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Model Predictive and SDRE Control of DC Microgrids with Constant Power Loads: A Comparative Study

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***Abstract*—In this paper a model predictive controller (MPC) for dc microgrids (MGs) with constant power loads (CPLs) is provided. In order to, a simple dc microgrid with nonlinear model to define an optimal tracking control problem based on minimization of a cost function with the finite-prediction horizon is utilized. This proposed control strategy guarantees the stability of the closed-loop system and can tracks the output voltage to reference voltage value. The performance of the MPC controller is investigated and effectiveness of it compared with State-Dependent Riccati Equation (SDRE) controller, in Matlab/Simpower.**

***Index Terms*-- Constant power Load, dc microgrids, model predictive control, state dependent riccati equation, optimal control, voltage control.**

I. INTRODUCTION

Microgrid (MG) is similar to like a power system in small-scale that has connected components such as type of power converters, energy storage systems (ESSs), distributed generators (DGs), and different type of loads in a common bus. This new grids have the ability to operate in two mode connection and disconnection of the main grid and according to the type of load connected to grid are divided into three categories: 1) ac microgrid, 2) dc microgrid and 3) hybrid ac-dc microgrid In the past decades, significant progress has been made in the performance of ac MGs (e.g., islanding detection and autonomous operation [1],[2] and power-sharing of parallel-connected multiple inverters [3],[4]). However, dc MGs have gained much importance in the recent time because they have superior efficiency, fewer conversion losses, and do not have big challenges such as:1) need for control of frequency and phase,2) evaluation reactive power flow and power quality [5], [6]. To supply energy in dc systems such as: home appliances, space crafts, naval ships, electric vehicles, submarines, telecommunication systems and village areas dc MGs are suggested. Also, dc MGs are used for large-scale wind power integration, commercial facilities, multi-terminal, high-voltage dc and low-voltage grid (e.g., data centers [7], isolated island [8], etc.).

The most essential component as an interfacing device in dc MG are electrical power converters. When tightly regulated, these loads behave like CPL at the input terminals [9].In [10] is proposed the study of CPLs in dc power grids as issue fundamental to automotive. This type of load has a negative impedance property at the input terminals that may be affect the system stability [11], [12]. When dc MGs operate in islanded mode, this impact becomes more considerable. To cope with the impact of instability caused by the negative impedance property CPLs, have been proposed different solutions in the literature such as 1) placement of ESSs at dc bus, 2) using control methods (linear control and nonlinear control), 3) passive resistance damping and 4) load shedding [13], [14]. In this paper, the focus on control methods is significant.

The simplest method to achieve regulated dc voltage in MGs is linear control methods. Linear controllers to stabilize dc systems with CPLs has been proposed in [13]–[15]. These controllers consider the system stability only around the equivalence points. In [16] a linear algorithm region of attraction (ROA) based on semidefinite optimization is expressed to simplify the analysis of stability in dc MGs. A modern linear control approach is presented in [17]. The negative resistance specification of CPLs, leads to the nonlinearity and time dependency of converters, therefor the classical linear control methods, face some stability limitations. To assure the stability of the system, a nonlinear proportional–integral (PI) stabilizing controller is proposed in [18]. The main problem of the method is its variable switching frequency. Feedback linearization method is proposed in [19] avoiding such an issue. The authors in [12] introduce a

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nonlinear sliding-mode control to develop a control law guaranteeing an expand region of local stability and improve large-signal stability. In this paper, the main objective is to find an optimal switching of states in each sampling time, such that the output voltage (dc bus voltage) is regulated along its reference trajectory by changes in the reference trajectory and variations in the power load. MPC, as an advanced control strategy, defines a cost function based on control objectives while can be considered in it, the constraints of the state variables and the manipulated variables, i.e., the control inputs MPC can be used for direct switching control of converters by optimizing a user-defined performance index using a collocation-based [20], [21]. Recently, in [22]–[24], various control strategies have been proposed for the switching control of dc/dc power converters with applications in microgrids. Based on comprehensive analysis of study on optimal control for dc microgrids with CPL. Except that, in [26] is designed an Hybrid Model Predictive Control (HMPC) with considering Power as cost function and is applied to dc/dc boost converter with CPL to control voltage, there is no considerable work done on MPC control to this systems.

