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On the Design of Suboptimal Controller for DC Microgrids with CPL

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Abstract

In this paper, a suboptimal controller is proposed for a DC microgrid interfaced with constant power loads (CPLs). Towards this end, a nonlinear model of the DC microgrid is utilized to define an optimal tracking control problem based on a discounted quadratic infinite-horizon cost function. The problem is solved using a State-Dependent Riccati Equation (SDRE) technique. This feedback control technique can regulate the load voltage to its desired value while guaranteeing stability of the closed-loop system. The performance of the proposed SDRE tracking controller is evaluated and compared with two other well-known nonlinear controllers, feedback linearization and backstepping, through some numerical simulations. The obtained results verify the effectiveness of the proposed SDRE controller.

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Keywords: Constant power load, DC microgrids, State- SDRE control, suboptimal control, voltage control.

1. Introduction

A microgrid (MG) is a small-scale power system, consists of distributed generators (DGs), energy storage systems (ESSs), interface devices and loads that are interconnected, with the capability to operate in both grid connected and islanded mode. This new concept, is classified into 1) ac microgrid, 2) dc microgrid and 3) Hybrid ac-dc microgrid. During the past decades, significant progress has been made in performance of ac MGs (e.g.,

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islanding detection and autonomous operation [1], [2] and power sharing of parallel-connected multiple inverters [3], [4]). Nevertheless, nowadays, increasing attention has been drawn to dc MGs [5], [6], due to their interesting features such as: 1) higher efficiency, 2) less conversion losses, 3) no need for control of frequency and phase, reactive power flow and power quality, which are all big challenges in ac MGs. DC MGs are proposed for power supply of applications with dc loads like home appliances, electric vehicles, naval ships, space crafts, submarines, telecom systems and rural areas. Multi terminal high-voltage dc grid and low-voltage dc MG have been proposed for large-scale wind power integration, commercial facilities (e.g., data centers [7], isolated island [8], etc.).

Power electronic converters are essential components to interface loads to dc MGs. When tightly regulated, these loads behave like constant power load (CPL) at the input terminals [9], [10].The study of CPLs in dc power networks is fundamental to automotive [11]. The negative impedance characteristics at the input terminals may affect the system stability [12], [13]. This impact becomes more significant when MG operates in islanded mode. Different solutions have been suggested in the literature cope with this issue, i.e., negative impedance instability problem such as: 1) passive resistance damping, 2) load shedding, 3) placement of ESSs at dc bus and 4) utilizing strategies (linear control and nonlinear control) [14], [15]. The main focus of this paper is on control strategies.

Linear controllers are the simplest strategy to achieve a regulated dc voltage in MGs [10]. Linear control methods consider the system stability only around the equivalence points. Linear controllers to stabilize dc systems with CPLs has been proposed in [16]–[18].

In this paper, a suboptimal controller based on SDRE technique is designed for dc MGs with CPLs at their input terminal. The performance of the proposed control is compared with two other well-known nonlinear control strategy (Feedback linearization and Backstepping) through some numerical simulations. The rest of this paper is organized as follows. In Section 2, the state space model of a simplified dc MG with a CPL is presented. Three different control methods (SDRE technique, backstepping, and feedback linearization) are designed to solve the problem of instability in dc MGs, in Section 3. In Section 4, simulation results and comparison among the above mentioned controllers are explained. Finally, Section 5 concludes the paper.

2. System Description and Problem Statement

To solve this nonlinear tracking problem in an optimal method, a discounted quadratic cost function is defined and solved using the SDRE tracking controller proposed in [19]. To demonstrate the effectiveness of the designed tracking controller, its performance is compared with two other well-known controllers (feedback linearization and backstepping). Towards this end, a nonlinear model of the dc MG is utilized. The schematic diagram of such a system i.e., dc MG with CPL is depicted in Fig.1.

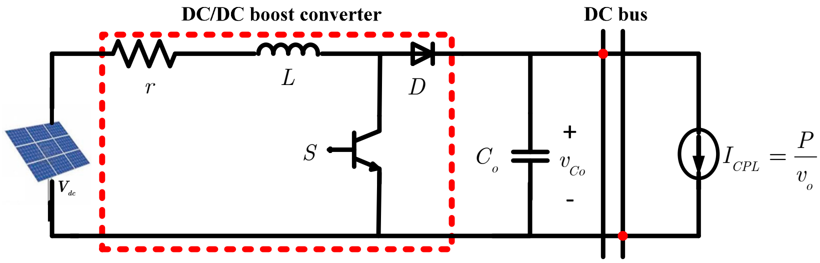

Fig. 1. The schematic diagram of a dc MG with CPL.

