Impact of Controlled Plug-In EVs on Microgrids: A Military Microgrid Example

Tulga Ersal, Changsun Ahn, Ian A. Hiskens, *Fellow, IEEE*, Huei Peng, and Jeffrey L. Stein

***Abstract*—Increasing concerns about energy security and reliability are intensifying the interest in microgrid and vehicle-to-grid (V2G) technologies. Although the role of V2G technology within the context of optimal scheduling for larger grids has received much attention in the literature, its role within the regulation of microgrids has not yet been studied extensively. In this paper, we focus on the voltage and frequency regulation problem. We develop a microgrid model that is representative of the microgrid architecture considered in the SPIDERS (Smart Power Infrastructure Demonstration for Energy Reliability and Security) project of the Department of Defense. The model is parameterized to reflect the characteristics of Camp Smith, HI, the targeted installation of the SPIDERS project, and the long term Army goals regarding renewable energy penetration and reduction in fuel consumption. The model is augmented by power, frequency, and voltage control algorithms for the inverters that connect microsources to the microgrid. It also incorporates charging/discharging control algorithms for plug-in electric vehicles (PEVs) to take advantage of their capacity as both controllable loads and sources. Using this model, we study the impact of PEVs on the microgrid at different penetration levels and for different control parameters, with the aim of identifying the conditions needed for the vehicle-to-grid technology to have a positive impact on microgrid performance.**

***Index Terms*—Electric vehicles; frequency control; microgrid; vehicle-to-grid; voltage control**

I. Introduction

Industrial and political plans to increase energy security, sustainability, and resilience require the stable and reliable integration of renewable resources and the effective use of the distributed energy storage capacity provided by the vehicle-to-grid (V2G) technology. Microgrids were proposed as an effective way to meet such requirements. The concept of a microgrid has been defined as an aggregation of loads and micro-sources operating as a single system that is seen as a single controlled unit by the total grid network [1]. Several kinds of power sources, such as wind, solar, geothermal, and fossil fuel, can be involved in electric power generation in microgrids. The intermittent characteristics of renewable power sources, as well as disturbances such as unplanned islanding of the microgrid, may cause stability issues, and hence effective control and management of multiple power sources and storage devices becomes crucial.

This paper considers voltage and frequency regulation in microgrids, and focuses specifically on the role of V2G technology in microgrid regulation. The small inertias of microgrids make the regulation problem more challenging, especially during islanding [1, 2]. Islanding may happen due to planned outages for maintenance, for example, but also due to unexpected failures in the main grid or the microgrid. Without appropriate short time-scale control, significant fluctuations in frequency and voltage can occur due to an imbalance between power supply and demand. Stable operation under such unexpected failures is crucial for applications where sustaining the critical loads is important for security or safety, and V2G technology could help achieve this goal.

This work is at the intersection of two rapidly evolving technologies: V2G and microgrids. The impact of integrating vehicles into the grid in a large scale has received much attention in the literature [3-13]. Researchers have shown that the existing generation capacity can readily accommodate the penetration of plug-in electric vehicles (PEVs), if the PEV charging is carefully controlled [3]. More importantly, V2G technology could increase the integration of renewable power sources into the grid [5, 10, 12, 14, 15], reduce emissions [8, 10, 12, 16], help with ancillary services such as regulation, spinning reserves, and peak power [4, 5, 9, 14, 15, 17], thereby offering economic benefits [4, 9, 15, 17]. To achieve such goals, researchers have proposed and analyzed different control schemes [18-23]. Control techniques for other controllable loads such as thermostatically controlled loads [24] or other sources such as photovoltaic systems [25, 26] could also impact V2G systems [13, 25].

These V2G control approaches mainly focus on the scheduling problem within the context of large grids. Such optimal scheduling techniques typically focus on longer time-horizon performance and may thus not respond to sudden interruptions fast enough, which is critical for regulation of microgrids. The importance of regulation was recognized in the microgrid literature from the beginning, and researchers proposed various control methods, such as droop control [1, 27-31] or integral control of inverters [32], even though these earlier works did not explicitly consider V2G technology. Thus, the two bodies of literature grew initially independently. Recent work, however, started taking PEVs into account and proposed control methods for PEV charging/discharging based

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on droop characteristics for decentralized frequency and voltage control [33, 34]. Such decentralized control techniques have also been compared to centralized approaches [34]. However, the relationship between PEV penetration level (i.e., the ratio of PEV power to total power generation) and regulation performance is still an open research question.