In this paper, an optimal controller based on MPC technique is designed for voltage control of dc MGs with CPL at their input terminal. The performance of the proposed control is compared with SDRE tracking nonlinear control strategy through some numerical simulations. The controller are designed based on averaged model of the nonlinear system. The rest of this paper is organized as follows. In Section II, the average small signal model of dc MG with a CPL is presented. Section III shows the design of the MPC and SDRE control methods to solve the problem of instability in dc MGs, simulation results and comparison studies in MATLAB/Simpower are provided in Section IV. Section V concludes the paper.

II. THE AVERAGE SMALL SIGNAL MODEL OF A DC MICROGRID

The schematic diagram of a dc MG with CPL is shown in Fig.1 including Photovoltaic (PV), dc/dc boost converter and nonlinear load.

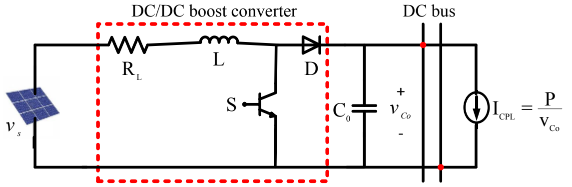


Figure 1. The schematic diagram of a simple dc MG with CPL.

In this figure, PV is represented as constant voltage source with input voltage v_s, v_o is the output voltage of the CPL which is considered equal to voltage v_{C0}, across the output capacitor filter (C_0), R_L is internal resistance of input inductor (L) and C_0, P is power load, S and D (diode) are the two power switches where S is the controllable switch (MOSFET or IGBT), and D is the uncontrollable switch [25].

Two types of models are often derived for such a system: averaged-based model [26] and hybrid automation model [27]. In average model two different dynamics are associated with the switch positions for dc/dc boost converter, The first mode is when the controllable switch is closed and the energy is stored in the inductor, and second mod, is when the controllable switch is opened and the inductor is connected to the output and energy is released through it to the load In the hybrid model, when the switch S is OFF mode $(S=0)$, all possible dynamics of the converters in both continuous and discontinuous current (CCM, DCM) of operations are considered. In this work average-based modeling scheme is utilized. The state space equation of the nonlinear dynamics system based on an average model by using of circuit laws:

$$\dot{x}(t) = \begin{cases} A_1 x(t) + B_1 u, & S = 1 \\ A_0 x(t) + B_0 u, & S = 0 \end{cases} \tag{1}$$

$$y(t) = Cx(t) \tag{2}$$

where the matrix values and other parameters are as:

$$x(t) = \begin{bmatrix} i_L(t) & v_o(t) \end{bmatrix}^T, \; u = v_s(t), \tag{3}$$

$$A_0 = \begin{bmatrix} \frac{-R_L}{L} & \frac{-1}{L} \\ \frac{1}{C_o} & \frac{-P}{C_o v_o^2} \end{bmatrix}. \; A_1 = \begin{bmatrix} \frac{-R_L}{L} & 0 \\ 0 & \frac{-P}{C_o v_o^2} \end{bmatrix} \; B_1 = B_0 = \begin{bmatrix} \frac{1}{L} & 0 \end{bmatrix}^T, \tag{4}$$

In this case, one can derive the average model as:

$$\dot{x}(t) = (1 - S)(A_0 x(t) + B_0 u) + S(A_1 x(t) + B_1 u) \tag{5}$$

III. NONLINEAR CONTROLLER DESIGN

In this section, an MPC controller is designed and applied to the nonlinear system in Fig. 1. The obtained closed-loop system has optimal performance with a predefined cost function that captures the control objectives. Also, in order to evaluate the effectiveness of the proposed controller a SDRE tracking nonlinear controller is considered.

A. Proposed MPC Controller

Applications of MPC controller in power electronics is started in the 1980s [28]. In the past decade, with increasing the betterment of high-speed microprocessors, interest to use of MPC method in systems contains power electronic converters has increased considerably [29]–[32]. In MPC, the designer defines a cost function due to the control objectives. Moreover, the constraints of the state variables or the manipulated variables can be considered in objective function. In this paper, the main control objective is to derive an optimal switching of states of converters such that their output voltage is regulated along its reference trajectory under different disturbances. Fig. 2 shows the control diagram of the MPC strategy for one unit of a dc MG with CPL. Steps design of the proposed control method is detailed below.

