

Active Power Decoupling Method Based on Dual Buck Circuit With Model Predictive Control

Shunlong Xiao¹, Student Member, IEEE, Xiao Li¹, Student Member, IEEE, Haiyu Zhang¹, Student Member, IEEE, and Robert S. Balog^{1,2}, Senior Member, IEEE

Renewable Energy & Advanced Power Electronics Research Laboratory^{1,2}

¹Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA

²Electrical and Computer Engineering Program, Texas A&M University at Qatar, Doha, 23874, Qatar

Email: xiaoshunlong@gmail.com, robert.balog@ieee.org

Abstract— Single phase inverter and rectifier systems have double line frequency ripple power which is inherent to the ac-side of the circuit but adversely affects the dc-side performance. Typically, an aluminum electrolytic capacitors is placed at the dc side to absorb this power ripple, but reduces the power density and reliability of the converter. Therefore, active decoupling methods have been proposed in the literature to transfer the ripple power to smaller storage components by extra switches to the converter. However, the existing active power circuits are mostly composed of half bridge circuit, which has inherent shoot-through potential problem and could degrade the system reliability. Moreover, the existing active power decoupling methods are normally implemented through predetermined voltage of storage component using conventional PI control method, which limits the decoupling dynamic performance of the system. In this paper, a novel active power decoupling method based on dual buck circuit and model predictive control is proposed. The dual buck circuit is composed of two separate buck converters operating in each half cycle and two split small dc-link capacitors to eliminate the dc-link voltage ripple. The topology is free of shoot-through and deadtime concern and the control is independent with that of the main power stage circuit, which makes the design simpler and more reliable. By applying model predictive control, the proposed control strategy is proved to have good dynamic performance by both simulation and experimental results.

Keywords—Active power decoupling; dual buck converter, Model Predictive Control (MPC); dc-link capacitor

I. INTRODUCTION

Single phase rectifiers and inverters have wide applications in residential and industrial power conditioning systems. However, the inherent double line frequency ripple power in single phase system could be adverse to both dc and ac side [1-4]. To address this problem, active decoupling methods are considered to transfer the ripple power to smaller storage components through added active circuit, which permits large fluctuation of voltage or current (usually ac), therefore both the auxiliary circuit components and the dc-link capacitor can be small in size and weight [5-11]. In many existing active power decoupling (APD) circuits [5-10], at least one phase leg with

TABLE 1: System Parameters

Parameter	Value
System power rating, P_m	1 kW
DC-link voltage, V_{dc}	300 V
DC-link capacitance, C	110 μ F
AC output frequency, f_0	60 Hz
APD's inductance, L_1	1 mH
Filter inductance, L_f	3mH
AC voltage, $V_{ac(RMS)}$	110 V
Sampling Time, T_s	1 μ s

two switches is needed, which required dead-time control to prevent shoot through problems between the switches in one leg. In order to achieve a simple and compact design with a high reliability, a APD circuit based on the dual buck circuit is considered. The split dc-link capacitors are directly utilized as energy storage components rather than a voltage stiffening component [12]. Moreover, a control strategy based on model predictive control (MPC) is proposed for this power decoupling circuit. MPC is a powerful class of controllers using the discrete model of a system to predict the future system behavior and choose the optimal control actuation [13-16]. As such, the technique has numerous advantages over classical control methods including the simple structure for inclusion of operational constraints and multi-objectives in the MPC cost function [13]. Benefiting from the good transient performance of the MPC method, the proposed controller achieves good transient performance in tracking system load transition. Since the instantaneous ripple power is directly buffered into the power decoupling module, its energy storage capability to buffer the ripple power is fully performed. In summary, the new control method has the following benefits:

- 1) Fast dynamic response to the load transient compared with conventional method based on d-q transformation;
- 2) maximum utilization of potential capacity to minimize the capacitance;
- 3) Simple implementation and controller design;
- 4) inductor current is controlled instead of capacitor voltage, reducing the order of the control system, enabling fast response.