In this paper we analyze the effect of the PEV penetration level on regulation performance of a conceptual military microgrid. The U.S. Department of Defense (DoD) is considering microgrids as a solution to address its needs for improved energy security and reliability of military bases. This interest in military microgrids is well exemplified by the SPIDERS (Smart Power Infrastructure Demonstration for Energy Reliability and Security) project, which aims to demonstrate the first complete DoD installation with a secure microgrid capable of islanding. Such microgrids are expected to increase efficiency and resilience during both grid-connected and islanded operations by making effective use of the renewable and non-renewable resources and the distributed energy storage capacity provided by the V2G technology.

Towards this goal, we have created a microgrid model that is representative of the architecture considered in the SPIDERS project. The model is parameterized to reflect the characteristics of Camp Smith, HI, the targeted installation of the SPIDERS project, and the long term army goals regarding renewable energy penetration and reduction in fuel consumption. The model is augmented by power, frequency, and voltage control algorithms for the inverters that connect microsources to the microgrid, as well as charge/discharge control algorithms for PEVs. Using this model, we then study the impact of PEVs on the microgrid within the scope of voltage and frequency regulation.

The rest of this paper is organized as follows. Section II describes the microgrid model considered in this study. Section 0 first describes the scenario considered, along with the performance metrics and goals. Simulation results are then presented and discussed. Finally, conclusions are given in Section IV.

II. Microgrid Model

The microgrid considered in this paper is adopted from the SPIDERS operational concept. The simplified configuration, as shown in Fig. 1, consists of three feeders with two renewable energy sources, two conventional microsources, and two loads that are considered to be critical and thus need to be supplied at all times. In addition, a collection of PEVs are considered explicitly to take into account their ability to act as both a load and a power source.

Many forms of distributed generation connect to the AC backbone grid through inverters. For the purposes of this example, we assume that the renewable sources and the PEVs are connected to the grid through inverters, and hence, their dynamics are of interest.

A model for the inverter-grid interface is shown in Fig. 2. The primary goals of an inverter are to regulate the terminal bus voltage magnitude V_t and the active power delivered to the grid P_{gen}. This is achieved by controlling the modulation

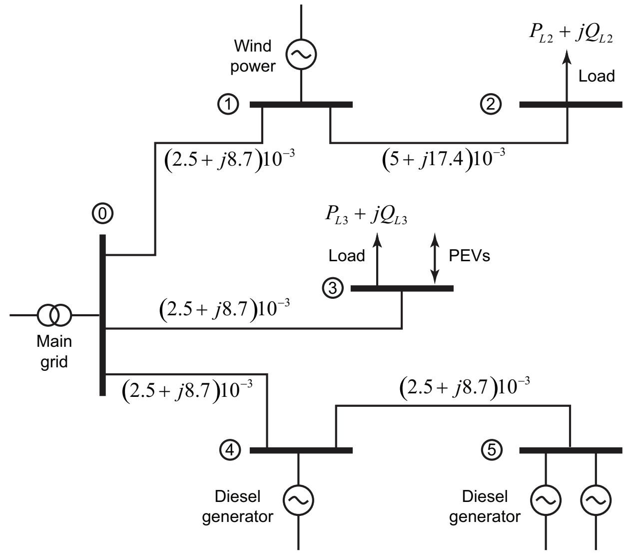

Fig. 1. SPIDERS microgrid example.

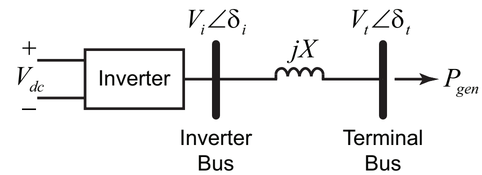

Fig. 2. Inverter-grid interface model.

index m of the inverter, which effectively controls the inverter voltage magnitude V_i through the relationship

$$V_i = m\frac{V_{dc}}{V_{base}}, \quad (1)$$

and the inverter firing angle, which effectively determines the phase angle δ_i.