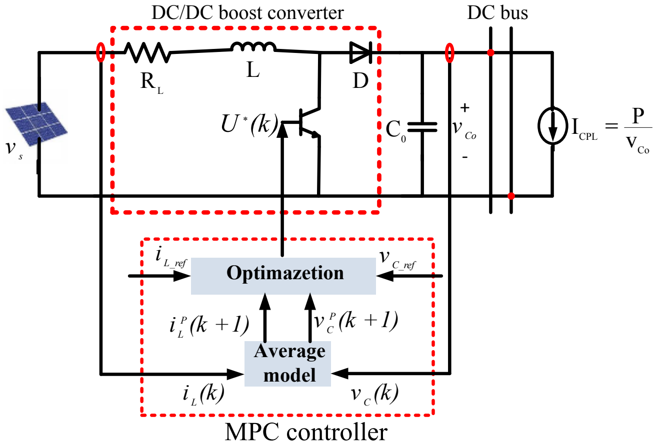


Figure 2. General schematic of MPC controller for a dc MG with CPL.

Step 1: *Modeling of system in discrete time*

To design the MPC controller, it must be considered an appropriate discrete time model of the desired system. The continuous-time equation given by (5), as the average model of the system, is discretized using the Euler approximation approach.

$$\frac{dx(t)}{dt} = \frac{x(k+1) - x(k)}{T_s} \qquad (6)$$

As a result, in the following discrete time model:

$$\begin{cases} x(k+1) = (1-S)(E_0 x(k) + Fu) + S(E_1 x(k) + Fu) \\ y(k+1) = Gx(k) \end{cases} \qquad (7)$$

where $E_0 = I + A_0 T_s$, $E_1 = I + A_1 T_s$, $F = BT_s$ $G = C$, I is the identity matrix of dimension two and T_s is the sampling interval.

Step 2: *Calculation of cost function*

To design of the cost function, the error between the predicted value of the variables states and the reference desired value over the prediction horizon based on control objective, is taken into consideration. Here the cost function considered as:

$$J(k) = \frac{1}{N}\sum_{1}^{N} \left| i_L^p(k+1) - i_{L\_ref} \right| + \left| v_C^p(k+1) - v_{C\_ref} \right| + \lambda \left| \Delta u(k) \right| \qquad (8)$$

where N is prediction horizon, $i_L^p(k+1)$ and $v_C^p(k+1)$ are parts of the variables prediction, i_{L_ref} and v_{C_ref} are parts of the reference that v_{C_ref} is constant and i_{L_ref} be achieved using the power balance equation $P_{in} = P_{out}$. Thus, the desired current is calculated as

$$P_{in} = V_s i_L \quad ,P_{out} = P_{Load} \quad \Rightarrow I_{L\_des} = \frac{P_{Load}}{V_s} \qquad (9)$$

in which P_{in}, P_{out} and P_{Load} are input power, output power, and power load, respectively. To better improve the transient response of the output voltage, a proportional term of voltage error, i.e., $v_{o\_ref} - v_o$ is also added to the above equation. Therefore, the reference inductor current can be achieved as:

$$I_{L\_ref} = I_{L\_des} + h(v_{o\_ref} - v_o) \qquad (10)$$

that $h \in R^+$ is the small-ripple approximation for regulation of output voltage in steady state. $\Delta u(k)$ is error between two consecutive switching states, which is calculated as:

$$\Delta u(k) = u(k) - u(k-1) \qquad (11)$$

and $\lambda > 0$ is the weighting factor making the tradeoff between the tracking errors and the switching frequency.

Step 3. *Optimization problem*

At each sample time, minimizing the cost function leads to the optimization problem to be achieved as follows:

$$U^*(k) = \arg\min J(k) \qquad (12)$$
$$\textit{Subj. to (7)}$$

The switching sequence achieved by minimizing the cost function is a sequence in the form U^*, where $U^*(k) = u^*(k), u^*(k+1), \ldots$ and it's only first element is applied in each sampling time.

