and subsequently global controller design based on the comprehensive model for a multi-SST FREEDM system. Feasibility analysis of the FREEDM system is essential to answer the maximum net power capability that the system can handle. Once the feasibility bounds are known, the system parameters can be designed accordingly to provide the required power flow and energy exchange flexibility. The developed feasibility bounds can then be used to determine the operational range based on the different loading conditions and then, methods have been developed to expand the operational range. Derived results have been utilized for the development of the power sharing methods in the multi-SST FREEDM system to maintain the feasibility of the total 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 developed based on power sharing among neighboring SSTs to maintain feasibility which was 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 one another, and their parameters are based on the GEN-II SST model. The developed methods have been shown to be successful in maintaining the system to converge to feasible equilibria following the load perturbations. In one of the methods where the node voltages were kept constant for power sharing following a load change in one of the SSTs, it has been shown that the change in power only effects the input current of the impacted SST and its immediate neighbors while the voltages and currents of other SSTs that are farther from the impacted SST maintain constant voltage and power. Similarly, in the other method where the node currents are held constant for a change in load for one SST, it has been shown that the voltages of the neighboring SSTs are adjusted while maintain the current constant.

For the task of a system distributed controller development, a 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 dynamical 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:

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

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 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. This controller is being implemented in the hardware of the GEH testbed on top of nominal PI controllers to maintain both regulation and stability.

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

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

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

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

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

2.7.4.3 Impedance Based Stability Analysis and Local Controller Development for Solid State Transformer

The SMC thrust evaluated system stability among multiple grid-tied solid state transformers using the impedance based frequency domain passivity theory [13]. In addition to the FREEDM distribution system, the power electronic converters used for power processing and interfacing units have been penetrating into numerous grid applications, such as in renewable energy distributed generation, flexible ac transmission systems, microgrids, and high voltage dc (HVDC) transmission. Any power electronics based system similar to the FREEDM system are actively controlled units that introduce highly nonlinear and time varying dynamics, and add significant complexity to the design of local controllers especially with higher levels of penetration. The commonly used approach for designing local controllers for such converters are based on the so called 'Minor Loop Gain (MLG)' or 'Global Minor Loop Gain (GMLG)' to cover a range of grid impedance values. A number of passive and active damping or virtual resistor based methods are available in the literature for designing the local controllers, but all of these resonance damping techniques fail beyond a critical frequency depending on the controller delay. The challenges for designing the controllers for such power electronic based converters are two-fold: (1) Grid Impedance variation, and (2) interaction among multiple converters. A single SST can become unstable due to grid impedance variation; also, for the same grid impedance, interaction between multiple converters may cause instability. The controllers have been developed to guarantee closed-loop stability and performance of the FREEDM system under various operating conditions and load demands.

A current controlled power electronics converter and its local controller can be modelled as a current injection source in parallel with its output admittance *Y(s)* which is a function of both the controller parameters as well as the converter filter parameters. The impedance model of a three converter system connected to the grid with the tie-line impedances and its equivalent circuit are shown in Fig. 5. The grid impedance seen by the farthest converter from the point of common coupling is

$Z_{TH} = f(Y_1, Y_2, Z_g, Z_{12}, Z_{23})$ and $Y(s) = Y_3(s)$

where $Y_1(s), Y_2(s)$, and $Y_3(s)$ are all active and their interaction leads to extremely complex system dynamics which may cause harmonic resonance instability. Local controllers that are not sensitive to grid impedance variation and can prevent harmonic resonance instability due to multiple converter interaction are the most desirable. In a FREEDM like architecture neighboring SSTs directly contribute to actively shape the impedance that one SST sees looking into the point of common coupling.