The following nonlinear state space representation describes the dynamics of the system based on average model [19]:

$$\begin{cases} \dot{x}_1(t) = -\dfrac{P}{C_o x_1(t)} + \dfrac{x_2(t)}{C_o} \\ \dot{x}_2(t) = -\dfrac{1}{L}x_1(t) - \dfrac{r}{L}x_2(t) + \dfrac{1}{L}V_{dc}(t) \end{cases} \tag{1}$$

where $x = [v_c \quad i_L]^T$ is the state variable vector including capacitor voltage and inductor current, r is resistance of the source and filter ($r = r_{dc} + r_L$), L and C_o are the inductor and capacitor of the filter, $V_{dc}(t)$ is control input and P is load power of CPL that is assumed constant. The control objective is to find the feedback control law $V_{dc}(t), t \geq 0$ such that the capacitor voltage $x_1(t)$ tracks a desired constant value in steady state and the other state variable $x_2(t)$ is bounded.

3. Nonlinear Control Design

In this section, an SDRE tracking controller is designed to solve the control problem defined in Section 2. The obtained closed-loop system has suboptimal performance with a predefined quadratic cost function. Two different nonlinear controllers are also designed in order to investigate the abilities of the SDRE controller.

3.1. The Proposed SDRE Tracking Controller

The SDRE technique was proposed by Person in 1962 to solve the optimal regulation problem for nonlinear systems [19].SDRE provides an effective algorithm for synthesizing nonlinear feedback controls by allowing for nonlinearities in the system states, while offering design flexibility through state-dependent weighting matrices. The formulation of the suboptimal controller for nonlinear system of Fig.1 is presented in this section. As mentioned before, the control objective is to find $V_{dc}(t)$ such that the state variable $x_1(t)$ tracks a constant value (here the reference voltage), $x_1^r(t) = 200v$. To achieve this objective in an optimal method, the following optimization problem is considered.

- Nonlinear optimal tracking voltage problem of a dc MG with CPL: Design objective of this controller is to find the feedback control law $V_{dc}(t), t \geq 0$ such that $x_1(t)$ track the desired trajectory $x_1^r(t), t \geq 0$, when t tends to infinity and the following cost function is minimized:

$$J = \int_0^\infty 2e^{-\gamma t}\left[(x_1(t)-x_1^r(t))^T Q(x(t))(x_1(t)-x_1^r(t))+V_{dc}^T R(x(t))V_{dc}(t)\right]dt, \tag{2}$$

According to [23], the dynamic of the desired trajectory is as follows:

$$\begin{cases} \dot{x}_1^r(t) = 0 \\ y_d(t) = x_1^r(t) \end{cases} \tag{3}$$

In the SDRE tracking controller, a state-dependent coefficient (SDC) representation of the augmented state-variable $X(t) = e^{-\gamma t}[x(t) \quad x_1^r(t)]^T$ is considered. The process is simply to rewrite (4), since the augmented system has three state variables. There are many infinity number of ways to construct such a representation. The following one is used in our design:

$$\dot{X}(t) = \begin{bmatrix} -\gamma+\dfrac{-P}{Cx_1(t)} & \dfrac{1}{C} & 0 \\ \dfrac{-1}{L} & -\gamma+\dfrac{-r}{L} & 0 \\ 0 & 0 & -\gamma \end{bmatrix} X(t) + \begin{bmatrix} 0 \\ \dfrac{1}{L} \\ 0 \end{bmatrix} U(t), \tag{4}$$

where $\gamma > 0$ is a constant and $U(t) = e^{-\gamma t}V_{dc}(t)$, that objective is to find the feedback control law $U(t), t \geq 0$ and the following cost function is minimized:

$$J = \int_0^\infty \left(X^T(t)\hat{Q}(e^{-\gamma t}X(t))X(t)+U^T(t)RU(t)\right)dt, \tag{5}$$

$$U(t) = -K(e^{-\gamma t}X(t))X(t) \quad \& \quad K(e^{-\gamma t}X(t)) = R^{-1}\hat{B}^T(e^{-\gamma t}X(t))\hat{P}(e^{-\gamma t}X(t)) \tag{6}$$

