Performance of a DC Multi-Converter Power System due to Variations of Plant Parameters

Juan C. Jimenez and Chika O. Nwankpa

Center for Electric Power Engineering (CEPE), Drexel University, Philadelphia, PA 19104

INTRODUCTION

The evolution of power systems has not only involved massive increase in load levels and types but also variations of what constitutes transmission/distributions networks[1].

Due to numerous reasons, such as the need for reliable supply to critical loads and the integration of alternative energy sources, the notion of extended use of power electronic converters has is being realized for new and future electrical power systems.

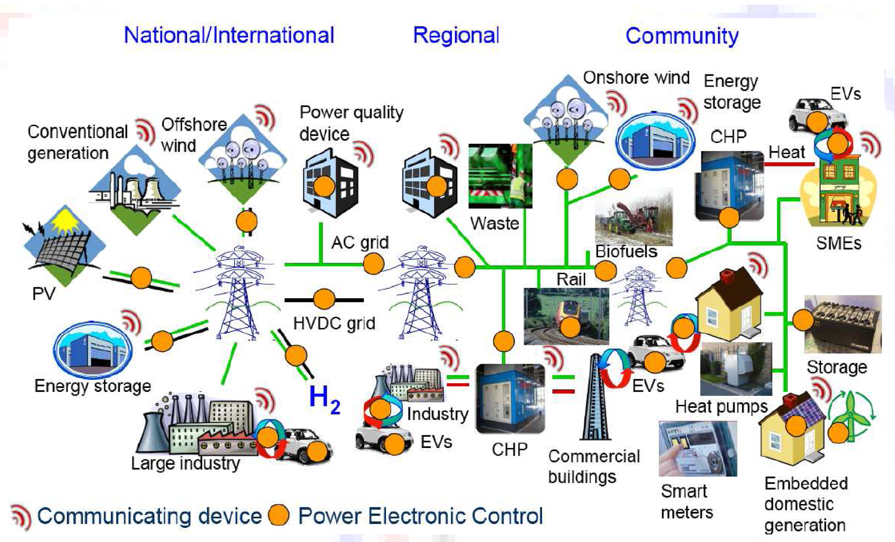


Figure 1. A vision of a smartgrid (Source: Power electronics: a strategy for success, www.bis.gov.uk)

MOTIVATION

Tolbert et al. [2] stated that approximately 30% of all electric power generated presently utilizes power electronics somewhere between generation and consumption and by 2030 this is expected to increase as much as 80%.

It is imperative to acknowledge the critical role played by power electronics as an enabling technology in power systems and their impact on performance and efficiency of these systems.

Teaching and research of power electronics have been topology motivated neglecting the dynamics related to the converters and the interconnected system based on them.

OBJECTIVES

- To develop system models that take into account the nonlinear behavior of DC/DC converters
- To investigate models' impacts on power system studies by using a previously developed observability formulation[3]
- To quantify the operational performance of the system through a measure of observability

STAND-ALONE CONVERTER SYSTEM

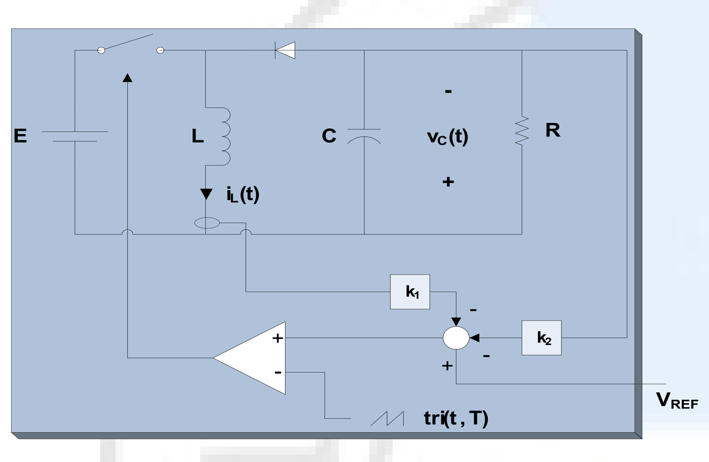
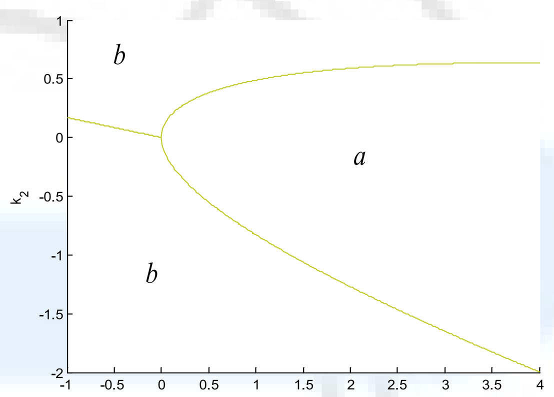