B. SDRE Tracking Controller

In 1962, was proposed the SDRE technique to solve the optimal regulation problem in nonlinear systems [33]. SDRE control strategy while offering design flexibility through state-dependent weighting matrices, an effective algorithm provides to combination nonlinear feedback controls considering nonlinear states in the system. In this subsection, is presented the formulation of the suboptimal controller for the nonlinear system of Fig.1. The control objective is guaranteed to tracking the output voltage which is equal to the state variable x_2, tracks a constant value (here the reference voltage) $x_2^r = 200v$. In an optimal method, to attain the control objective, optimization problem is considered as follows:

Nonlinear Optimal Tracking Voltage Problem of a dc MG with one CPL: In this controller, the purpose of design is to find the feedback control law such that x_2 track the desired trajectory $x_2^r(t), t \geq 0$ in steady state while the following cost function is minimized:

$$J = \int_0^\infty 2e^{-\gamma t}\left[(x_2(t) - x_2^r(t))^T Q(x(t))(x_2(t) - x_2^r(t)) + U^T R(x(t))U(t)\right]dt, \qquad (13)$$

According to [34], the dynamic of the desired trajectory is:

$$\begin{cases} \dot{x}_2^r(t) = 0 \\ y_d(t) = x_2^r(t) \end{cases} \tag{14}$$

A state-dependent coefficient (SDC) equal to of the augmented state-variable equal to $X(t) = e^{-\gamma t}[x(t) \quad x_2^r(t)]^T$ is considered, in the SDRE tracking controller. In our design, among there are many infinite numbers of ways that to construct such a representation, the following way is used.

$$\dot{X}(t) = \begin{bmatrix} -\gamma + \frac{-r}{L} & \frac{-1}{L} & 0 \\ \frac{1}{C} & -\gamma + \frac{-P}{Cx_1(t)} & 0 \\ 0 & 0 & -\gamma \end{bmatrix} X(t) + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} U(t), \tag{15}$$

where $\gamma > 0$ is a constant and $U(t) = e^{-\gamma t} V_s(t)$.In here, to find the feedback control law $U(t), t \geq 0$ is the purpose by minimizing the following cost function.

$$J = \int_0^\infty X^T(t)\hat{Q}(e^{-\gamma t}X(t))X(t) + U^T(t)RU(t) \; dt, \tag{16}$$

$$U(t) = -K(e^{-\gamma t}X(t))X(t) \tag{17}$$

where $K(e^{-\gamma t}X(t)) = R^{-1}\hat{B}^T(e^{-\gamma t}X(t))\hat{P}(e^{-\gamma t}X(t))$ and $\hat{P}(e^{-\gamma t}X(t))$ is the solution of the following state-dependent algebraic Riccati that can be solved for pointwise:

$$\hat{A}^T(e^{-\gamma t}X(t))\hat{P}(e^{-\gamma t}X(t)) + \hat{P}(e^{-\gamma t}X(t))\hat{A}(e^{-\gamma t}X(t)) - \hat{P}(e^{-\gamma t}X(t)) \\ \hat{B}(e^{-\gamma t}X(t))R^{-1}\hat{B}^T(e^{-\gamma t}X(t))\hat{P}(e^{-\gamma t}X(t)) + \hat{Q}(e^{-\gamma t}X(t)) = 0 \tag{18}$$

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 law is applied to the nonlinear system. As can be seen, summary of the SDRE tracking controller is brought in Fig. 3.

IV. SIMULATION RESULTS

Performance of MPC controller strategy is studied under various scenarios and compared with the SDRE control approach, in this section. The dc MG test system shown in Fig.1 is implemented in MATLAB/SimPowerSystems. A power supply with a nominal input voltage of $V_{in} = 150V$ is used to simulate the PV system behavior. Electrical and control parameters of the test system are listed in Table I. For the MPC controller, because of fast dynamic of the system, the prediction horizon is equal to $N = 3$ and the sampling time is chosen $T_s = 2.5e-6s$. Effectiveness of the proposed MPC controller is investigated and compared with SDRE tracking controller under the two following scenarios.

***Scenario 1:* 50% *variation in power load*.**

Fig. 4 shows frequent power load change for this scenario. The CPL power changes is considered from $300W$ to $150W$ at $t = 1s$ and from $150W$ to $300W$ at $t = 2s$.

