Extremum Seeking-based Adaptive Voltage Control of Distribution Systems with High PV Penetration

Wei, C.; Benosman, M.

TR2016-131 September 2016

Abstract

With the increasing capacity of grid-connected PV systems, ancillary service such as voltage regulation at point of common coupling (PCC) is available from PV systems by controlling the amount of reactive power injected to the grid. This paper proposes an adaptive voltage control method of distribution systems with high-level PV penetration. The modelfree extremum seeking (ES) control algorithm is used to autotune the PI feedback gains of the voltage controller to respond dynamically to system changes. The PI gains of the voltage controller are updated online through the minimization of a cost function, which represents the voltage controller performance. The proposed ES-based adaptive voltage controller is tested in a distribution system model with a 5-MW PV system built in Matlab/Simulink. Simulation results show that compared with traditional PI controller, the proposed voltage controller can easily adapt to load changes and grid faults, thus improving the power system reliability and voltage stability.

Conference on Innovative Smart Grid Technologies (ISGT)

Extremum Seeking-based Adaptive Voltage Control of Distribution Systems with High PV Penetration

Chun Wei
Dept. of Electrical and Computer Engineering
University of Nebraska-Lincoln
Lincoln, NE, USA
Email: cwei@huskers.unl.edu

Mouhacine Benosman
Mitsubishi Electric Research Laboratories
Cambridge, MA, USA
Email: benosman@merl.com

Abstract—**With the increasing capacity of grid-connected PV systems, ancillary service such as voltage regulation at point of common coupling (PCC) is available from PV systems by controlling the amount of reactive power injected to the grid. This paper proposes an adaptive voltage control method of distribution systems with high-level PV penetration. The model-free extremum seeking (ES) control algorithm is used to auto-tune the PI feedback gains of the voltage controller to respond dynamically to system changes. The PI gains of the voltage controller are updated online through the minimization of a cost function, which represents the voltage controller performance. The proposed ES-based adaptive voltage controller is tested in a distribution system model with a 5-MW PV system built in Matlab/Simulink. Simulation results show that compared with traditional PI controller, the proposed voltage controller can easily adapt to load changes and grid faults, thus improving the power system reliability and voltage stability.**

Index Terms—**Distribution system, extremum seeking, PI control, PV system, adaptive voltage control, gains auto-tuning.**

I. INTRODUCTION

As a clean pollution-free and inexhaustible energy source, solar energy has experienced dramatic development in the last decade, and the global capacity of solar power is expected to reach 980 GW by 2020 [1]. The penetration of distributed generation (DG) from renewable resources like PV system is rapidly increasing because of the distinctive advantages such as simple allocation, high dependability, low maintenance and more environmental friendly. Moreover, due to the fundamental changes in policies of governments, declining cost of solar modules and increasing efficiency of solar cells, more and more PV systems are being connected to the distribution system (DS) [2].

The grid integration of PV systems via power electronic converters is becoming the most important application of PV system. With the increased number of grid-connected PV systems, ancillary services such as voltage regulation can be obtained from PV systems by controlling power electronic converters [3]-[4]. The voltage source converter (VSC), which is capable of operating in four quadrants, is mostly used for integration of PV systems to the power grid. Since the voltage at the point of common coupling (PCC) of a grid-connected VSC can be dynamically regulated by controlling the reactive power injected by the VSC to the power grid, the PV systems can be used as a dynamic voltage regulator in the DS [5]-[6].

Conventional PI controller has been extensively used for the control of VSC in the DS. However, it has been reported that PI controller with fixed gain fails to operate well in case of load changes and high penetration of DGs. The PI controller parameters have great influence on the dynamic response of the DG and incorrect parameter selections may cause slow, oscillatory, or unstable response that can lead to system instability [3]. Moreover, manual methods like trial and error adjustment is very time-consuming and tedious, which makes it unfeasible for utility engineers to perform when system changes and parameter variations occur.