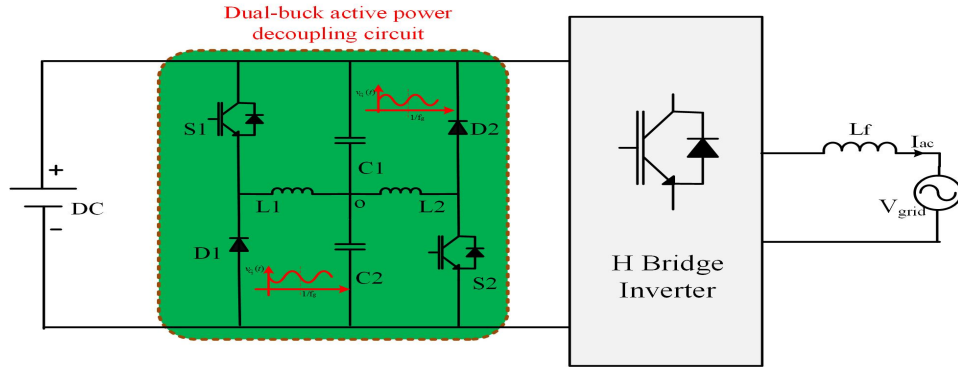


Fig. 1. System configuration in study

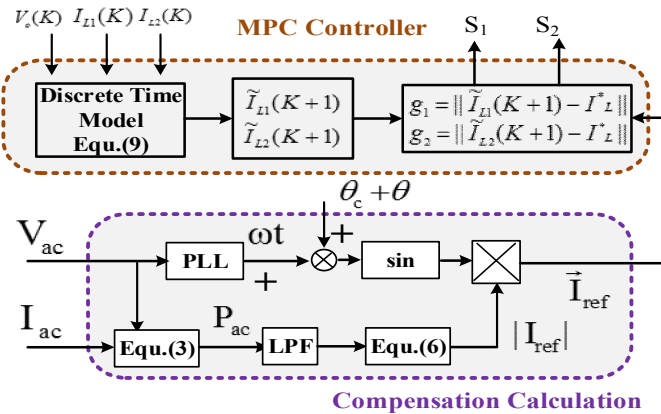


Fig. 2. System control strategies

The rest of this paper is organized as follows. Section II describes the system configuration, space model of the system, and prediction model of the system. Section III illustrates the proposed MPC based method for dual-mode inverter in DG systems. The operation modes and transition process of the system are discussed in detail. Section IV presents the proposed phase detection and adjustment algorithm, which is followed by the stability analysis of system in section V. In section VI, the simulation and experimental results are provided to verify the performance and effectiveness of the proposed control strategy.

II. DUAL-BUCK ACTIVE POWER DECOUPLING CIRCUIT ANALYSIS

The proposed dual buck based active power decoupling (APD) circuit as shown in Fig. 1. The topology is, in principle, two separate buck converters, which is made up of a left bridge leg (S1,D1,L1) and a right bridge leg (S2,D2,L2), terminated with a split dc link, which is operated as the energy storage device or the buffer for the ripple power. Each bridge works on complimentary half cycle of the ac fundamental period, two identical capacitors are connected in series in the dc link. In this way, the dc-link capacitors may function to absorb the system ripple power. The voltages across two capacitors are controlled to have a dc component with a value equal to half of

dc link voltage and an ac component with the fundamental line frequency. The ac component of the two capacitors has complementary phase relationship such that the voltage ripple cancels out and the sum of voltages is the constant dc link voltage. The capacitors can be alternatively discharged to zero in case that high ripple power compensation is required. Two capacitors exchange ripple power with main circuit by charging and discharging action. The charging/discharging current is smoothed by the inductors. Due to the unidirectional current through inductor in each leg, each phase leg will work in a different half cycle. When current through inductor L1 is positive, the left phase leg works. In this mode, S2 is always OFF, and S1 is driven by a gate signal with the diode D1 freewheeling the inductor current to the capacitor C1 and C2. Capacitor C1 discharge its energy while Capacitor C2 works in charging mode. The same analysis can be applied to the right half bridge.

There are four operating modes for the proposed decoupling circuit. Each phase leg has two operating modes during every switching period, and only works in half cycle, which is determined by the capacitor current. The operating condition is illustrated in Figure 3. The following analysis is based on the CCM operating condition, while the operating principle and analysis are also applicable to DCM.