This paper considers inverter control that is based on the use of a phase-locked loop (PLL) to ensure synchronization to the AC-side voltage. Specifically, the inverter control strategy proposed by Hiskens and Fleming [32] is utilized. The dynamics of this controller are given by the following set of differential-algebraic equations:

$$\begin{aligned}
\dot{m} &= K_1\left(V_{\text{set}} - V_t\right) \\
\dot{\theta} &= K_2\left(P_{\text{set}} - P_{\text{gen}}\right) \\
\dot{x} &= K_3\left(\delta_t - \delta_p\right) \\
\dot{\delta}_p &= \omega_p \\
0 &= V_i - \frac{mV_{\text{dc}}}{V_{\text{base}}} \\
0 &= \theta - \left(\delta_i - \delta_p\right) \\
0 &= x - \left(\omega_p - K_4\theta\right) \\
0 &= P_{\text{gen}} - \frac{V_iV_t}{X}\sin\left(\delta_i - \delta_t\right).
\end{aligned} \quad (2)$$

The first two equations in (2) correspond to integral control of V_t and P_{gen}, where V_{set} and P_{set} are the set values for V_t and P_{gen}, respectively. The third and fourth equations describe the PLL dynamics, which also involves integral control, but also damping due to the term $K_4\theta$ in the definition of the variable x. The variable δ_p represents the PLL phase angle, and its time derivative, ω_p provides an estimate of the deviation of system frequency from nominal. The sixth and seventh equations define the variables θ and x, respectively. Finally, the last equation in (2) gives the active power delivered to the grid.

In this study, (2) is used to model all the inverters; i.e., for both the renewable sources and the PEVs. In addition to (2), the equations for the renewable sources are augmented with the following exogenous input for the power setpoint

$$P_{set} = P_{ren}(t), \tag{3}$$

where $P_{ren}(t)$ is the available power from the renewable source at time t. Using all the available power from the renewable sources ensures their maximum utilization. The renewable generation is assumed to change affinely according to

$$P_{ren}(t) = \begin{cases} P^0_{\text{wind}} - a_{\text{wind}}t & \text{for wind} \\ P^0_{\text{solar}} - a_{\text{solar}}t & \text{for solar} \end{cases}. \tag{4}$$

The slopes a_{wind} and a_{solar} are calculated based on the maximum drops observed in the data shown in Fig. 3.

For the PEVs, (2) is augmented with the following power setpoint equation:

$$P_{set} = \begin{cases} -P_{PEV} & \omega_p \geq 0 \\ \dfrac{P_{PEV}}{\omega_0}(\omega_{\text{p}} - \omega_0) & 2\omega_0 < \omega_p < 0, \\ P_{PEV} & \omega_p \leq 2\omega_0 \end{cases} \tag{5}$$

which has a droop characteristic with saturation. P_{PEV} is the maximum total PEV power, representing the PEV penetration level, and a negative value indicates charging, whereas ω_0 is a negative control parameter determining the critical frequency at which the PEVs should switch from the charging to discharging mode or vice versa. This droop control equation is illustrated in Fig. 4.

Finally, the diesel generators are assumed to have integral terminal-voltage regulation through control of reactive power as follows:

$$\dot{Q} = K_Q(V_t - V_{set}). \tag{6}$$

The active powers of the diesel generators are fixed to the desired generation levels and are not subject to control within the time scale of interest.

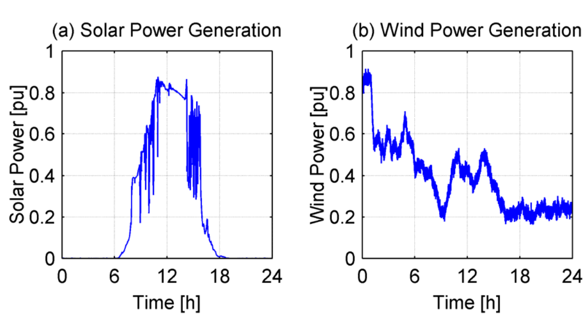

Fig. 3. Example renewable power source profile for the Hawaiian region [35, 36].

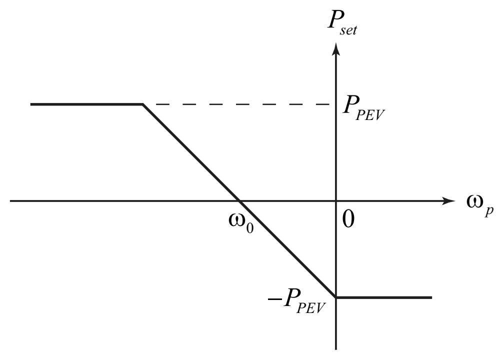

Fig. 4. PEV droop control scheme.

III. Simulation Results

The microgrid model described above is simulated for an islanding scenario. Initially, the system is assumed to be at steady state, with all the vehicles charging at maximum power. At time $t_0 = 0$, the microgrid is disconnected from the main grid, and the resulting transient dynamics are simulated for 5 seconds. The model parameters are summarized in Table I. The parameters were chosen to reflect the characteristics of Camp Smith, HI, the targeted installation of the SPIDERS project, and the long term Army goals regarding renewable energy penetration (25% penetration by 2025) and reduction in fuel consumption (20% reduction by 2015). The PEV penetration level P_{PEV} and the PEV frequency control parameter ω_0 were varied to explore their effects on performance.