To cope with the aforementioned deficiencies of traditional PI control and increase the reliability of the control system, an online and automatic tuning approach is much more advantageous to adjust control parameters than trial and error methods. Intelligent control algorithms such as fuzzy logic and artificial neural networks have been used to tune the control parameters online recently. However, the applications of these algorithms increase the control system complexity [7]. Other approaches, such as particle swarm optimization, may require detailed system parameters, real-time system information, and fast communications. It may not be suitable for a real, large DS application.

Extremum seeking (ES) is a well-known approach by which one can search for the extremum of a cost function associated with a given process performance without the need for a precise model of the process [8]-[9]. Several ES algorithms have been proposed, and many applications of ES algorithms have been reported [10]-[11]. In this paper, we propose an adaptive voltage control method of DS with high PV penetration based on the model-free ES algorithm. The PI gains of the voltage controller are updated online to respond dynamically to system changes through the minimization of a cost function, which represents the voltage controller

---

The work has been done during the internship of Chun Wei at MERL.

performance. A detail model of a DS with 5-MW grid-connected PV system is built in Matlab/Simulink to test the proposed ES-based adaptive voltage controller. Simulation results show that compared with traditional PI controller, the proposed voltage controller can easily adapt to load changes and grid faults, thus improving the power system reliability and voltage stability.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

The configuration of a 5-MW PV array connected to a 25-kV DS via a three-phase converter is shown in Fig. 1. The PV array consists of 1720 parallel strings. Each string has 7 SunPower SPR-415 modules connected in series. Each module has the maximum output power 415 W, totally forming a 5-MW PV system. The power electronic interface includes the three-phase DC/AC converter and two dc-side capacitors with voltage v_{dc} 520 V. The converter is modeled using a 3-level VSC based on IGBT bridge PWM-controlled. The inverter choke RL and a small harmonics filter C are used to filter the harmonics generated by the IGBT bridge. A 250V/25kV three-phase transformer is used to connect the inverter to the utility DS. The utility DS is modeled as a typical North American distribution grid. It includes a 25-kV feeder, loads, and an equivalent 120-kV transmission system. The PCC voltage is denoted as v_t. By generating or consuming a certain amount of reactive power, the inverter is controlled to regulate v_t.

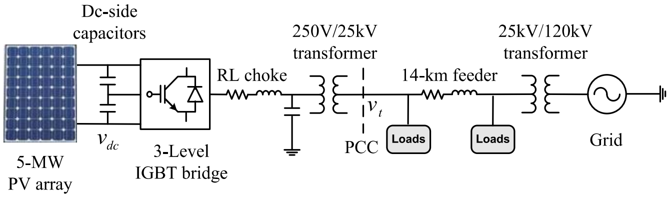


Fig. 1. Single-line diagram of a 5-MW PV array connected to a 25 kV distribution system.

B. Control of Grid-Connected VSC

The proposed control scheme for the three-phase grid-connected VSC is based on the concept of instantaneous power on the synchronous rotating *dq* reference frame as shown in Fig. 2. The control system contains five major parts, which are maximum power point tracking (MPPT) controller, PCC voltage controller, v_{dc} regulator, current regulator and PWM generator. All the control variables are feasible to be locally measured.

The MPPT controller and PCC voltage controller are responsible for determining the active and reactive power exchange between the PV system and the utility grid. The main purpose of a grid-connected PV system is to transfer the maximum solar energy into the utility grid. To achieve this, a MPPT controller is used to maximize the instant power generated by the PV array. Perturbation and observation (P&O), also known as hill climb search method, is used because of simple structure and the few measured variables that are necessary. The MPPT controller automatically varies the v_{dc} reference signal of the v_{dc} regulator in order to obtain a dc voltage which will extract maximum power from the PV array. The generated v_{dc} reference is set to the v_{dc} regulator to determine the required i_d (active component) reference for the current regulator.