where $\hat{P}(e^{-\gamma t}X(t))$ is the solution of the following state-dependent algebraic riccati that can be solved for pointwise:

$$\hat{A}^T(e^{-\gamma t}X(t))\hat{P}(e^{-\gamma t}X(t)) + \hat{P}(e^{-\gamma t}X(t))\hat{A}(e^{-\gamma t}X(t)) - \hat{P}(e^{-\gamma t}X(t))\hat{B}(e^{-\gamma t}X(t))R^{-1}\hat{B}^T(e^{-\gamma t}X(t))\hat{P}(e^{-\gamma t}X(t))$$

$$+\hat{Q}(e^{-\gamma t}X(t)) = 0 \tag{7}$$

if the triple $(\hat{A}(e^{-\gamma t}X(t)),\ \hat{B}(e^{-\gamma t}X(t)),\ \hat{Q}^{1/2}(e^{-\gamma t}X(t)))$ is pointwise stabilizable and detectable, the SDRE has a unique symmetric positive semi definite solution for $\hat{P}(e^{-\gamma t}X(t))$, thus the control low can be applied to the nonlinear system. Summary of the SDRE tracking controller have been brought in the following flowchart. The results of this method comparing two other well-known controllers, i.e., feedback linearization and backstepping is presented in the following subsection.

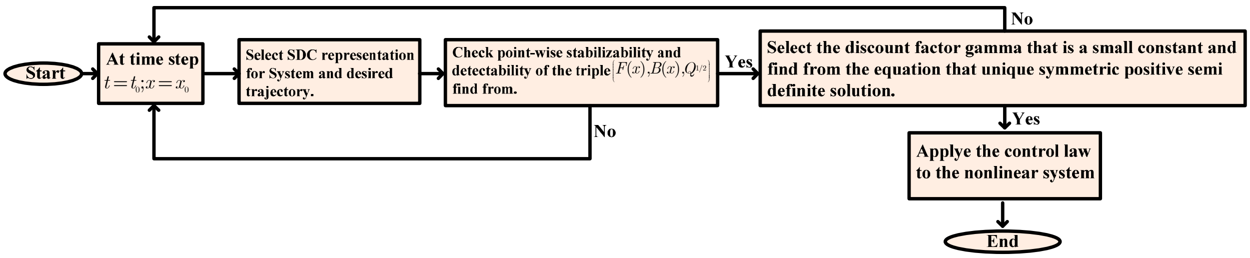

Fig. 2. The flow chart of the proposed SDRE tracking technique.

3.2. Backstepping Controller

The backstepping approach, a recursive Lyapunov based scheme, was proposed in the beginning of 1990s. With this method the construction of feedback control laws and Lyapunov functions is systematic, following a step-by-step algorithm [20]. In this method, a stage of design is done for each state variable. The two steps of the design procedure are detailed below:

Step 1. Start with the first equation of (1), we define a state error variable z_1, where $\dot{z}_1 = \dot{x}_1 = -\frac{P}{C_o x_1} + \frac{x_2}{C_o}$. Since the reference voltage is supposed to be constant, $\dot{V}_{dc}$ is zero and derive the dynamics of the new coordinate.

$$\dot{z}_1 = \dot{x}_1 = -\frac{P}{Cx_1} + \frac{x_2}{C} \tag{8}$$

We view x_2 as a control variable and define a virtual control law for (8), say α, and z_2 let be an error variable representing the difference between the actual and virtual controls of (8).

$$z_2 = x_2 - \alpha \tag{9}$$

Therefor, $x_2 = z_2 + \alpha$ and $\dot{z}_1 = \dot{x}_1 = -\frac{P}{C_o x_1} + \frac{z_2 + \alpha}{C_o}$. In this step, our objective is to design a virtual control law α which makes $z_1 \to 0$. Consider a control Lyapunov function:

$$V_1 = \frac{1}{2}z_1^2 \to \dot{V}_1 = z_1\dot{z}_1 = z_1\left[-\frac{P}{C_o x_1} + \frac{z_2+\alpha}{C_o}\right] \tag{10}$$

In order to remove the nonlinear term is $\frac{P}{C_O x_1}$, the virtual control function is set as follows, would make the first order system sustainability:

$$\alpha = -k_1 z_1 + \frac{P}{x_1} \Rightarrow \dot{\alpha} = -\left[k_1 + \frac{P}{x_1^2}\right]\dot{x}_1 \tag{11}$$

choose a positive constant k_1, then the time derivative of V become:

$$\dot{V}_1 = -\frac{k_1}{C_o} z_1^2 + \frac{1}{C_o} z_1 z_2 \tag{12}$$

If become $z_2 = 0$, then $\dot{V}_1 = -\frac{k_1}{C_o} z_1^2$ and z_1 is guaranteed to converge to zero asymptotically.