TABLE I
Model Parameters

parameter	value	parameter	value
K_1	10	P_{G4}	2
K_2	20	P_{G5}	2
K_3	20	P_{base}	1 MVA
K_4	10	V_{base}	4 kV
X	0.2	a_{wind}	0.04
V_{set}	1	a_{solar}	0.01
P_{L2}	4.2	P^0_{wind}	1
Q_{L2}	0.5	P^0_{solar}	1.5
P_{L3}	1.8	K_Q	0.01
Q_{L3}	0.2	V_{dc}	480 V

The performance metrics are chosen as the deviation in voltage at terminal 2 from the steady state value and the deviation of microgrid frequency as seen by the PEVs from its

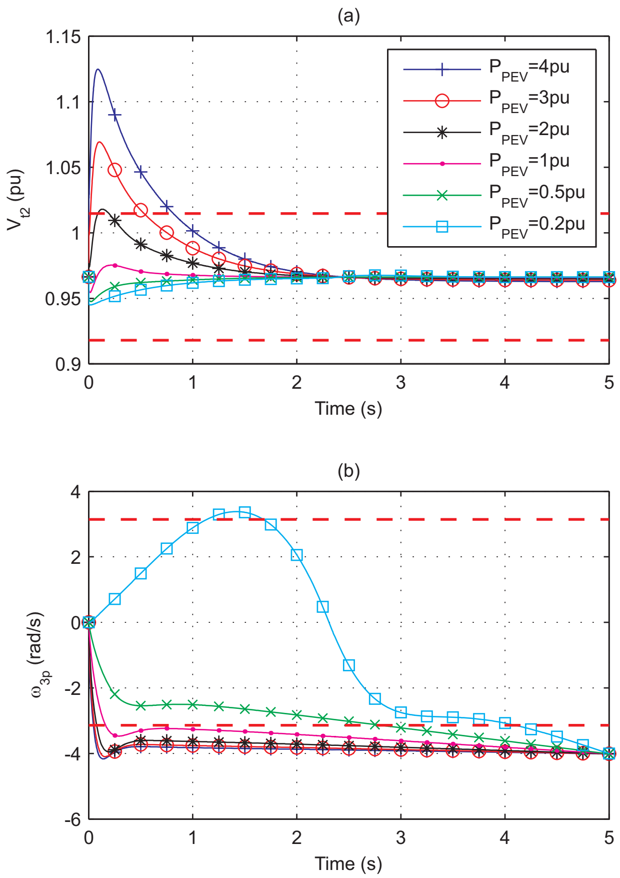

Fig. 5. The impact of PEV penetration level on (a) the voltage at terminal 2, and (b) the microgrid frequency as seen by the PEVs, for $\omega_0 = -4$ rad/s. Dashed horizontal lines represent the corresponding performance goal limits.