By using the VSC, the reactive power injected/absorbed into/from the utility grid can be controlled. Thus, the improvement of the voltage profile in the PCC of the PV system can be obtained. The PCC voltage of the PV system is controlled by the voltage controller through the modulation of the reactive component of the output current i_q. To this aim, the magnitude of the voltage vector at the PCC is compared to a voltage reference. An error signal is produced and then fed to a PI controller, whose parameters are automatically tuned by the ES algorithm. Based on the current references $i_d$andi_q, the current regulator determines the required reference voltages for the inverter. A vector control approach is used, with a reference frame oriented along the grid voltage vector position θ_g that is measured by a phase lock loop (PLL), enabling independent control of the active and reactive power. The voltage reference in the *dq* form is transformed to *abc* components through the phase angle θ_g to obtain the positive sequence components of the ac voltage at the PCC. Once the reference voltages for the inverter are obtained, firing signals to the IGBTs based on the required reference voltages are generated by the PWM generator for the 3-level VSC.

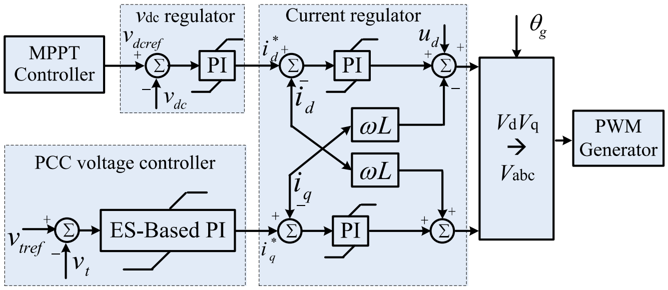


Fig. 2. The proposed control scheme for the three-phase grid-connected VSC.

C. Control of PCC Voltage

The control diagram of the PCC voltage regulation using a PI feedback controller is included in Fig. 2. The PCC voltage is measured and its RMS value, v_t, is calculated. The RMS value is then compared to a voltage reference v_{tref}, which could be a utility specified voltage schedule and can be adjusted. The error between the actual and reference voltage is fed back to adjust the reference output current component i_q^* , which is the magnitude of the reactive current reference used to regulate v_t to the reference v_{tref}. The control scheme can be specifically expressed as

$$i_q^* = K_P[v_{tref}(t) - v_t(t)] + K_I \int_0^t [v_{tref}(t) - v_t(t)]dt \qquad (1)$$

where K_P and K_I are the proportional and integral gain parameters of the PI controller. The two gain parameters of the PI controller affect the voltage regulation dynamics. Therefore, it is an important issue to set the gains to optimize the PI controller performance for an effective and efficient voltage regulation. In this paper, we use the model-free ES algorithm to auto-tune the PI gains online.

III. ES-BASED AUTO-TUNING FOR PI CONTROLLER GAINS

In this section two scalar gradient-based ES control algorithms will be introduced, including the ES for the case of time independent cost function (static optimization) and time-varying cost function (functional optimization), denoted as ES1 and ES2, respectively. The gain auto-tuning method for the PI controller is designed using the two ES algorithms for different cost functions that have been selected.

A. ES1 for Cases of Static Optimization

The basic scheme for a single gradient-based ES controller is shown in Fig. 3. The algorithm injects a sinusoidal perturbation $a\sin\omega t$ into the system, resulting in an output of the cost function $Q(\hat{\theta})$. This output $Q(\hat{\theta})$ is subsequently multiplied by $a\sin\omega t$. The resulting signal, $\dot{\xi}$, is an estimate of the gradient of the cost function with respect to θ. The gradient estimate is then passed through an integrator k_{ai}/s and added to the modulation signal $a\sin\omega t$. The corresponding equations for the basic multi-parameter ES algorithm is:

$$\dot{\xi}_i = a_i k_{ai}\sin(\omega_i t)Q(\hat{\theta}) \tag{2}$$

$$\hat{\theta}_i = \xi_i + a_i\sin(\omega_i t) \tag{3}$$

where $\omega_i \neq \omega_j$, $\omega_i+\omega_j \neq \omega_k$, i, j, k_{ai}, $\in \{1, 2, n\}$, and$\omega_i > \omega^*$, with ω^* large enough to ensure the convergence. If the parameters a_i, ω_i, and k_{ai} are properly selected, the cost function output $Q(\hat{\theta})$ will converge to an neighborhood of the optimal cost function value $Q(\theta^*)$.