Step 2. Derive the dynamics of the new coordinate for z_2:

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha} = -\frac{1}{L}x_1 - \frac{r}{L}x_2 + \frac{1}{L}V_{dc} + \left[k_1 + \frac{P}{x_1^2}\right]\dot{z}_1 \tag{13}$$

in which V_{dc} is a control input. Our objective is to design the actual control input V_{dc} such that z_1, z_2 converge to zero. To this end, a Lyapunov function is chosen as V : $V = V_1 + \frac{1}{2}z_2^2$ where it's derivative is

$$\dot{V} = \dot{V}_1 + z_2\dot{z}_2 = -\frac{k_1}{C_o} z_1^2 + \frac{1}{C_o} z_1 z_2 + z_2\left[-\frac{1}{L}x_1 - \frac{r}{L}x_2 + \frac{1}{L}V_{dc} + \left[k_1 + \frac{P}{x_1^2}\right]\dot{z}_1\right] \tag{14}$$

By replacing (8) and (13) in equation (14), one can write

$$\dot{V} = -\frac{k_1}{C_o} z_1^2 + \frac{1}{C_o} z_1 z_2 + z_2\left[-\frac{1}{L}x_1 - \frac{r}{L}x_2 + \frac{1}{L}V_{dc} + \left[k_1 + \frac{P}{x_1^2}\right]\left[-\frac{P}{Cx_1} + \frac{z_2 + \alpha}{C}\right]\right] \tag{15}$$

We are finally in the position to design control V_{dc} by making $\dot{V}$ semi-definite negative as follows:

$$V_{dc} = x_1 + rx_2 - L\left[\left[k_1 + \frac{P}{x_1^2}\right]\dot{z}_1\right] - \frac{L}{C_o} z_1 - k_2 z_2 \tag{16}$$

Where L, k_1 are positive constants and choose a positive constant k_2, then the time derivative of V become:

$$\dot{V} = -\frac{k_1}{C_o} z_1^2 - \frac{k_2}{L} z_2^2 \quad if \quad k_1, k_2 > 0 \rightarrow \dot{V} \leq 0 \tag{17}$$

The Lyapunov function for the whole system that is positive definite, can be calculated as

$$V = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 \tag{18}$$

The controller ensures convergence of z_1 and z_2 ,i.e, if $t \rightarrow \infty$ then $z_1, z_2 \rightarrow 0$. Since $x_1 = z_1 + 200$ $x_2 = z_2 + \alpha$, and $\alpha = -k_1 z_1 + \frac{P}{x_1}$, one can conclude that z_1 and z_2 are converged to their nominal value.

3.3. Feedback Linearization Controller

Feedback linearization is a common approach used in controlling nonlinear systems. The approach involves with a transformation of the nonlinear system into an equivalent linear system through a change of variables and a suitable control input. Feedback linearization methods are classified as: 1) Input-stat Linearization controller 2) Input-Output Linearization controller. In this section the second method is investigated [21].

- Input-Output Linearization controller: When certain output variables are of interest, as in tracking control problems, the state model is described by state and output equations. Linearizing the state equation, as done in the previous section, does not necessarily linearize the output equation [21].

Step 1. Repeatedly taking the derivative of output to achieve a relation between input and output. which V_{dc} is control input.

$$y = x_1 \Rightarrow \dot{y} = \dot{x}_1 = -\frac{P}{C_o x_1} + \frac{x_2}{C_o} \Rightarrow \ddot{y} = \frac{P}{C_o x_1^2}\dot{x}_1 + \frac{1}{C_o}\dot{x}_2 = \frac{P}{C_o x_1^2}\left[-\frac{P}{C_o x_1} + \frac{x_2}{C_o}\right] + \frac{1}{C_o}\left[-\frac{1}{L}x_1 - \frac{r}{L}x_2 + \frac{1}{L}V_{dc}\right] \quad (19)$$