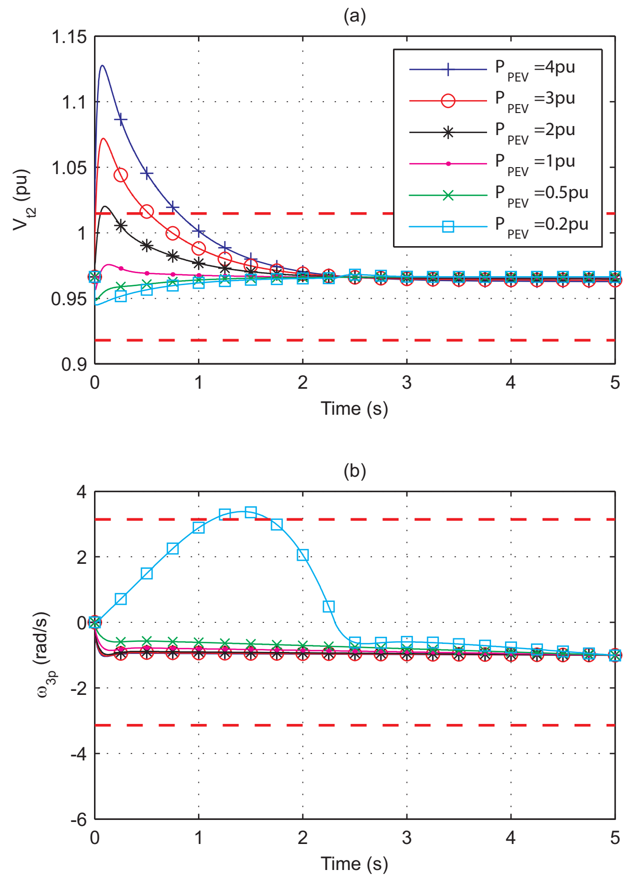

Fig. 6. The impact of PEV penetration level on (a) the voltage at terminal 2, and (b) the microgrid frequency as seen by the PEVs, for $\omega_0 = -1$ rad/s. Dashed horizontal lines represent the corresponding performance goal limits.

nominal value. The performance goals are to keep the voltage deviation within 5% and the frequency deviation within 0.5 Hz or, equivalently, π rad/s.

Simulation results are summarized for various PEV penetration levels in Figs. 5 and 6 for $\omega_0 = -4$ rad/s and $\omega_0 = -1$ rad/s, respectively. Based on these results, the following may be concluded.

Fig. 5a shows that increasing PEV penetration levels increase the transient deviation from the steady state voltage value, negatively affecting the voltage regulation task. For P_{PEV} of 3pu or above, the voltage deviation cannot be maintained within the desired 5% limit during the transient response. Hence, without any changes in the control strategy, the voltage regulation goals place an upper limit on the PEV penetration level.

A comparison of Fig. 5b with Fig. 6b reveals that decreasing ω_0 in magnitude increases the performance in terms of frequency regulation, since it leads to less deviation in frequency. It also increases robustness, as the frequency regulation performance becomes less sensitive to the PEV penetration level. This improvement in performance and robustness is achieved for $P_{PEV} = 0.5$ pu and above. When P_{PEV} is 0.2 pu, for example, the transient frequency response violates the desired limits regardless of the range of values considered for ω_0 in this study (i.e, from -4 to -1 rad/s). This is because the microgrid is providing power to the main grid in this case before islanding, and after islanding the PEVs are not capable of absorbing the excess generation, because they are already charging at their maximum power level. The PEVs cannot regulate the frequency until renewable generation drops sufficiently. This example shows that there also exists a lower limit for PEV penetration level for healthy microgrid operation.

Fig. 5b and 6b show that the gradual reduction in renewable generation causes a gradual drop in frequency, the rate of which depends on the ratio P_{PEV} / ω_0. As this ratio decreases in magnitude, the rate of frequency drop increases in magnitude. Hence, the ratio P_{PEV} / ω_0 should be designed such that the frequency change rate is slow enough to give the slower control mechanisms (which are not considered in this study) enough time to respond before the maximum frequency deviation limits are reached.

A comparison of Figs. 5a and 6a shows that the effect of ω_0 on voltage regulation performance is negligible. Thus, the negative effect of increasing P_{PEV} on voltage regulation cannot be reduced using ω_0. To accommodate increased P_{PEV}, the inverter controller must be retuned. Specifically, increased P_{PEV} requires an increase in the integral voltage control gain K_1 for the PEVs. Fig. 7 shows the effect of a range of values of K_1 on the transient voltage performance. As seen in the figure, very large gains may be necessary to quickly bring the voltage within the desired limits. This shows that control

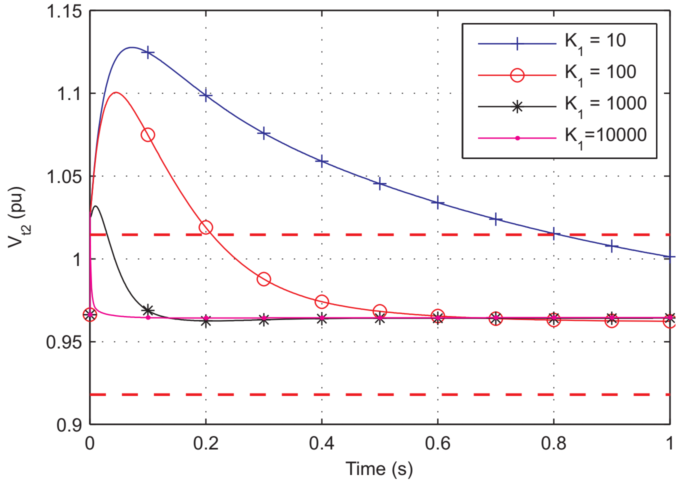

Fig. 7. The effect of K_1 of PEV inverter on voltage dynamics at terminal 2 ($P_{PEV} = 4$ pu , $\omega_0 = -1$ rad/s).

design may be coupled to PEV penetration levels, which is an important consideration if plug-and-play operation is desired. Note, however, that K_1 has no effect on the initial spike in voltage at $t = 0$ when grid connection is lost, as K_1 affects voltage dynamically and not statically.