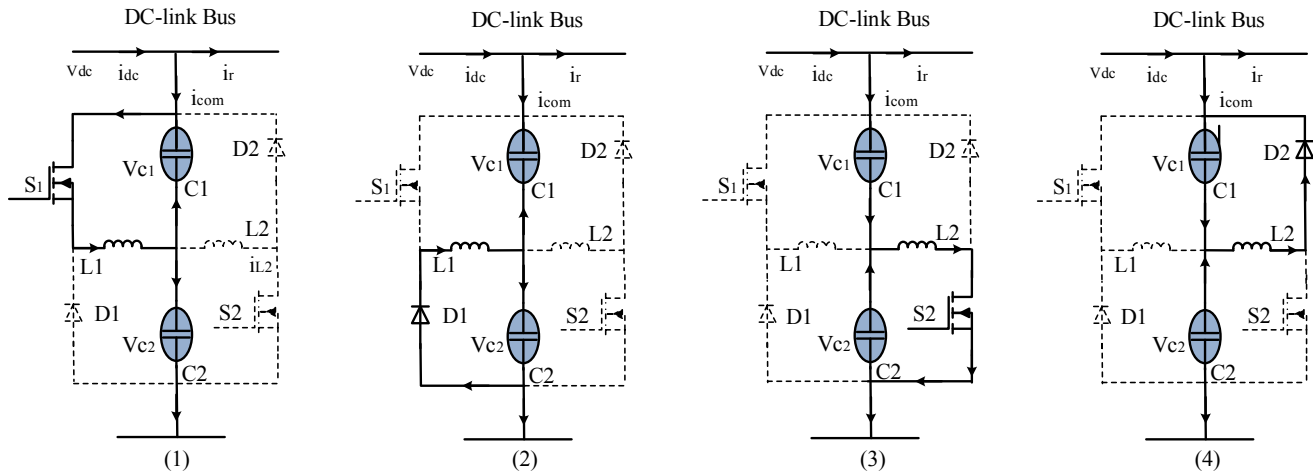


Fig. 3. Operating modes of the power decoupling circuit.

(1) When S_1 is ON, S_2 is OFF. The circuit operation is shown as Figure 3(1), the inductor current increases linearly

$$L_1 \frac{di_{L1}}{dt} = V_{dc} - V_{C2} = V_{C1} \quad (1)$$

In this case, C_1 works in discharging condition and it sends energy to L_1 . While current through C_2 is determined by condition of main circuit and the ripple power value. The voltage stress of the freewheeling diode D_1 is the input voltage.

(2) When S_1 is OFF, S_2 is OFF and the current through inductor L_1 is nonzero. The current i_{L1} will continue to run through the freewheeling diode D_1 . The circuit operation is shown as Figure 3(2), the inductor current decreases linearly

$$L_1 \frac{di_{L1}}{dt} = -V_{C2} \quad (2)$$

In this case, the current through C_1 is equal to i_{com} . While current through C_2 is equal to the sum of i_{com} and i_{L1} . The voltage stress of the switch S_1 is the input voltage.

When the capacitor current changes direction, another phase leg begins to operate and then the circuit operate in the other two modes. When the right phase leg operates, the switch in left phase leg will keep off.

(3) When S_2 is ON, S_1 is OFF. The circuit operation is shown as Figure 3(3), the inductor current increases linearly

$$L_2 \frac{di_{L2}}{dt} = V_{dc} - V_{C1} = V_{C2} \quad (3)$$

In this case, C_1 works in discharging condition and sends energy to L_2 . While current through C_2 is determined by condition of main circuit and the ripple power value. The voltage stress of the freewheeling diode D_2 is the input voltage.

(4) When S_2 is OFF, S_1 is OFF and the current through inductor L_2 is nonzero. The current i_{L2} will continue to run through the freewheeling diode D_2 . The circuit operation is shown as Figure 3(4), the inductor current decreases linearly

$$L_2 \frac{di_{L2}}{dt} = -V_{C1} \quad (4)$$

In this case, the current through C_2 is equal to i_{com} . While current through C_1 is equal to the sum of i_{com} and i_{L2} . The voltage stress of the switch S_2 is the input voltage.

This circuit has the following advantages: High reliability since no shoot-through concern and no need of deadtime consideration; Less storage components since DC link capacitors are used to buffer dc power and decouple ac power simultaneously; Simple and reliable control due to its independent power decoupling module with main circuit. The detailed operation of the circuit will be introduced in final paper.