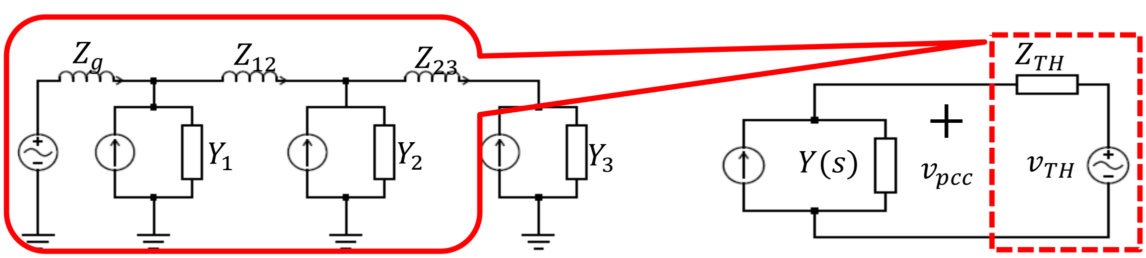

Fig. 5 Impedance based model of a three-SST FREEDM system.

Frequency domain passivity theory has been used to analyze the effect of output admittance $Y(s)$ on stability in case of grid impedance variation or multiple converter interaction. The stability of the equivalent system is defined by the poles of $1 + Y(s)Z_{eq}(s) = 0$. $Y(s)$ 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 the frequency range of interest. A negative conductance behavior at a range of frequencies signify amplification of disturbance or oscillation at any frequency within that range. Both $Y(s)$ and $Z_{eq}(s)$ to be passive is a sufficient condition, but not a necessary one.

A predictive current control (PCC) method using frequency domain passivity based active damping has been developed to stabilize such interconnected power electronic converters and frequency domain passivity theory has been used to assess system stability. 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. It is to be noted that implementation of all existing control methods suffers from performance issues due to bandwidth limitation imposed by current and voltage sensors, noise filter, and anti-aliasing filters which is also true for the proposed PCC method. However, the PCC method and a modified PCC method has been shown to have superior performance compared to of all other existing controller methods in literature. The experimental validation of the concept has been carried out in the GEH testbed.

2.7.5 Validation of the Research:

The following provides the list of the most relevant and most cited papers published by FREEDM researchers in the system modeling, theory, and controls area. The selected publication list is following by the invention disclosure portfolio related to the SMC thrust.

1. M. T. A. Khan, A.A. Milani, A. Chakrabortty, I. Husain, “Dynamic Modeling and Feasibility Analysis of a Solid-State Transformer-Based Power Distribution System,” *IEEE Transactions on Industry Applications*, Volume: 54, Issue: 1, Pages: 551 – 562, Year: 2018.

2. D. G. Shah and M. L. Crow, “Stability Design Criteria for Distribution Systems with Solid-State Transformers,” *IEEE Transactions on Power Delivery*, vol. 29, no. 6, pp. 2588-2595, Dec. 2014.

3. G. T. Heydt, B. Chowdhury, M. L. Crow, D. Haughton, B. D. Kiefer, F. Meng, B. R. Sathyanarayana, “Pricing and control in the next generation power distribution system,” *IEEE Transactions on Smart Grid*, v. 3, No. 2, 2012, pp. 907 – 914.

4. D. Haughton, G. T. Heydt, “A linear state estimation formulation for smart distribution systems,” *IEEE Transactions on Power Systems*, 2013. (109 citations).

5. G. Heydt, “The next generation of power distribution systems,” *IEEE Transactions on Smart Grid*, v. 1, No. 3, December, 2010, pp. 225 – 235.

6. W Wang, Y Xu, M Khanna, A survey on the communication architectures in smart grid, *Computer Networks* 55 (15), 3604-3629, 2011 (549 Citations).

7. W. Wang, Z Lu, Cyber security in the smart grid: Survey and challenges Computer Networks 57 (5), 1344-1371, 2013 (470 Citations).

8, X Lu, W Wang, J Ma, “An empirical study of communication infrastructures towards the smart grid: Design, implementation and evaluation,” IEEE Transactions on Smart Grid 4 (1), 170-183, 2013 (93 Citations).

9. Z. Zhang and M.-Y. Chow, “Convergence Analysis of the Incremental Cost Consensus Algorithm under Different Communication Network Topologies in a Smart Grid,” *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 1761–1768, 2012.

10. Z. Zhang and M.-Y. Chow, “Incremental Cost Consensus Algorithm in a Smart Grid Environment,” in *IEEE Power & Energy Society General Meeting, Detroit, MI, USA, 2011.*, 2011.