Figure 2. Buck-boost converter with voltage and current feedback control

Boundaries of regions of operation, (b'^{2} - 4a'c') = 0



Single equilibrium point (area *a*)

Two equilibrium points (*solid line*)

Three equilibrium points (area *b*)

Figure 3. Regions of operation of a buck-boost converter with E = 1V, R = 5Ω and V_c^0=0.85V

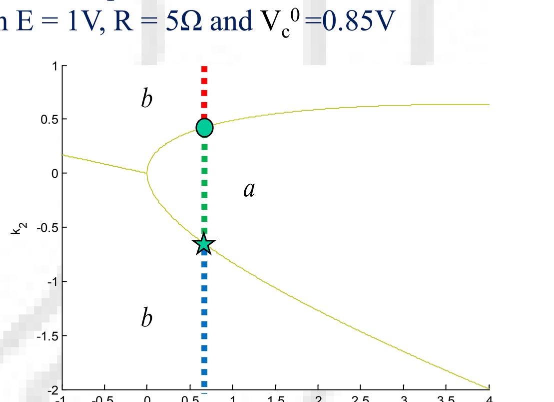


Figure 4. Regions of operation (selected k_1 = 0.6)

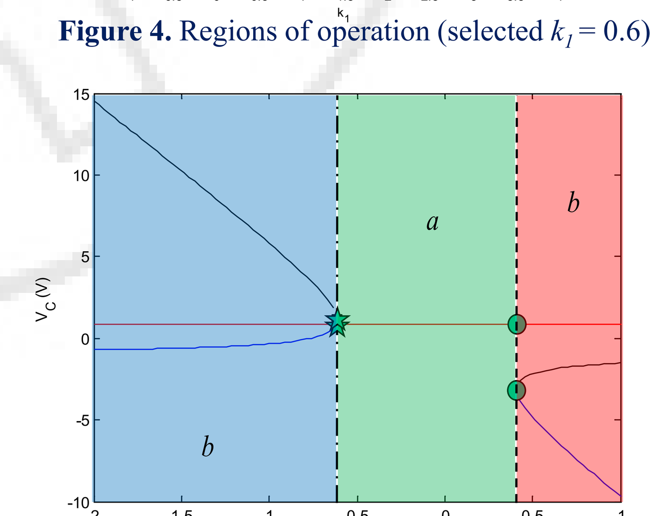


Figure 5. Bifurcation diagram when k_1=0.6 and V_C^0=0.85V

The average state-space is given by:

$$\dot{x}=\left[d(t)A_1+(1-d(t))A_2\right]x+\left[d(t)B_1+(1-d(t))B_2\right]u$$

where $d(t)=V_{ref}-k_1 i_L-k_2 v_C$

The conventional average model due to the substitution of feedback control is:

$$\frac{di_L}{dt}=\frac{1}{L}\left(-v_C+V_{ref}v_C-k_1 i_L v_C-k_2 v_C^2+EV_{ref}-k_1 E i_L-k_2 E v_C\right)$$

$$\frac{dv_C}{dt}=\frac{1}{C}\left(-V_{ref}i_L+k_1 i_L^2+k_2 v_C i_L+i_L-\frac{v_C}{R}\right)$$