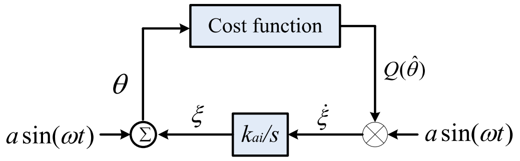


Fig. 3. Block diagram of the basic gradient-based extremum seeking control algorithm.

B. ES2 for Cases of Functional Optimization

The block diagram of the ES control algorithm for the case of functional optimization is shown in Fig. 4. There is no perturbation signal between the integral function and the system, which is different from the basic ES control algorithm. The corresponding equation for the multi-parameter ES algorithm is [12]:

$$\dot{\hat{\theta}}_i = a\sqrt{\omega_i}\cos(\omega_i t) - k\sqrt{\omega_i}\sin(\omega_i t)Q(\hat{\theta},t) \tag{4}$$

where a and k are positive numbers, $\omega_i \neq \omega_j i$, j, $\in \{1, 2, n\}$, and$\omega_i > \omega^*$, with ω^* large enough to ensure the convergence.

C. PI Controller Gains Auto-Tuning

ES is used to tune the PI parameters of the PCC voltage controller such that the tracking error of the closed loop system with an unknown plant is minimized. The effectiveness of the PI controller is quantified using a cost function. Two types of cost functions are designed in this paper for ES1 and ES2, respectively.

For ES1, the following cost function evaluated at the conclusion of a voltage variation (such as that caused by the load changes) is used:

$$Q(\theta,t) = \int_{t_0}^{T} [v_{tref}(t) - v_t(t)]^2 dt \tag{5}$$

wheret_0 and T are the times during the voltage variation at which we begin and end taking into account the error during calculation of the cost function, respectively; θ isa vector that contains the PI parameters, $\theta = [K_P, K_I]^T$.

For ES1, the variations of the estimated gains are given by

$$\begin{aligned}
\dot{\xi}_{K_P} &= a_{K_P}\sin(\omega_1 t)Q(\hat{\theta}_{K_P},t)\\
\hat{K}_P(t) &= \xi_{K_P}(t) + a_{K_P}\sin(\omega_1 t)\\
\dot{\xi}_{K_I} &= a_{K_I}\sin(\omega_2 t)Q(\hat{\theta}_{K_I},t)\\
\hat{K}_I(t) &= \xi_{K_I}(t) + a_{K_I}\sin(\omega_2 t)
\end{aligned} \tag{6}$$

The ES algorithm uses the discrete value of the cost function generated at the completion of each iteration to compute the next set of controller parameters, θ. When a new voltage variation happens, the PI controller will perform with the new controller parameters and the process continues iteratively in this fashion until optimal parameters are found.

For ES2, the following cost function evaluated at each sampling time Δt is used:

$$Q(\theta,\Delta t) = [v_{tref}(t) - v_t(t)]^2 \tag{7}$$

For ES2, the variations of the estimated gains are given by

$$\begin{aligned}
\dot{\hat{K}}_P(t) &= a_1\sqrt{\omega_1}\cos(\omega_1 t) - k_1\sqrt{\omega_1}\sin(\omega_1 t)Q(\hat{\theta}_{K_P},\Delta t)\\
\dot{\hat{K}}_I(t) &= a_2\sqrt{\omega_2}\cos(\omega_2 t) - k_2\sqrt{\omega_2}\sin(\omega_2 t)Q(\hat{\theta}_{K_I},\Delta t)
\end{aligned} \tag{8}$$

The ES algorithm uses the discrete value of the cost function generated at each sampling time to compute the set of controller parameters θ for the next sampling time.

The block diagram of the overall ES PI tuning scheme is shown in Fig. 5.