Scenario 2:* 10% *variation in the desired reference voltage

In this study, we assume the reference voltage changes frequently 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 $t = 2s$ Figs. 5(a) and 6(a) show the performance of the designed MPC controller in compared with SDRE controller in regulating the dc voltage under frequent load change and reference voltage changes, respectively. A faster response with no fluctuation and very low steady-state error of the MPC controller achieves comparing the SDRE controller can be seen. The performance of the proposed controller in limiting the inductor current between $0 < i_L \leq 4A$ under frequent power load and reference voltage variations are shown in Figs. 5 (b) and 6 (b)b , respectively. Controlled inductor current using the MPC controller in this Figs, shows that proposed controller is online, calculates the state variables at any time and predicts their future value. Figs. 5(c) and 6(c) indicate the CPL current for both scenarios.

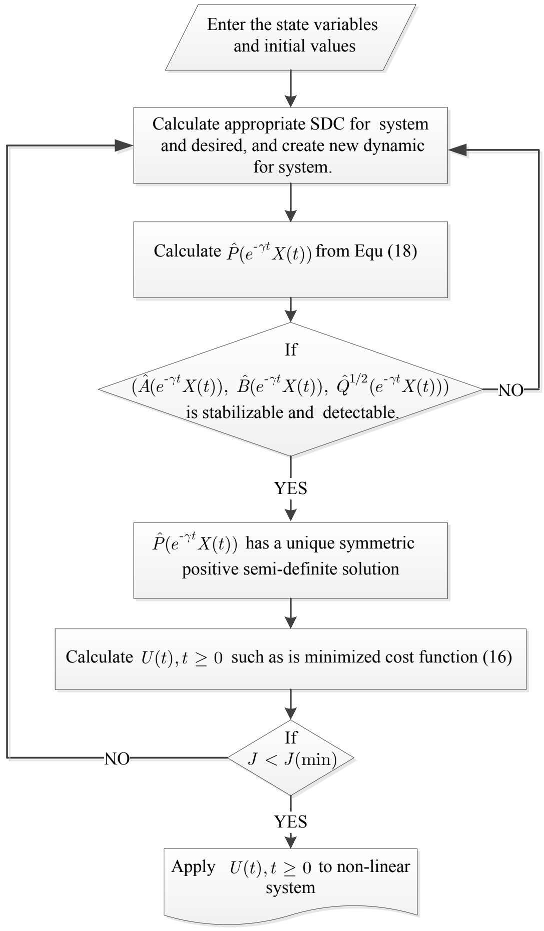


Figure 3. The flow chart of the SDRE tracking technique.

TABLE I. ELECTDICAL AND CONTROL PARAMETERS

parameter	**Symbol**	**value**
Circuit parameters		
DC voltage	v_{o_ref}	$200v$
DC load power	P	$300W$
Inductor resistance	R_L	0.3Ω
Filter inductance	L	$450\mu H$
Filter capacitance	C_o	$220\mu F$
Initial conditions inductor	$x_{0,1}$	$2A$
Initial conditions capacitor	$x_{0,2}$	198
Control parameters		
prediction horizon	N	3
Sampling Time	T_s	$2.5e-6s$
Proportional term	Q	100
Proportional term	R	0.2

The simulation results show the superior performance of the MPC controller, in this paper. While the results obtained by the SDRE controller is noisy with considerable steady state error in dc voltage, the proposed MPC controller achieves faster response with very less overshoot and steady state error.

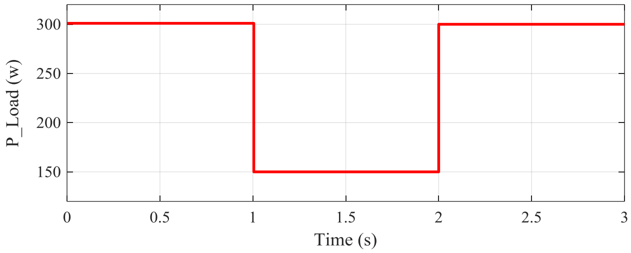
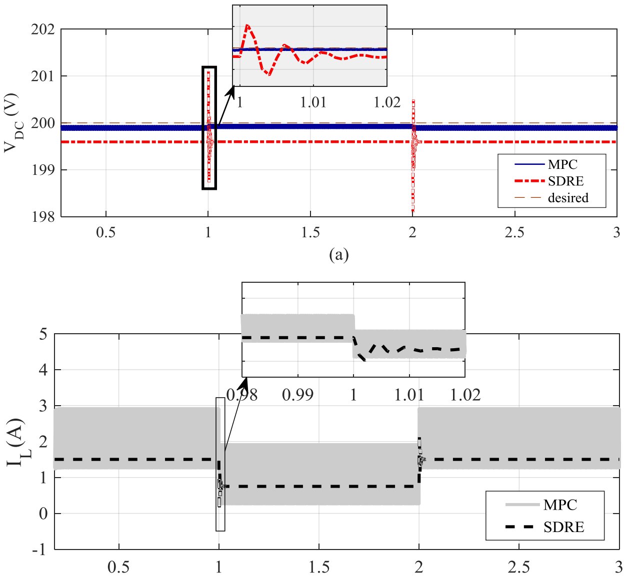
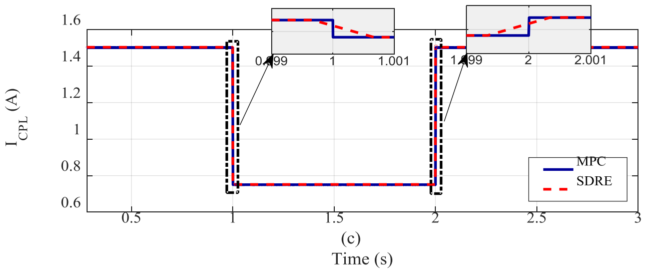


