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Published in:
IEEE Transactions on Power Electronics

DOI (link to publication from Publisher):
10.1109/TPEL.2018.2822314

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2018.2822314, IEEE Transactions on Power Electronics

A Model Predictive Control for Renewable Energy Based AC Microgrids without Any PID Regulators

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[1]

***Abstract*— This letter presents a novel model predictive control strategy without involving any proportional-integral-differential (PID) regulators for practical renewable energy based ac microgrids. The proposed method consists of a model predictive power control (MPPC) scheme and a model predictive voltage control (MPVC) scheme. By controlling the bidirectional buck-boost converters of the battery energy storage systems based on the MPPC algorithm, the fluctuating output from the renewable energy sources can be smoothed, while stable dc-bus voltages can be maintained as the inverters inputs. Then, the parallel inverters are controlled by using a combination of the MPVC scheme and the droop method to ensure stable ac voltage output and proper power sharing. Compared with the traditional cascade control, the proposed method is simpler and shows better performance, which is validated in simulation on MATLAB/Simulink and on Real-Time Laboratory (RT-LAB) platform.**

***Index Terms*—MPC, energy storage system, microgrid, DC-DC, DC-AC, droop control, RT-LAB**

I. Introduction

For decades, cascade linear control has dominated the power electronic control techniques. However, this approach has major drawbacks [1]. First, the control structure is complicated with multiple feedback loops and PWM modulation, which leads to slow dynamic response. Second, the tuning of the proportional-integral-differential (PID) parameters is time-consuming, which makes the controller not easy to implement. In a practical ac microgrid, fluctuating output from renewable energy sources can cause oscillations in dc-bus voltage, which in turn, may further deteriorate the power quality on the ac side. As a result, traditional cascade control may no longer be effective to deal with this fluctuation.

In microgrids with multiple energy sources and converters, to achieve load sharing between distributed generation units (DGs) according to droop characteristic, inner current and outer voltage feedback loop control is commonly used [2]. In the last few years, much research efforts have been paid to obtain satisfactory and excellent performance by using traditional PID methods for ac microgrids. For example, by introducing power derivative-integral terms into a conventional droop together with inner voltage/current feedback loops, fast transient response in power sharing between inverters can be achieved [3]. Adaptive virtual impedance is proposed to achieve good performance for the reactive power sharing nonlinear loads [4-5]. By combing the virtual impedance and secondary control, the active and reactive powers can be shared with mismatched feeder impedance [6]. The effectiveness of droop function may however be deteriorated by incorporating such cascade linear control. Another concern is that, in existing research, the inputs of the distributed inverters are usually connected to dc power sources to simulate a variety of renewable energy resources. For control techniques development of inverters, it is reasonable and sufficient because this assumption can facilitate the design process. From the viewpoint of practical applications, however, the intermittent nature of such energy resources must be considered.

Recently, the model predictive control (MPC) scheme, in which the optimal switching state of the power converter is determined according to a specified cost function, has been adopted to obtain better performance [7]. Still, MPC is seldom reported in the coordinated control of multiple converters in microgrids, although some system-level algorithms have been proposed to achieve a variety of goals such as minimizing system operating costs and economic load dispatch [8]. These

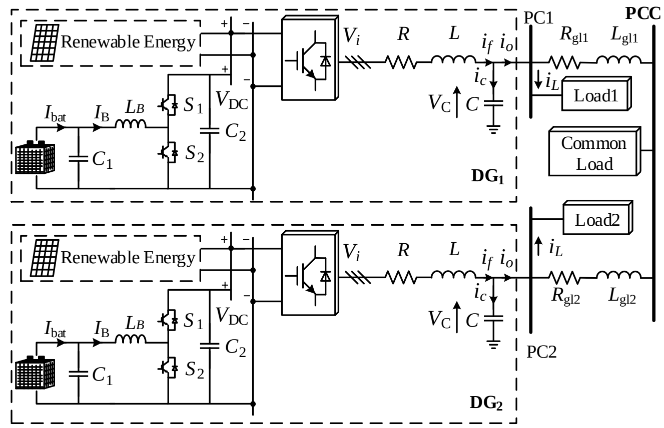

Fig. 1. Topology of a PV-battery-based ac microgrid.