III. RIPPLE COMPENSATION DESIGN AND CONTROL IMPLEMENTATION BASED ON MODEL PREDICTIVE CONTROL

To simplify the analysis, assume the dual-buck converter works at continuous conduction mode (CCM) and assume the voltage and current at AC side are in the form as

$$\begin{aligned} v_{ac}(t) &= V_{ac} \sin \omega t \\ i_{ac}(t) &= I_{ac} \sin(\omega t + \theta) \end{aligned} \quad (5)$$

Then the instantaneous power can be calculated as

$$p_{ac}(t) = \frac{1}{2} V_{ac} I_{ac} \cos \theta - \left[\frac{1}{2} V_{ac} I_{ac} \cos(2\omega t - \theta) + \frac{\omega L_f I_{ac}^2}{2} \sin(2\omega t + 2\theta) \right] \quad (6)$$

As indicated above, the C_1/C_2 voltages and currents should be controlled as equation (7):

$$\begin{cases} v_{C2}(t) = \frac{V_{dc}}{2} + V_c \sin(\omega t + \theta_c) \\ v_{C1}(t) = \frac{V_{dc}}{2} - V_c \sin(\omega t + \theta_c) \\ i_{C2}(t) = C \omega V_c \cos(\omega t + \theta_c) \\ i_{C1}(t) = -C \omega V_c \cos(\omega t + \theta_c) \end{cases} \quad (7)$$

Here, the two decoupling capacitors are assumed to be equal to each other i.e. $C_1=C_2=C$. Since the working principle of the two buck converters are identical, only the left bridge leg is discussed in the rest paper. Taking the inductor reactive power into consideration, the instantaneous C1 ripple power $P_{c1}(t)$ is

$$P_{c1}(t) = \frac{v_{ac} i_{ac}}{2} - L_1 \frac{di_{ac}}{dt} i_{ac} \quad (8)$$

In each half cycle, the average energy stored in the inductor is zero and from equations (6) to (8), the following equations are derived which are used to generate the current reference i_{Lref} for the inductors in the APD circuit:

$$I_{ref} = 2 * I_{C1} = \sqrt{\frac{P_{ac_2w}}{2(\frac{1}{C\omega} - wL)}} \quad (9)$$

$$\begin{cases} \theta_c = \theta - \frac{\pi}{4} \\ P_{ac_2w} = \sqrt{(V_{ac} I_{ac})^2 + 2wLV_{ac} I_{ac}^3 \sin(\theta)} \end{cases}$$

The voltage of inductor L1 is

$$v_{L1} = L_1 \frac{di_{c1}}{dt} i_{c1} = v_{s1} - v_o \quad (10)$$

Converting (1) into a discrete time model by the Euler forward method, the inductor current can be predicted by

$$i_{L1}(k+1) = i_{L1}(k) + \frac{T_s}{L_1} (v_{s1} - v_o) \quad (11)$$

Thus the behavior of the system can be predicted at the next sampling time (K+1) and the predicted model of the inductor when switch is ON and OFF is given as

$$\begin{cases} i_{L1}(k+1) = i_{L1}(k) + \frac{T_s}{L_1} (V_{ac}(k) - v_o(k)) & \zeta = 1 \\ i_{L1}(k+1) = i_{L1}(k) + \frac{T_s}{L_1} (0 - v_o(k)) & \zeta = 0 \end{cases} \quad (12)$$

where T_s is the sampling period; $i_{L1}(k)$ is the inductor L1 current at the kth time instant; $i_{L1}(k+1)$ is the predicted current at the (k+1)th time instant; $V_{ac}(k)$ and $v_o(k)$ are the voltages of dc bus and neutral point respectively.