With the assumption that at least one real solution V_c^0 exists, the determinant (b'^{2}-4a'c') determines the other types of solutions.

$$\frac{k_1}{RE}V_C^3+V_C^2\left(k_2+\frac{2k_1}{R}\right)+V_C\left(1-V_{ref}+k_2E+\frac{k_1E}{R}\right)-EV_{ref}$$
$$=\left(V_C-V_C^0\right)\left(a'V_C^2+b'V_C+c'\right)$$

DC MULTI-CONVERTER POWER SYSTEM

Modeling

The general model used to investigate power system dynamics is that of the Differential Algebraic Equations (DAE) of type:

$$\begin{bmatrix}\dot{x}\\0\end{bmatrix}=\begin{bmatrix}f(x,y,u,N)\\g(x,y,u,N)\end{bmatrix}\Rightarrow F(\dot{z},z,N)-u=0$$

The dynamics of interest in the multi-converter power system in Fig. 6, with *i* load converters and *j* source converters, are those of converters and main DC bus. Its DAE model is[4]:

$$\frac{di_{L_j}}{dt}=\frac{1}{L_j}\left(V_{ref_j}v_1-k_{2_j}v_1^2-k_{2_j}e_jv_1-k_{1_j}i_{L_j}v_1-v_1+e_jV_{ref_j}-k_{1_j}e_ji_{L_j}\right)$$

$$\frac{di_{L_i}}{dt}=\frac{1}{L_i}\left(V_{ref_i}v_i-k_{2_i}v_i^2-k_{2_i}v_1v_i-k_{1_i}i_{L_i}v_i-v_i+v_1V_{ref_i}-k_{1_i}v_1i_{L_i}\right)$$

$$\frac{dv_i}{dt}=\frac{1}{C_i}\left(i_{L_i}+k_{1_i}i_{L_i}^2+k_{2_i}v_ii_{L_i}-V_{ref_i}i_{L_i}-\frac{P_i}{v_i}\right)$$

$$\frac{dv_1}{dt}=\frac{i_{C_T}}{C_T}=\frac{\sum i_j-\sum i_{S_i}}{C_{EXT}}$$

$$0=\sum P_i-\sum P_j$$

Measurement vector, $p = h(z,N)$, is added to the DAE model for the development of an observability-based performance indicator of the system.