[1]This work is supported by Hong Kong Research Grant Council under Grant PolyU252040/17E and by Hong Kong Polytechnic University under Grant 1-ZE7J. (Corresponding Author: J. Hu)

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2018.2822314, IEEE Transactions on Power Electronics

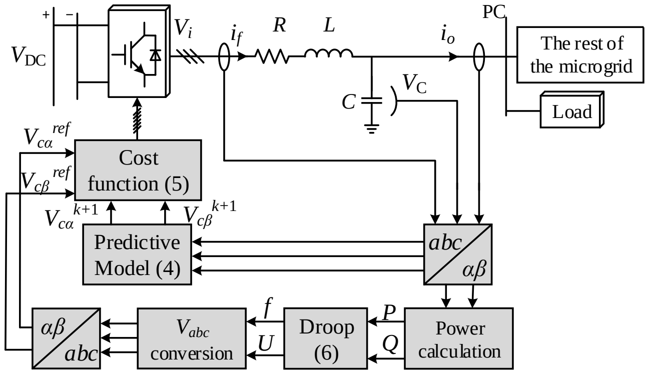

Fig. 2. Block diagram of the combination of droop and MPVC for inverters.

algorithms are designed and implemented at the system level. Nevertheless, the structures of the microgrids and the control of power converters have not been considered. Now the question becomes: In renewable energy based ac microgrids with multiple power converters as interfaces, is it possible to replace all the traditional cascade voltage or current feedback loops by using MPC approaches; And, to what extent, the overall system performance can be improved.

In this letter, a new control strategy based on MPC is developed for ac microgrids. The topology of the ac microgrid is shown in Fig. 1. The renewable energy resources could be the wind, solar, etc. Here, solar PV system is adopted as an example, which is not the main focus in this research. There are two parts in the whole system: PV-battery energy sources and parallel inverters with ac loads. A model predictive voltage control (MPVC) is incorporated with droop method to control the parallel inverters for load sharing, and a model predictive power control (MPPC) is developed to maintain the dc-bus voltages and smooth the PVs outputs.

II. MPVC of Parallel DC-AC Inverters

For a single inverter based isolated ac system, the target is to control the inverter to establish a stable and balanced output voltage for the loads. In MPVC, the voltage across the filter capacitor is the control objective. According to the circuit shown in Fig. 1, the dynamic behavior of the capacitor of the inverter LC filer can be expressed as

$$C\frac{d\boldsymbol{V}_c}{dt} = \boldsymbol{I}_C = \boldsymbol{I}_f - \boldsymbol{I}_o \tag{1}$$

The mathematical model of the inverter can be described as

$$\boldsymbol{V}_i = \boldsymbol{I}_f R + L\frac{d\boldsymbol{I}_f}{dt} + \boldsymbol{V}_c \tag{2}$$

Combining (1) and (2), the above models can be rewritten as a state-space system

$$\frac{d\boldsymbol{x}}{dt} = A\boldsymbol{x} + B\boldsymbol{y} \tag{3}$$

where

$$\boldsymbol{x} = \begin{bmatrix}\boldsymbol{V}_c \\ \boldsymbol{I}_f\end{bmatrix},\quad \boldsymbol{y} = \begin{bmatrix}\boldsymbol{V}_i \\ \boldsymbol{I}_o\end{bmatrix},\quad A = \begin{bmatrix}0 & 1/C \\ -1/L & -R/L\end{bmatrix},\quad B = \begin{bmatrix}0 & -1/C \\ 1/L & 0\end{bmatrix}$$

By solving the linear differential equation of (3), the following discrete-time form can be obtained

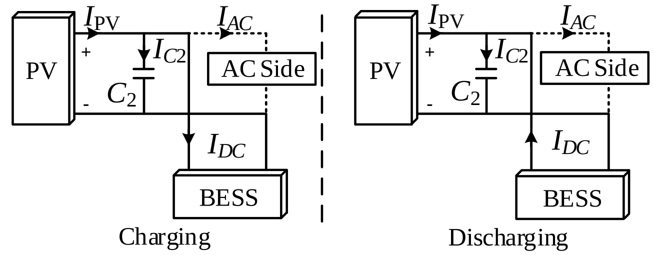

Fig. 3. Illustration of the currents flow within the system.

$$\boldsymbol{x}(k+1) = e^{T_s A}\boldsymbol{x}(k) + A^{-1}(e^{T_s A} - \boldsymbol{I}_{2\times 2})B\boldsymbol{y}(k) \tag{4}$$

where $\boldsymbol{I}_{2\times 2}$ is the identity matrix. Then, the capacitor voltage at $(k+1)^{th}$ instant can be predicted according to (4). To control the capacitor voltage tightly, the cost function is formulated as

$$J_V = \left(V_{c\alpha}^{ref} - V_{c\alpha}^{k+1}\right)^2 + \left(V_{c\beta}^{ref} - V_{c\beta}^{k+1}\right)^2 \tag{5}$$

where $V_{c\alpha}$ and $V_{c\beta}$ are the real and imaginary components of the capacitor voltage, respectively. Based on this cost function, the voltage vector that generates the least value of J_V will be applied during the next sampling period. Because the α and β components are tightly controlled, the $\boldsymbol{V}_c$ can track its reference. Thus, stable and sinusoidal voltage can be established.