It is also worth noting the effect of the PEV control parameter K_4 on the performance metrics. Specifically, if K_4 is too low, it can cause undesired oscillations in both voltage and frequency (Fig. 8), as this parameter provides damping for the dynamic interaction between the P_{gen} controller and the PLL dynamics. Above a certain value of K_4, however, the performance metrics are no longer sensitive to that parameter.

Finally, the remaining PEV inverter control parameters K_2 and K_3 were also analyzed for values ranging from 1 to 1000, but the performance metrics were found to be robust to the changes considered.

IV. Summary and Conclusions

This paper considers the voltage and frequency regulation problem in microgrids and focuses on the impact of vehicle-to-grid (V2G) technology on this regulation. In particular, the dynamics that occur due to the inverter controllers within the first few seconds of a perturbation are of interest. A microgrid model has been developed that is representative of a planned military microgrid, and simulations have been undertaken to study the role of PEVs in controlling voltage and frequency in the microgrid immediately after the connection to the main grid is severed.

The simulation results suggest that there probably exists a range of PEV penetration levels, for which voltages and frequency in the microgrid can be satisfactorily regulated by the PEVs. When the PEV penetration level is below this range, the frequency regulation may suffer, whereas when the PEV penetration level is above this range, voltage regulation may suffer. In the latter case, the voltage regulation can be improved if a retuning of the inverter controller is feasible.

This paper considers only one particular control architecture and studies the sensitivity of the voltage and frequency regulation problems to the control parameters.

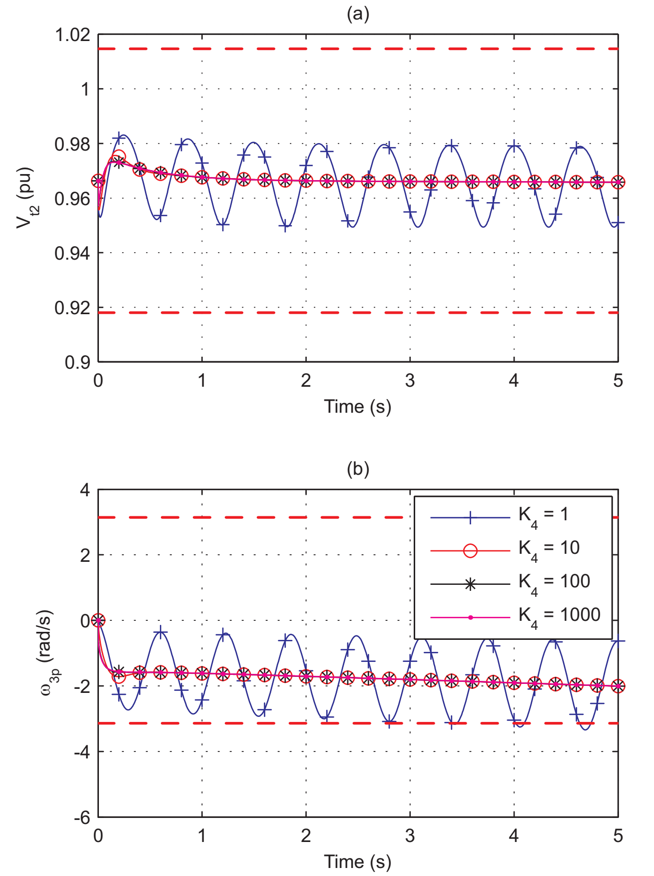

Fig. 8. The effect of K_4 of PEV inverter on (a) voltage at terminal 2, and (b) on microgrid frequency as seen by the PEVs ($P_{PEV} = 1$ pu , $\omega_0 = -2$ rad/s).

Other control architectures may yield different results. A comparative study of different control approaches is being undertaken as part of this on-going research.

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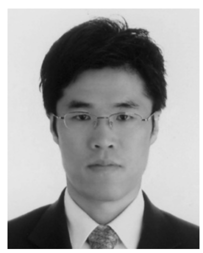

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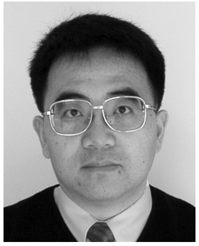

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