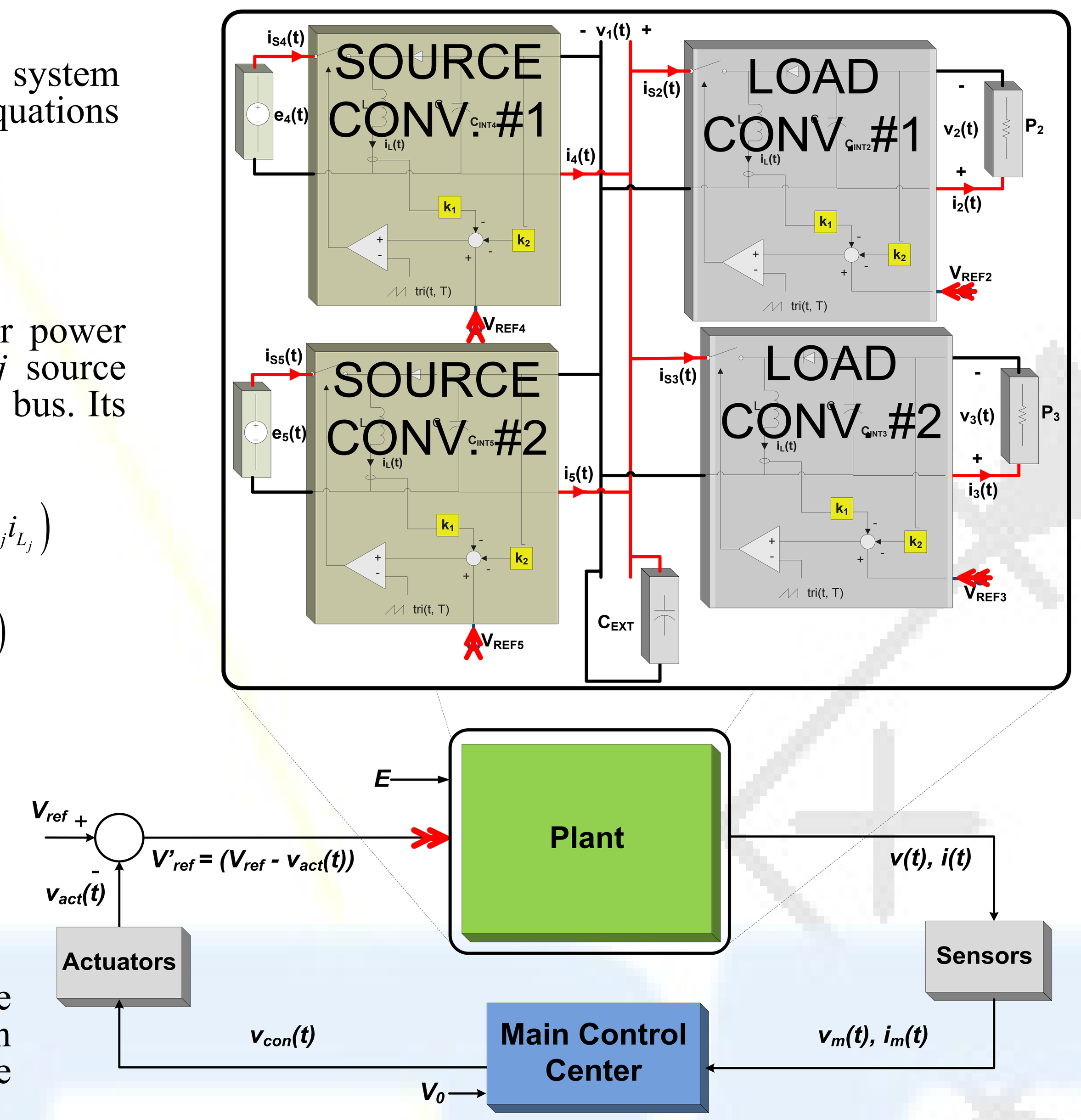


Figure 6. DC Multi-Converter based power system

Observability-based Performance Indicator

Differentiation indices *s* and *r* for the system (*F*) and observation (*h*) equations respectively, yield the following:

$$G=\begin{bmatrix}F(\dot{z},z,N)\\F_z(\dot{z},z,N)\dot{z}+F_{\dot{z}}(\dot{z},z,N)\ddot{z}\\\vdots\\\left(F(\dot{z},z,N)\right)^{(s)}\end{bmatrix}=\begin{bmatrix}u\\u^{(1)}\\\vdots\\u^{(s)}\end{bmatrix}\qquad H=\begin{bmatrix}h(z,N)\\h_z(\dot{z},z,N)\dot{z}\\\vdots\\h(\dot{z},z,N)^{(r)}\end{bmatrix}=\begin{bmatrix}p\\\dot{p}\\\vdots\\p^{(r)}\end{bmatrix}$$

The observability formulation is then derived and given in terms of a general matrix form of the following Jacobian:

$$J_O=\begin{bmatrix}\frac{G_z}{H_z}&\frac{G_{\dot{z}}}{H_{\dot{z}}}&\frac{G_w}{H_w}\end{bmatrix}=\begin{array}{c}\left[\begin{array}{cc|ccc}\frac{dF}{dz}&\frac{dF}{d\dot{z}}&0&0&\cdots\\\frac{dF^{(1)}}{dz}&\frac{dF}{dz}&\frac{dF}{d\dot{z}}&0&\cdots\\\vdots&\ddots&\ddots&\ddots&\ddots\\\hline\frac{dh}{dz}&0&0&0&\cdots\\\frac{dh^{(1)}}{dz}&\frac{dh}{dz}&0&0&\cdots\\\vdots&\vdots&\ddots&\ddots&\ddots\end{array}\right]\begin{array}{c}F\\F^{(1)}\\F^{(s)}\\h\\h^{(1)}\\h^{(r)}\end{array}\\\begin{array}{ccccc}x&\dot{x}&\ddot{x}&\dddot{x}&x^{(\sigma)}\end{array}\end{array}$$