Step 2. In this step, our objective is to design a control input, providing a linear relationship between output and input:

$$V_{dc} = -\frac{P}{C_o x_1^2}\left[-\frac{P}{C_o x_1} + \frac{x_2}{C_o}\right] + x_1 + x_2 + LC_o V \quad (20)$$

Since the reference voltage is supposed to be constant, $\dot{V}_{dc}$ is zero, therefore $\ddot{y} = V$, $\dot{y}_d = 0$

$$e = y - y_d \rightarrow \dot{e} = \dot{y} - \dot{y}_d \Rightarrow \ddot{e} = \ddot{y} - \ddot{y}_d \Rightarrow \ddot{e} = \ddot{y} = V \quad (21)$$

$$V = -k_1 e - k_2 \dot{e} = k_1(x_1 - 200) - k_2\left[-\frac{P}{C_o x_1} + \frac{x_2}{C_o}\right] \quad (22)$$

with selecting the constants k_1 and k_2 positive, the error become zero. Hence, the system has relative degree two in R^2. Therefore, it is both input-state and input-output linearizable and we conclude that the control V_{dc} is also bounded.

4. Simulation Results

The MG test system, shown in Fig.1, has been used to verify the effectiveness of the proposed SDRE controller. Electrical and control parameters of the test system are listed in Table I. Fig. 3 shows the performance SDRE controller under a frequent load changes. The CPL changes from 300W to 150W at $t=1s$ and from 150W to 300W at $t = 2s$. As can be seen, load voltage gradually reaches the desired voltage and current is bounded within the accepted region. To demonstrate the effectiveness of the designed tracking controller, its performance is compared with feedback linearization and backstepping control methods, and the results are presented in Fig. 4 and Fig. 5. As can be seen, while the backstepping method achieves a noisy response, feedback linearization offers steady-state error. To evaluate the effective performance of the proposed method, simulation studies under voltage reference changes and consideration of the parametric uncertainties are provided in Fig. 6 and Fig.7, respectively. Fig. 6 shows performance of the SDRE controller under reference voltage changes. The voltage changes from $200v$ to $180v$, at $t = 0.5s$, from $180v$ to $200v$, at $t = 1s$, from $200v$ to $220v$ at $t = 1.5s$, and from $220v$ to $200v$ at $t = 2s$. Fig.7 shows performance of the SDRE controller and parametric uncertainties where the CPL changes at $t = 1s$ and $t = 2s$ one hundred times accidentally.

Table 1. Electrical and control parameters.

Circuit parameters	Symbol	value	SDRE Control	
			Proportional term	Q 100 R 0.2
DC voltage	V_{dc}	200 v		
DC load power	P	300 w	Backstepping Control	
Inductor resistance	r	0.3 Ω	Proportional term	k_1 0.1 k_2 1.75
Filter inductance	L	450 µH		
Filter capacitance	C	220 µF		
Initial conditions inductor	2 A	$x_{0,1}$	Feedback linearization Control	
Initial conditions capacitor	$x_{0,2}$	198 v	Proportional term	k_1 0.9 k_2 7×10^{-5}

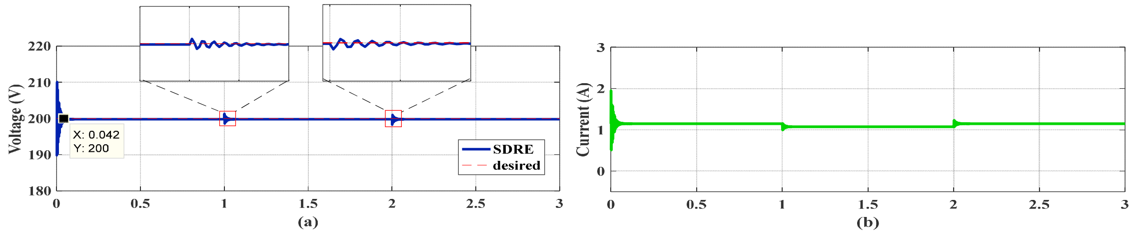

Fig. 3. Performance of the proposed SDRE controller under frequent load change: (a) load voltage, (b) inductor current.