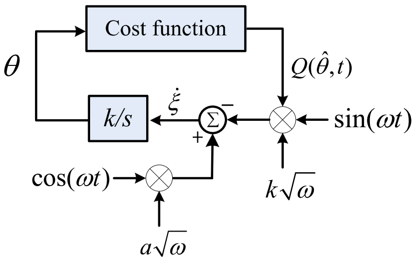


Fig. 4. Block diagram of the extremum seeking control algorithm for the case of functional optimization.

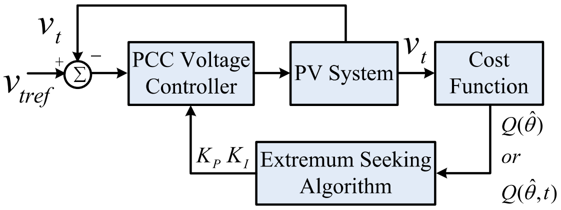


Fig. 5. Overall extremum seeking PI tuning scheme.

IV. SIMULATION RESULTS

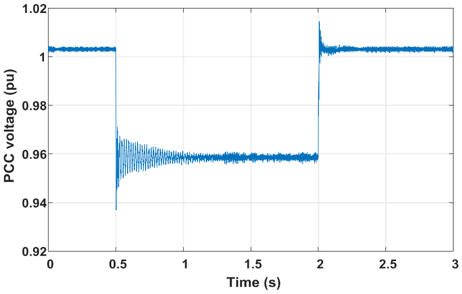
In this section, the proposed ES-based adaptive voltage controller is tested in a distribution system model with a 5-MW PV system shown in Fig. 1. The proposed two ES-based (ES1 and ES2) voltage controllers are tested under the load variation conditions. The performance of the voltage controller using ES2 algorithm under grid fault condition is also provided. All the performance of the voltage controller under both conditions are compared with the traditional PI controller. All the control parameters are list in Table I.

TABLE I. CONTROL PARAMETERS OF ES ALGORITHMS

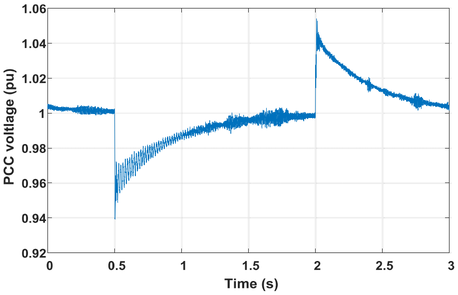
ES1	a_1	ω_1	a_2	ω_2	k_{ai}
	1	pi/100	10	0.15pi	1
ES2	a_1	ω_1	a_2	ω_2	k_1, k_2
	1	pi/100	25	0.06pi	1

A. Load variation with and without voltage controller

The PCC voltage of a DS will change if there are load variations in the system. As a result, a voltage controller is required to maintain the voltage within a certain range of the normal voltage, especially when the penetration of the renewable energy increases. Fig. 6 shows the simulation results of the system when there is a 3.75 MW inductive reactive power load switch on and off at the PCC with and without a voltage controller. Obviously, the voltage drops to 0.96 because of the load variation if there is no voltage controller to inject reactive power to the grid. On the contrary, the voltage recoveries to the normal value when a voltage controller is used. Therefore, the performance of the voltage controller is very important to the system and its parameters should be properly adaptively tuned online.



(a) Without voltage controller



(b) With voltage controller

Fig. 6. PCC voltage under load variation with and without voltage controller.

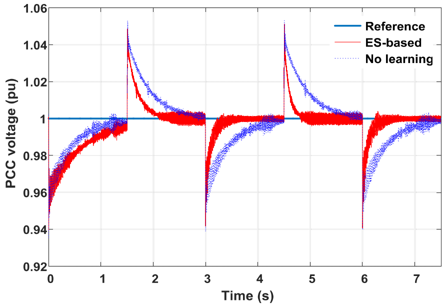


Fig. 7. PCC voltage under load variations with voltage controller based on ES1.