The operational performance of the system is quantified through a metric called condition number, *η*, if following conditions hold[3]:

$$1:rank(J_O)=n+rank\begin{bmatrix}G_{\dot{z}}&G_w\\H_{\dot{z}}&H_w\end{bmatrix}\qquad \eta=\frac{\lambda_{\max}(J_o)}{\lambda_{\min}(J_o)}$$

$2: rank(J_O)$ is constant rank on S

Simulation and Results

- For the static cases studies presented here, the system DAE is converted to a nonlinear algebraic model by setting derivatives to zero, and this set of equations is solved using MATLAB's *fsolve* function
- Per unit analysis
- Load at buses 2 and 3 are varied through the scalar quantity α (increased monotonically)

$$\begin{bmatrix}P_2\\P_3\end{bmatrix}=\begin{bmatrix}P_2^0\\P_3^0\end{bmatrix}+\alpha\begin{bmatrix}\Delta P_2\\\Delta P_3\end{bmatrix}$$

- $P_2^0 = P_3^0 = 0.5$ and under normal operating conditions $V_1^0 = 1.0$, $V_2^0 = 0.9$ and $V_3^0 = 0.85$
- To build J_o four measurements are used, they are output current of source converters, $i_x = (1\text{-}d_x)i_{Lx}$ and output power of load converters, $P_x = v_x i_x = v_x(1\text{-}d_x)i_{Lx}$
- The condition number, *η*, is then monitored along a given system load profile

Table 1. Converter's parameters

Converter	Case Study #1			Case Study #2		
	k_1	k_2	V_{ref}	k_1	k_2	V_{ref}
Load Conv.#1	0.06	-0.30	0.2670	0.02	-0.01	0.4858
Load Conv.#2	0.08	-0.20	0.3765	0.03	-0.04	0.4581
Source Conv.#1	0.24	-0.05	0.5844	0.24	-0.05	0.5844
Source Conv.#2	0.15	-0.10	0.4920	0.15	-0.10	0.4920