Figure 4. Step load change of the dc MG for scenario 1.



(b)



(c)

Figure 5. Compare performance of the proposed MPC and SDRE controllers under frequent power load changes: (a) dc bus voltage, (b) inductor current, (c) load current

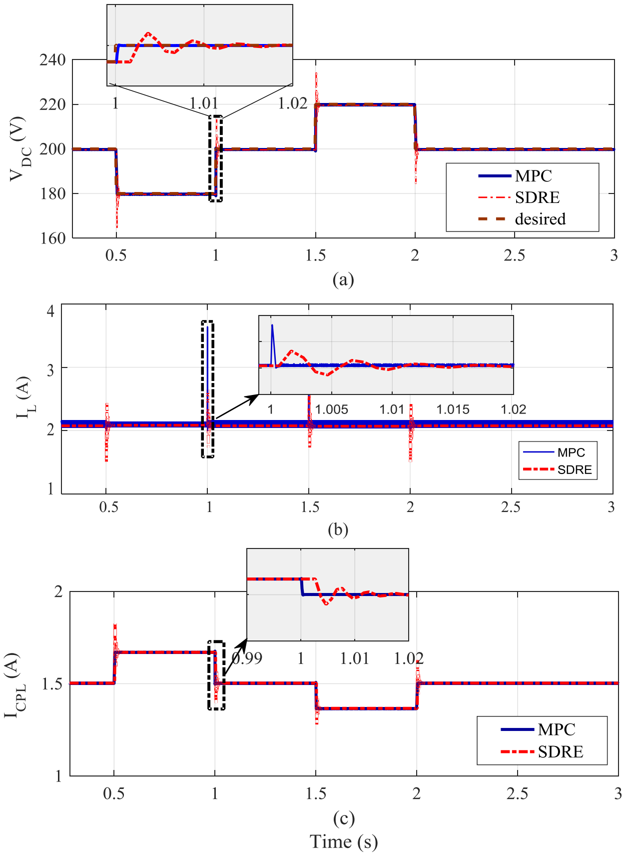


Figure 6. Compare performance of the proposed MPC and SDRE controller under frequent reference voltage change: (a) dc bus voltage, (b) inductor current, (c) load current

V. CONCLUSIONS

This paper proposes a MPC controller to stabilize and improve voltage regulation of dc microgrids interfaced with CPLs. The MPC controller is designed based on an average model of the nonlinear system. The advantage of the MPC control strategy is that the dc/dc converter in dc microgrid may be regulated via online optimization of a performance metric around multiple operating points. To investigate the performance of the MPC controller, a SDRE controller is designed and studied. Unlike the MPC strategy, the SDRE method requires extensive offline computation. The MPC uses nonlinear dynamics of the system while SDC representation of the augmented state-variable is considered in SDRE method. In addition, the SDRE controller can be applied to the system only when the converter's switch is ON and when switch is OFF, it does not guarantee stability and detectability condition. Some numerical simulations were carried out under load disturbances and reference voltage variation to evaluate and compare the designed controllers. The results show that the MPC controller provides superior performance comparing the SDRE controller providing faster response and less steady state error.

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