For parallel inverter based ac system, droop method is commonly adopted to achieve power sharing between DGs without interactive communication lines. It is expressed as [2]

$$\begin{cases} f_j = f^* - m_j\cdot(P_j - P^*) \\ U_j = U^* - n_j\cdot(Q_j - Q^*) \end{cases} \tag{6}$$

where j is the index indicating each inverter. f_j and U_j are the actual frequency and voltage, f^* and U^* the nominal frequency and voltage, P_j and Q_j the average active and reactive power, P^* and Q^* the nominal active and reactive power, and m_j and n_j the droop slopes.

Inspired by the effectiveness of voltage control of MPVC and the load sharing capacity of droop method, the new parallel inverter control strategy is developed, as described in Fig. 2. The traditional voltage and current feedback loops have been replaced by MPVC scheme.

III. MPPC of Bidirectional Buck-Boost Converters

The aim of the battery energy storage system (BESS) is to compensate the power gap caused by the PV output and the load demand through maintaining the dc-bus voltage. Fig. 3 illustrates the currents flow between the PV, BESS and the ac side. To keep the power balance within the microgrid, the BESS should discharge and be charged properly. By applying Kirchoff's current law (KCL), the relationship of the currents can be expressed as:

$$I_{DC} = I_{PV} - I_{C2} - I_{AC} \tag{7}$$

where I_{DC} denotes the current supplied or absorbed by BESS. I_{AC} denotes the current following into the inverter for ac loads. Consequently, the required power by BESS to keep the power balance within the microgrid can be calculated as

$$P_{BESS}^* = \left|I_{DC}\cdot V_{DC}^*\right| \tag{8}$$

where V_{DC}^* is the voltage reference for dc bus. According to the capacitor characteristic, the current flowing through the dc-bus capacitor, C_2, can be predicted as

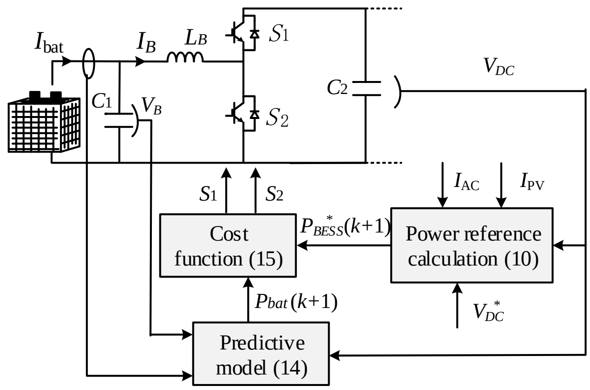

Fig. 4. Block diagram of MPPC to control buck-boost converters.

$$I_{C2}(k+1)=\frac{1}{N}(\frac{C_2}{T_s}(V_{DC}^*-V_{DC}(k)) \qquad (9)$$

where N is an integer coefficient used to limit the capacitor's current [9]. Combining (7), (8) and (9), the required power by BESS at next control instant can be written as

$$P_{BESS}^*(k+1)=\left|I_{DC}(k+1)\cdot V_{DC}^*\right| \qquad (10)$$

Since the power supplied or absorbed by BESS is actually controlled by switching the buck-boost converter, it is necessary to obtain the effect of switching states on power absorbed/supplied. Fig. 4 shows the circuit of the BESS including the battery and the converter. If S_2 is switching (1 or 0) and S_1 is kept OFF, it operates in boost mode. The battery discharges to supply power. On the contrary, If S_1 is switching (1 or 0) and S_2 is maintained OFF, it operates in buck mode. The battery is charged to absorb power. In boost operation, the circuit model can be written as

$$\begin{cases} S_2=1, S_1=0:\ L_B\dfrac{dI_B}{dt}=V_B \\ S_2=0, S_1=0:\ L_B\dfrac{dI_B}{dt}=V_B-V_{DC} \end{cases} \qquad (11)$$