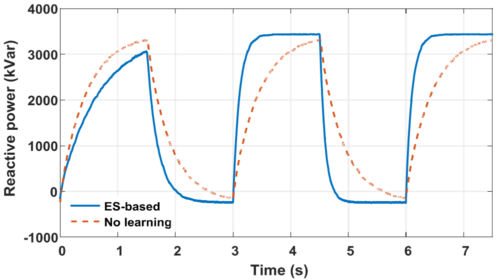


Fig. 8. Reactive power variations by the voltage controller during load changes.

B. PCC Voltage with Voltage Controller Based on ES1

The ES1 algorithm is used to tune the PI gains of the voltage controller adaptively to obtain a better performance of the PCC voltage control. To prove the effectiveness of the proposed auto-tuning algorithm, the same 3.75 MW load is used and switched on and off every 1.5 s. The simulation results are shown in Fig. 7. It takes about 1.5 s for the

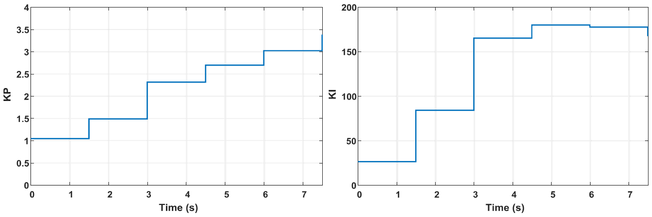


Fig. 9. Variations of K_P and K_I.

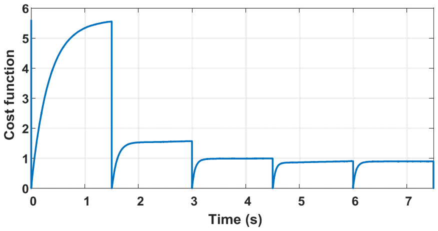
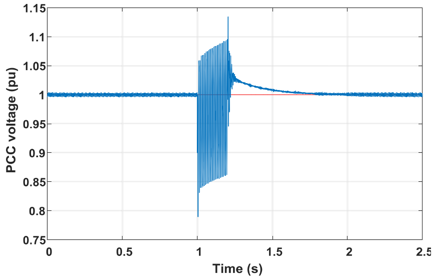


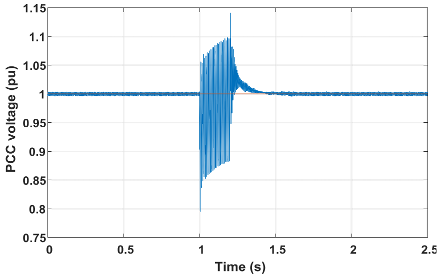
Fig. 10. Convergence of the cost function.

traditional PI controller to recover the voltage to the normal value. However, when the ES-based method is used, the PCC voltage recover to the normal value within only 0.5 s after a certain times of learning. Fig. 8 shows the reactive power variations during the load changes. A certain amount of reactive is injected to the grid to maintain the PCC voltage. By using the adaptive voltage controller, the injection of the reactive power is faster than that using the traditional PI controller. Fig. 9 shows the variations of K_P and K_I during this process. Converging trends can be seen from this figure.

Fig. 10 shows the variation of the cost function defined by (5). A convergence of the cost function can be seen. At the beginning, the value of the cost function is large. After two times of the load variations, the value of the cost function decreases to a small value and maintains at a certain level.



(a)With traditional PI controller



(b) With voltage controller based on ES2.

Fig. 11. PCC voltage under grid fault.

C. PCC Voltage under Grid Fault

The ES2 algorithm is used to tune the PI gains of the voltage controller adaptively to obtain a better performance of the PCC voltage control under grid faults. In this study, the grid fault of phase A to ground is applied at the PCC and the magnitude of phase A voltage is decreased to 90% of the normal value. Fig. 11 shows the PCC voltage under grid fault using the traditional PI controller and the voltage controller based on ES2. If the traditional PI controller is used, it takes about 0.6 s for the voltage to recover to the normal value after the grid fault clears. However, by using the voltage controller based on ES2, the PI gains adapt when the grid fault happen to make the voltage controller perform better after the fault clears. As can been seen, it only takes about 0.2 s for the voltage to recover to the normal value by using the new PI gains.