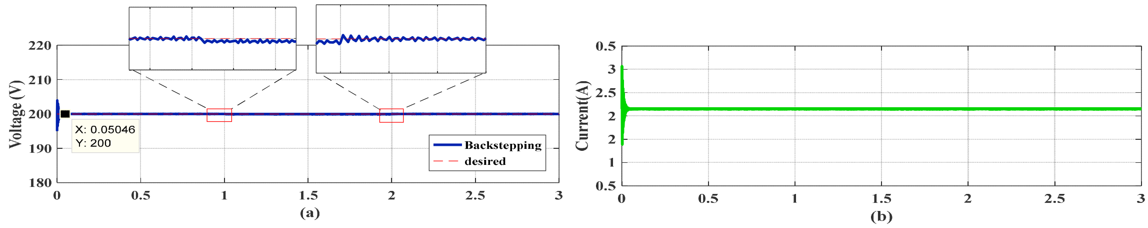

Fig. 4. Performance of the Backstepping controller under frequent load change: (a) load voltage, (b) inductor current.

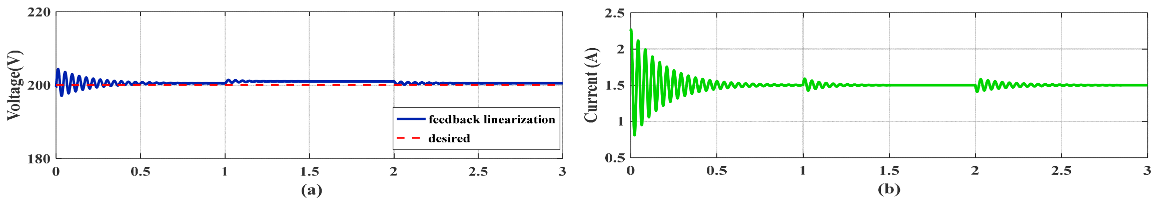

Fig. 5. Performance of the Feedback linearization controller under frequent load change: (a) load voltage, (b) inductor current.

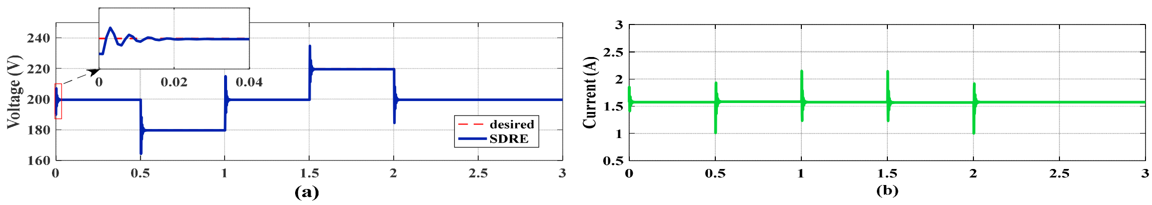

Fig. 6. Performance of the proposed SDRE controller in regulating the load voltage under reference voltage changes.

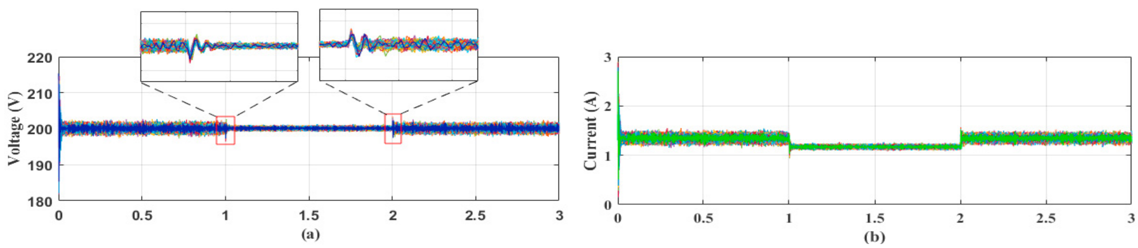

Fig. 7. Performance of the proposed SDRE controller under 30% parametric uncertainties: (a) load voltage, (b) inductor current.

5. Conclusion

This paper introduces a suboptimal methodology to assure stability of dc microgrids in the presence of CPLs. The nonlinear dynamic of such systems is formulated as a problem with quadratic bounds. A SDRE technique is proposed to stabilized the system and regulate its output voltage. The effectiveness of the proposed controller is verified under various simulation studies such as load changes, voltage reference changes, and parameter uncertainties. The comparative results studies show superior performance of the SDRE method comparing the other two well-known nonlinear controllers.

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