The discrete-time model for a sampling time T_s can be expressed as:

$$\begin{cases} S_2=1, S_1=0:\ I_B(k+1)=\dfrac{T_s}{L_B}V_B(k)+I_B(k) \\ S_2=0, S_1=0:\ I_B(k+1)=\dfrac{T_s}{L_B}(-V_{DC}(k)+V_B(k))+I_B(k) \end{cases} \qquad (12)$$

Similarly, the discrete-time models of the buck operation can be written as:

$$\begin{cases} S_2=0, S_1=1: I_B(k+1)=\dfrac{T_s}{L_B}(V_{DC}(k)-V_B(k))+I_B(k) \\ S_2=0, S_1=0: I_B(k+1)=-\dfrac{T_s}{L_B}V_B(k)+I_B(k) \end{cases} \qquad (13)$$

Considering the relatively slow change of the battery voltage and the equality of battery output current and inductor current, the battery output power can be predicted as

$$P_{bat}(k+1)=\left|I_B(k+1)\cdot V_B(k)\right| \qquad (14)$$

The required power of the BESS to keep the power balance with the microgrid should be provided by the battery through the buck-boost converter. Therefore, the following cost function should be minimized

TABLE I SYSTEM PARAMETERS

Parameters	values
PV system	
Module maximum power (W)	549
Array parallel module strings	66
Array series-connected modules	10
BESS (Lithium-ion battery & buck-boost converter)	
Nominal voltage (V)	500
Rated capacity (Ah)	1600
dc-bus voltage (V)	1k
PI controller at outer voltage loop (k_p, k_i)	10, 50
PI controller at inner current loop (k_p, k_i)	1.5, 1
Switching frequency for the traditional PI method	2kHz
Paralleled inverters	
Rated frequency f (Hz)	50
Nominal phase-to-phase voltage V_{rms} (V)	380
Filter inductance L (mH)	2
Filter capacitor C (μF)	250
DG1 and DG2 rating (kVA)	45, 42
Maximum voltage deviation (V)	10
Maximum frequency deviation (Hz)	1.5
Line resistance R_{gl1} and R_{gl2} (Ohms)	0.05, 0.04
Line reactance L_{gl1} and L_{gl2} (Ohms)	0.6, 0.48
PI controller at outer voltage loop (k_p, k_i)	58, 0
PI controller at inner current loop (k_p, k_i)	5, 0
Switching frequency for the traditional PI method	5kHz

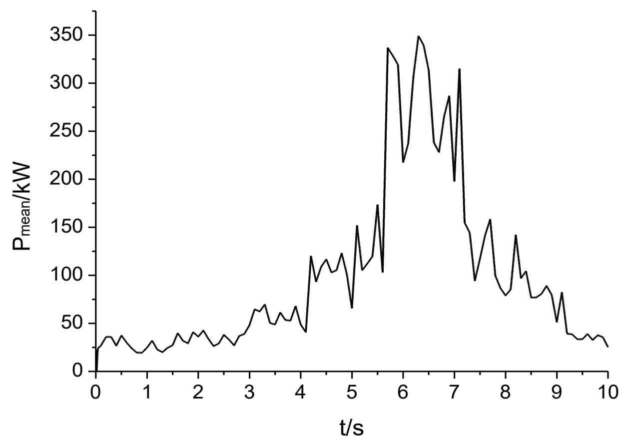

Fig. 5. Real-world PV output due to fluctuating solar irradiation.

$$J_P=\left|P_{BESS}^*(k+1)-P_{bat}(k+1)\right| \qquad (15)$$

Fig. 4 illustrates the proposed MPPC strategy. The PV system output current, I_{PV}, inverter input current, I_{AC}, actual dc-bus voltage V_{DC} and reference voltage V_{DC}^*, are first used to calculate the required BESS power. Meanwhile, the battery voltage and current, together with the actual dc-bus voltage, will be used to predict the battery current $I_B(k+1)$, leading to four possible values of $P_{bat}(k+1)$ according to (12) and (13). Then, the switching behavior that minimizes (15) will be selected to control the buck-boost converter. In this way, the dc-bus voltages can be maintained stable as the inputs for the parallel inverters. Compared to traditional cascade control with PID regulators, additional measurements of the PV current and the ac side current are needed for the proposed MPPC approach. Thus, additional current sensors and communications are required within the PV-BESS unit. It is noted that communication between parallel PV-BESS-Inverter units is still avoided due to the integration of droop method into the MPVC.