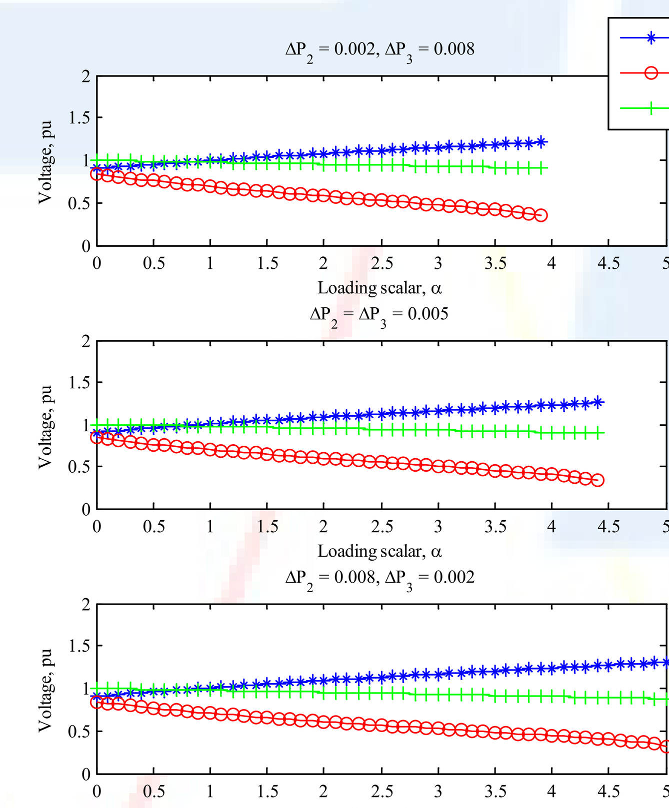


Figure 7. V-α curve for case study #1

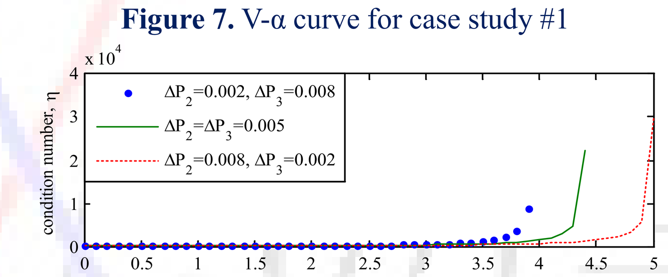


Figure 8. η-α curve for case study #1

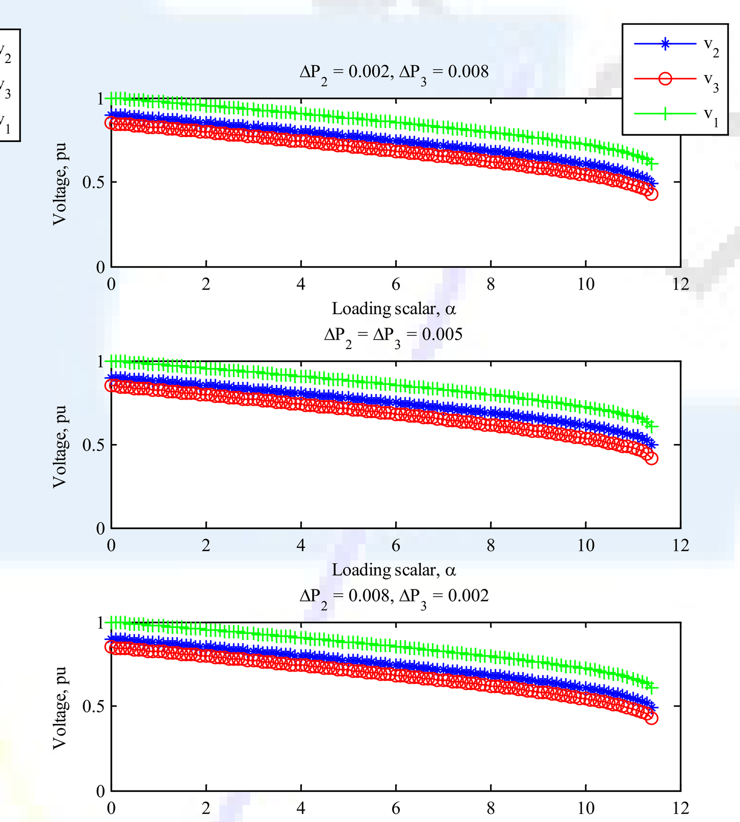


Figure 9. V-α curve for case study #2

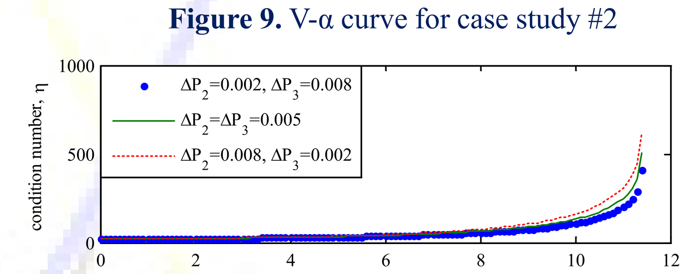


Figure 10. η-α curve for case study #2

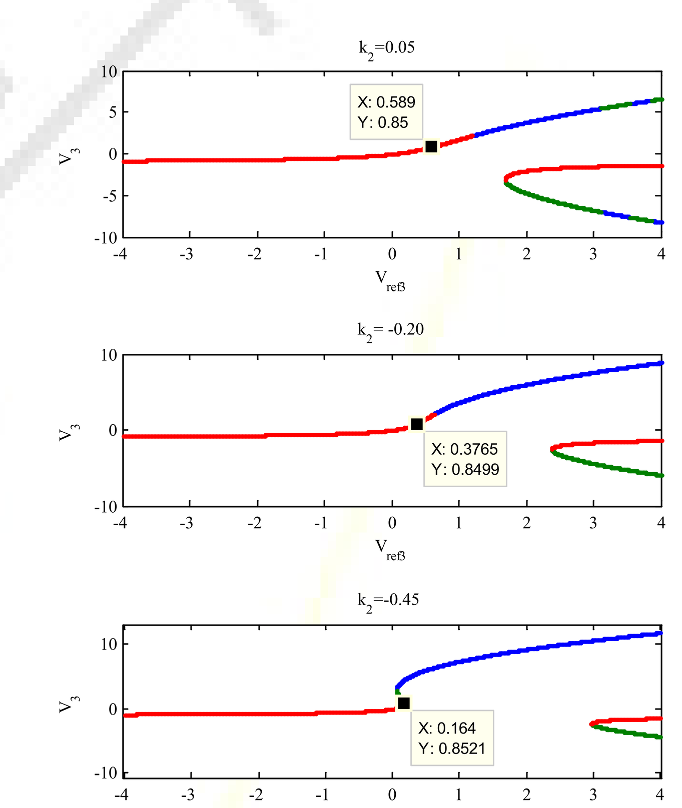


Figure 11. $V_3 - V_{ref3}$ curves for load converter #2 with k_1 = 0.08 and varying k_2

General Observations:

- Depending on converter's internal control gains and loading direction, the system can be driven to undesirable operating conditions in absence of a system-wide controller
- With internal control gains fixed, V_{ref} variations can change the equilibrium point structure of the system

CONCLUSIONS AND FUTURE WORK

- Model development for a DC system involving multi-converters has been presented
- It was shown through simulation the need and importance of acknowledging the critical role of nonlinear relationships between converters in the overall performance of a power electronics based power system
  - This opens the case for the development and need of a system wide controller that will aid local controllers maintain the system in stable operating conditions
- *Current and Future work:* To investigate the dependency of the observability-based performance indicator on available measurement sets in the system