Fig. 12 shows the variations of K_P and K_I under the grid fault. Both of them changes to a higher value to make a better performance of the voltage controller.

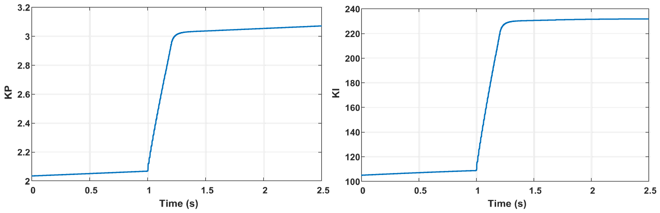


Fig. 12. Variations of K_P and K_I.

V. CONCLUSION

This paper has proposed an adaptive voltage control method of distribution systems with high-level PV penetration. The model-free extremum seeking (ES) control algorithm has been used to adaptively auto-tune the PI gains of the voltage controller to respond dynamically to system changes. The PI gains of the voltage controller has been updated online through the minimization of a cost function, which represents the voltage controller performance. The proposed ES-based adaptive voltage controller has been tested in a distribution system model with a 5-MW PV system built in Matlab/Simulink. Simulation results have shown that compared with traditional PI controller, the proposed voltage controller can easily adapt to load changes and grid faults, thus improving the power system reliability and voltage stability.

REFERENCES

[1] X. Li, Y. Li, and J. E. Seem, “Maximum power point tracking for photovoltaic system using adaptive extremum seeking control,” *IEEE Trans. Control Syst. Tech.*, vol.21, no. 6, pp. 2315-2322, Nov. 2013.

[2] J. Zeng, W. Qiao, and L. Qu, “An isolated multiport bidirectional DC-DC converter for PV-battery-DC microgrid applications,” in *Proc. Energy Conversion Congress and Exposition (ECCE)*, pp. 4978-4984, 2014.

[3] H. Li, F. Li, Y. Xu, D. T. Rizy, and J. D. Kueck, “Adaptive voltage control with distributed energy resources: algorithm, theoretical analysis, simulation, and field test verification,” *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1638-1647, Aug. 2010.

[4] B. K. Perera, P. Ciufo, and S. Perera, “Point of common coupling (PCC) voltage control of a grid-connected solar photovoltaic (PV) system,” in *Proc. IEEE IECON*, 2013.

[5] K. T. Tan, P. L. So, Y. C. Chu, and M. Z. Q. Chen, “Coordinated control and energy management of distributed generation inverters in a microgrid,”*IEEE Trans. Power Delivery*, vol. 28, no. 2, pp. 704-713, Apr. 2013.

[6] T. Wang, D. O’Neill, and H. Kamath, “Dynamic control and optimization of distributed energy resources in a microgrid,” *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2884-2894, Nov. 2015.

[7] S. Seidi Khorramabadi, and A. Bakhshai, “Critic-based self-tuning PI structure for active and reactive power control of VSCs in microgrid systems,” *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 92-103, Jan. 2015.

[8] M. Benosman, and G. M. Atinc, “Multi-parametric extremum seeking-based learning control for electromagnetic actuators,” in *Proc. American Control Conference (ACC)*, pp. 1914-1919, 2013.

[9] N. Killingsworth, and M. krstic, “Auto-tuning of PID controllers via extremum seeking,” in Proc. American Control Conference, 2005.

[10] M. Krstic, and A. Ghaffari, “Extremum seeking for wind and solar energy applications,” in Proc. 11th World Congress on Intelligent Control and Automation, 2014.

[11] D. B. Arnold, M. N. Pincetic, M. D. Sankur, D. M. Auslander, and D. S. Callaway, “Model-free optimal control of VAR resources in distribution systems: an extremum seeking approach,” IEEE Trans. Power System, in press.

[12] M. Benosman, “Extremum seeking-based indirect adaptive control and feedback gains auto-tuning for nonlinear systems,” available online: http://www.merl.com/publications/docs/TR2015-009.pdf.