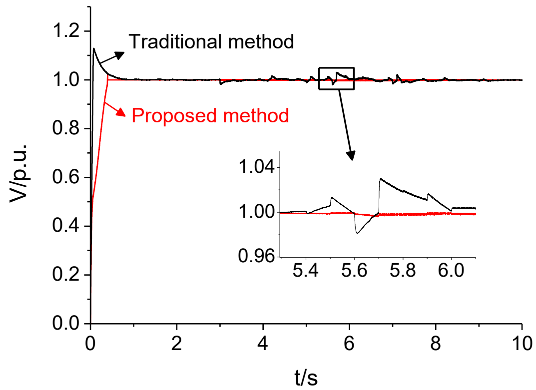

Fig. 6. DC- bus voltage of DG1.

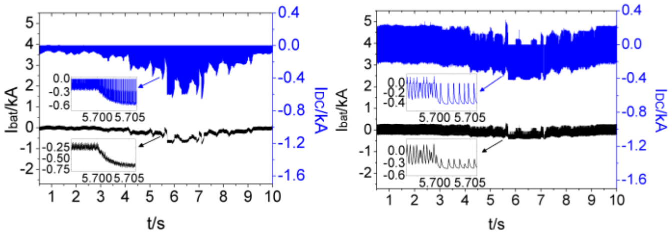

Fig. 7. Battery current (I_{bat}) and BESS current (I_{DC}), (a) traditional method, (b) proposed method.

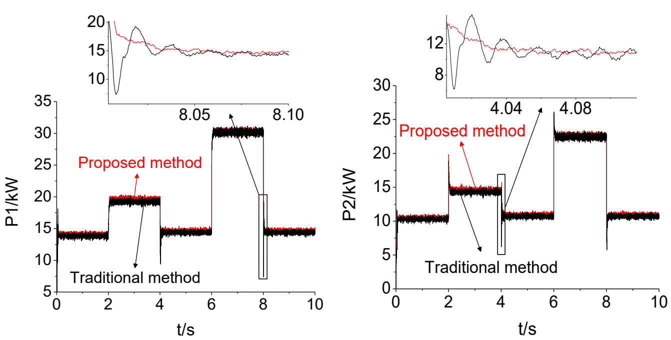

Fig. 8. Active power sharing between DGs, (a) DG1, (b) DG2

IV. VERIFICATION

The ac microgrid shown in Fig. 1 is modeled and implemented in both MATLAB/Simulink and the real-time laboratory test platform OP5700. To verify the proposed method with practical consideration, the real-world solar irradiation profile on 05-Jan-2018 is used for generating PV output, which is plotted in Fig. 5. The system parameters are listed in Table I. On the demand side, at 2s, DG2 local load increases from (7kW, 3.5kVar) to (17kW, 5kVar); at 4s DG1 local load decreases from (18kW, 7kVar) to (9kW, 2kVar). Then a common load (32kW, 15kVar) is switched in at 6s and cut off at 8s. In traditional control method, outer voltage and inner current feedback loops with two PI controllers are adopted for BESS buck-boost converters, while conventional droop control with inner double feedback loops is used for controlling the inverters. For a fair comparison, the average switching frequencies of the converters are the same for traditional method and the proposed method. To achieve this, the sampling frequency of the MPC is 25kHz, resulting in an