The proposed technique predicts the tracking error of the next sampling for both possible switching states per converter (switch ON and OFF) by calculating the cost functions (g_0 and g_1) as the equation (10):

$$g_{\zeta \in \{0,1\}} = \|\tilde{I}_L(k+1)_{\zeta \in \{0,1\}} - I_{Lref}^*(k+1)\| \quad (13)$$

The switching state that minimizes these cost function equation (10) will be applied to their corresponding converters as shown in Fig. 2. The control of the proposed active power decoupling circuit is independent with the control of the H

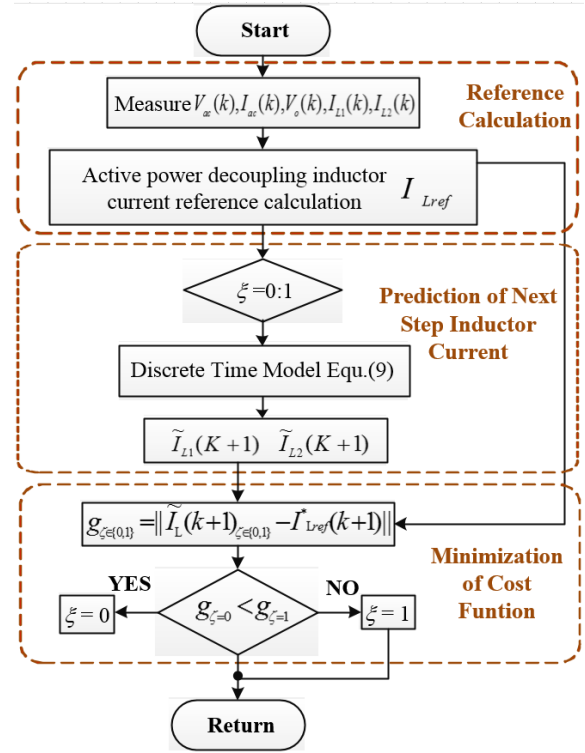


Fig. 4 Flow Chart of the MPC Implementation

bridge inverter, which is also controlled by the MPC but is not the focus of this paper. Figure 4 shows the detailed flowchart of the proposed MPC algorithm for the dual-buck APD circuit.

IV. RESULTS AND DISCUSSIONS

A 1kW prototype shown in Figure 7(1) was used to experimentally verify the performance of proposed power decoupling system and its operating principle. Table I lists the system specifications of the system. The dc-link capacitor used is only 110 uF, which is orders of magnitude smaller than the bulky capacitor without the active power decoupling circuit. The results of two case studies are discussed here to show the effectiveness of the proposed power decoupling system.

A. Case Study 1— Steady state performance with and without the proposed APD circuit

The steady state ac side active power is set to be 900W. When the proposed active power decoupling system is disabled, the ripple component in the dc bus voltage and current are noticeable as shown in Fig 5(1). In Fig. 5(2), those two waveforms have much smaller 2w ripple components under the same scale. The ripple magnitudes are reduced to 16.7% of those without the implementation of the proposed APD method, which clearly demonstrates the effectiveness of the proposed control system in diminishing the ripple power.