REFERENCES

[1] N Kezunovic, M.; McCalley, J.D.; Overbye, T.J., "Smart Grids and Beyond: Achieving the Full Potential of Electricity Systems," *Proceedings of the IEEE* , vol.100, no.Special Centennial Issue, pp.1329,1341, May 13 2012

[2] L. M. Tolbert, T. J. King, B. Ozpineci, J. B. Campbell, G. Muralidharan, D. T. Rizy, A. S. Sabau, B. W. McConnell, H. Zhang, W. Zhang, X. Yu, H. F. Huq, and H. Liu, *Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications*, ORNL/TM-2005/230, UT-Battelle, LLC, Oak Ridge National Laboratory, September 2005

[3] W. J. Terrell, "Observability of Nonlinear Differential Algebraic Systems," *Circuits, Systems and Signal Processing*, Vol. 16, No. 2, 1997, pp. 271-285

[4] J.C. Jimenez, S. Jayasuriya and C.O. Nwankpa, "Simulation platform development for the analysis of power electronic converter systems with plant and network coupling," *2014 Twenty-Ninth Annual IEEE Applied Power Electronics Conference and Exposition (APEC),* pp.1158,1164, 16-20 March 2014

ACKNOWLEDGMENTS: The authors would like to acknowledge and thank the United States Office of Naval Research for their financial support under grant nos. ONR N00014-14-1-0061 and ONR N00014-13-1-0611

Juan C. Jimenez jcj26@drexel.edu **Center for Electric Power Engineering (CEPE)** http://power.ece.drexel.edu **Chika O. Nwankpa** con22@drexel.edu