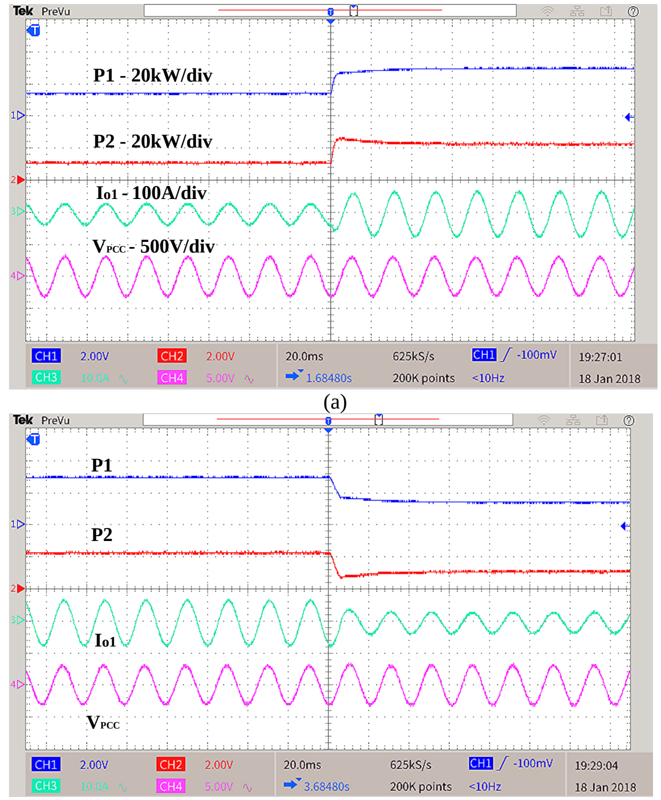

Fig. 9. Transient behavior for the proposed method, (a) connecting the common load at 6s, (b) switching off the common load at 8s. (RT-LAB) **CH1**: DG1 output active power, **CH2**: DG2 output active power, **CH3**: DG1 output current, **CH4**: PCC voltage.

average 5.0kHz switching frequency for the inverter and an average 1.9kHz switching frequency for the dc-dc converter, respectively.

Fig. 6 shows the comparison of dc bus voltage by using proposed method and traditional method. Clearly, under various solar irradiation and load condition, the dc-bus voltage is tightly controlled by using the proposed method. On the other hand, the dc-bus voltage presents large oscillations for traditional method, especially during rapid solar irradiation surge at around 5.7s. This demonstrates the excellent control performance of the proposed MPPC method. The dc-bus voltage of DG2 is similar to that of DG1, which is not shown here. Fig. 7 presents the response of the BESS to such fluctuating solar PV output and variable power demand. It can be seen that the battery keeps changing its operation mode between charging and discharging. In other words, I_{bat} fluctuates around zero A to compensate the time-varying mismatch between generation and consumption, as shown in Fig. 7(b). Also, it is observed that both battery current and BESS current of the proposed method present larger ripples than those of traditional method. This is because MPPC generates larger current to mitigate voltage oscillation in order to stabilize the dc-bus voltage. According to the equation $\Delta P = \Delta V \cdot \Delta I$, for the same ΔP, in order to mitigate ΔV, ΔI should be larger. So, larger BESS current I_{DC} is observed in the proposed method, which leads to larger ripples in battery current I_{bat}. Actually, the fluctuating battery current and BESS current with larger ripples are also attributed to the nature of the proposed

MPPC method. With time-varying mismatch between power generation from renewable energy and power demand from load, the required BESS power P^*_{BESS} to compensate the power gap will be fluctuating around zero (i.e., oscillating between positive and negative rapidly). According to the cost function (15) consisting of (10) and (14), I_{DC} and I_{bat} will therefore fluctuate around 0A sharply. The larger current ripple may lead to higher losses in the converter and higher thermal stress on the battery itself. From the viewpoint of power smoothing and dc-bus stabilization, however, such larger ripples are not necessarily defined as "worse" because they contribute to smaller dc-bus voltage oscillations and effective elimination of power unbalance within the microgrids.

Fig.8 compares the power sharing between the proposed method and traditional method. It can be seen that, for both methods, the parallel inverters can adjust their output automatically to meet the varying power demand because of the droop method. But, the active power by using the proposed method presents a smoother and faster transient performance than that by using traditional method, due to the better voltage control capability of MPVC. For a better observation, the zoom-in waveforms of P_1 at 8s and P_2 at 4s are re-plotted, as shown in Fig. 8(a) and (b), respectively. Since the output reactive powers present the similar response, they are not plotted here.

The dynamic performance of the proposed method is further evaluated by connecting and switching off the common load (32kW, 15kVar). Fig. 9 presents the system transient behavior. As can be seen, the inverters can share their output in a fast and safe manner when load changes. Meanwhile, the voltage for the load is very stable and sinusoidal.

V. CONCLUSION

In this letter, a new model predictive control strategy has been proposed for ac microgrids with PVs and energy storage. This method addresses the problems of traditional cascade linear control including complicated feedback loops, slow dynamics and time-consuming PID tuning. Accordingly, a model predictive power control (MPPC) is developed to maintain the dc voltage and smooth the PV output, while a model predictive voltage control (MPVC) is incorporated with droop method to control the inverters for load sharing. The proposed control strategy has been validated in both Simulink simulation and Real-time Laboratory platform. The test results verified that, under fluctuating power generation and various load condition, the control scheme maintain the dc-bus voltage with much less oscillations. Moreover, the power sharing among inverters is faster and smoother, while the ac voltage is kept stable.

Acknowledgment

The authors would like to thank the anonymous reviewers for insightful comments and helpful suggestions on this work.

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