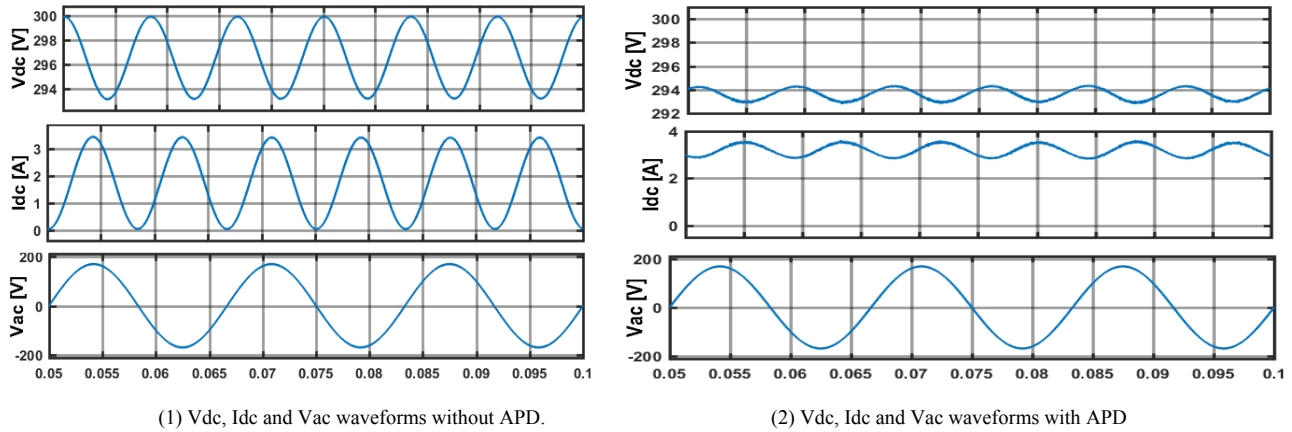


Fig. 5. Case 1: Steady state performance of simulation results

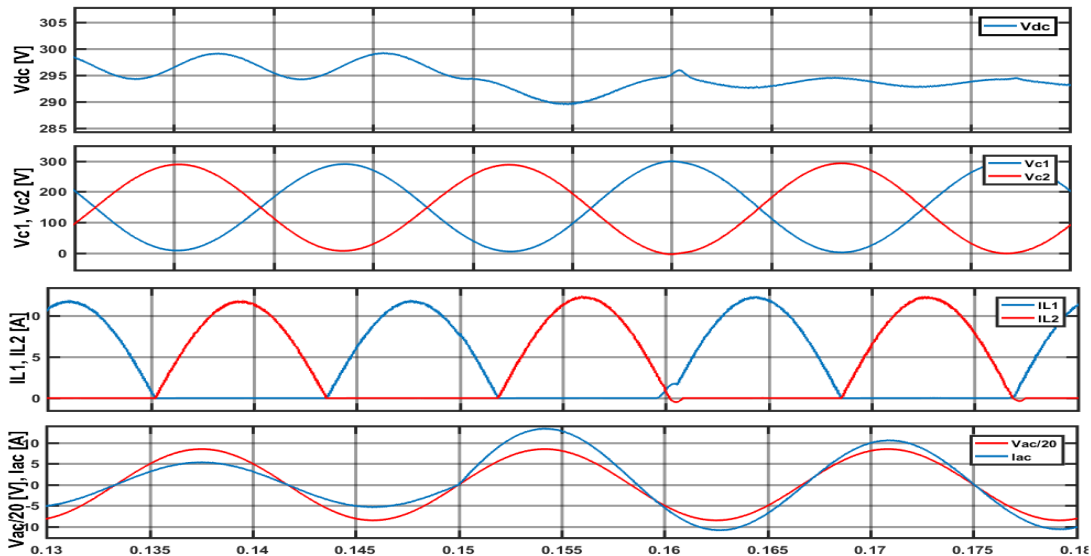


Fig. 6. Case 2: Dynamic responses during ac transient

B. Case Study 2—Dynamic performance during ac transient

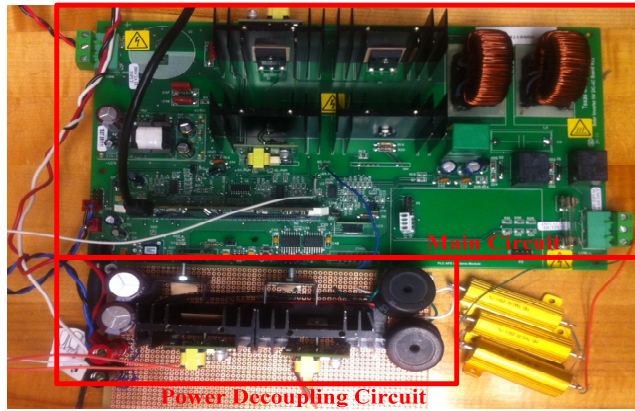
Figure 6 shows the power dynamic response of the system when the active power steps from 450W to 900W at 0.15s. The ac voltage magnitude is scaled down by 20 to compare with the ac current on the same axis. In experimental result in Fig. 7(2), the capacitor voltages V_{C1} , V_{C2} are controlled to ranging from 0 to V_{dc} (200V), exploiting the full energy buffer capacity of the two small dc split capacitors, and the inductor current i_{L1} , i_{L2} tracks the i_{Lref} accurately in each half cycle even during ac load transient, thanks to the fast dynamic characteristic of the MPC. Therefore, the dc bus voltage always remains relatively clean even under load transient. It can be seen that the proposed topology and control method can eliminate double line frequency ripple power and diminish the voltage ripple at dc link greatly even with smaller capacitor. The voltage in two capacitors have complementary ac component, which ensures the small fluctuation on dc link voltage. Each phase leg in power decoupling module operates in half cycle. The experimental results coincide well with simulation results.