11. N. Rahbari-Asr, Y. Zhang, and M.-Y. Chow, “Consensus-based distributed scheduling for cooperative operation of distributed energy resources and storage devices in smart grids,” *IET Generation, Transmission & Distribution*, vol. 10, no. 5, pp. 1268–1277, 2016.

12. A. A. Milani, M. T. A. Khan, A. Chakrabortty, and I. Husain, “Equilibrium Point Analysis and Power Sharing Methods for Distribution Systems Driven by Solid-State Transformers,” *IEEE Transactions on Power Systems*, Volume: 33, Issue: 2, Year: 2018, Pages: 1473 – 1483.

13. M.A. Awal, W. Yu and I. Husain, "Predictive Current Control for Stabilizing Power Electronics Based AC Power Systems" *IEEE Energy Conversion Congress & Expo (ECCE2017),* Cincinnati, OH, Oct. 2017.

The following are also important SMC publications:

1. R. Gao, X. She, I. Husain and A. Huang, “Solid-State Transformer Interfaced Permanent Magnet Wind Turbine Distributed Generation System with Power Management Functions,” *IEEE Transactions on Industry Applications.* Year: 2017, Volume: 53, Issue: 4, Pages: 3849 – 3861.

2. S. Falcones, R. Ayyanar, and X. Mao, “A DC–DC Multiport-Converter-Based Solid-State Transformer Integrating Distributed Generation and Storage, *IEEE Transactions on Power Electronics*, Year: 2013, Volume: 28, Issue: 5, Pages: 2192 – 2203 (150 Citations)

3. T. Yao, I. Leonard, R. Ayyanar, K. Tsakalis, “Mu synthesized robust controller for multi-SST islanded smart grid,” *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016.

4. N. Otero, H. Rahimi-Eichi, J. J. Rodriguez-Andina, and M.-Y. Chow, "FPGA Implementation of an Observer for State of Charge Estimation in Lithium-Polymer Batteries," in IEEE *International Conference on Mechatronics and Control*, Jinzhou, China, July 3-5, 2014. (2014 IEEE ICMC'2014 Best Paper Award)

5. H. R. Eichi, U. Ojha, F. Baronti, and M.-Y. Chow, “Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles,” *Industrial Electronics Magazine*, vol.7, no.2, pp.4-16, June 2013. (2013 Best Paper Award for the IEEE Industrial Electronics Magazine)

6. W. Su, H. Rahimi-Eichi, W. Zeng, M.Y. Chow, "A Survey on The Electrification of Transportation in A Smart Grid Environment," *IEEE Trans. on Industrial Informatics*, vol.8, no.1, pp.1-10, Feb. 2012. (2012 IEEE IES Student Best Paper Award)

2.7.6 Intellectual Property (Licensing and Patents)

IP License Number or Name	IP License Title or Name	IP Category: FP, PP, C, T	Brief Description of Technology	Owner of IP	Year
14/889,840	Large-Scale, Time-Sensitive Secure Distributed Control Systems and Methods	FP	The method includes detecting an anomaly at a module among a plurality of modules in a network. The method also includes adjusting a reputation level of the module associated with the detected anomaly. Further, the method includes controlling interaction of the module associated with the detected anomaly within the network based on the adjusted reputation level.	NC State	2016
14/925,710	Method and Apparatus for Estimating State of Charge (SOC) of Battery in Electric Vehicle	FP	The apparatus may include a driving history data storage configured to store driving history data for different categories and a battery SOC estimator configured to estimate the SOC of a the battery with respect to the driving route based on the driving profile.	NC State; Samsung Electronics Co Ltd	2017
14/601,819	Method and Apparatus for Estimating Battery Life	Filed/ 1-21-2015			
14/285,853	Battery Parameters, State of Charge (SOC), and State of Health (SOH) Co-Estimation	Filed/ 5-23-2014		NC State	
PCT/US2014/038915	Large-Scale, Time-Sensitive Secure Distributed Control Systems and Methods	Filed/ 5-21-2014		NC State	

FP= Full Patent; PP = Provisional Patent; C= Copyright; T= Trademark