V. CONCLUSION

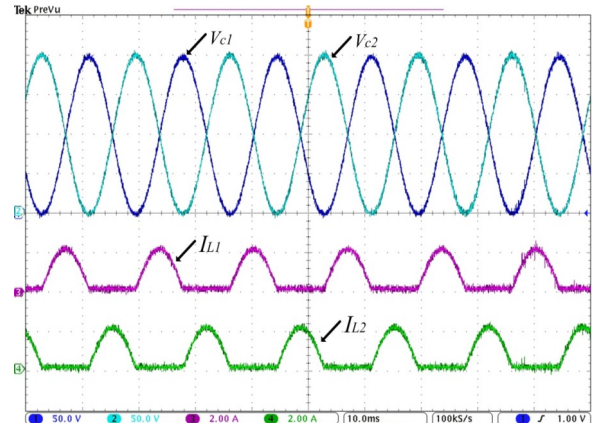
A novel active power decoupling system based on model predictive control and dual buck circuit is proposed to address the ripple power issue inherent in the single phase inverter/rectifier. Detailed description on circuit's operation and controller design are given in the final paper Both simulation and experimental results verifies the effectiveness of the APD system in improving system fault tolerance and dynamic response compared with conventional methods.

ACKNOWLEDGMENT

This publication was made possible by NPRP grant # 7-299-2-124 from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.



(1) Experimental prototype setup.



(2) Steady state performance of power decoupling circuit.

Fig. 7. Experimental Results

REFERENCES

- [1] X. Liu and H. Li, "An Electrolytic-Capacitor-Free Single-Phase High-Power Fuel Cell Converter With Direct Double-Frequency Ripple Current Control," *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 297-308, 2015.
- [2] M. Yilmaz and P. T. Krein, "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151-2169, 2013.
- [3] S. Harb, M. Kedia, H. Zhang, and R. S. Balog, "Microinverter and string inverter grid-connected photovoltaic system: A comprehensive study," in *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, 2013, pp. 2885-2890.
- [4] H. Zhang, X. Li, B. Ge, and R. S. Balog, "Capacitance, dc Voltage Utilization, and Current Stress: Comparison of Double-Line Frequency Ripple Power Decoupling for Single-Phase Systems," *IEEE Industrial Electronics Magazine*, vol. 11, no. 3, pp. 37-49, 2017.
- [5] H. Han, Y. Liu, Y. Sun, M. Su, and W. Xiong, "Single-phase current source converter with power decoupling capability using a series-connected active buffer," *IET Power Electronics*, vol. 8, no. 5, pp. 700-707, 2015.
- [6] S. Harb and R. S. Balog, "Reliability of Candidate Photovoltaic Module-Integrated-Inverter (PV-MII) Topologies: A Usage Model Approach," *IEEE Transactions on Power Electronics*, vol. 28, no. 6, pp. 3019-3027, 2013.
- [7] Y. Tang, F. Blaabjerg, P. C. Loh, C. Jin, and P. Wang, "Decoupling of Fluctuating Power in Single-Phase Systems Through a Symmetrical Half-Bridge Circuit," *IEEE Transactions on Power Electronics*, vol. 30, no. 4, pp. 1855-1865, 2015.
- [8] G. R. Zhu, S. C. Tan, Y. Chen, and C. K. Tse, "Mitigation of Low-Frequency Current Ripple in Fuel-Cell Inverter Systems Through Waveform Control," *IEEE Transactions on Power Electronics*, vol. 28, no. 2, pp. 779-792, 2013.
- [9] P. F. Ksiazek and M. Ordonez, "Swinging Bus Technique for Ripple Current Elimination in Fuel Cell Power Conversion," *IEEE Transactions on Power Electronics*, vol. 29, no. 1, pp. 170-178, 2014.
- [10] R. Wang *et al.*, "A High Power Density Single-Phase PWM Rectifier With Active Ripple Energy Storage," *IEEE Transactions on Power Electronics*, vol. 26, no. 5, pp. 1430-1443, 2011.
- [11] B. Ge *et al.*, "An Active Filter Method to Eliminate DC-Side Low-Frequency Power for a Single-Phase Quasi-Z-Source Inverter," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 8, pp. 4838-4848, 2016.
- [12] X. Li, S. Xiao, H. Zhang, R. S. Balog, and B. Ge, "Dual buck based power decoupling circuit for single phase inverter/rectifier," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016, pp. 1-6.
- [13] C. Bordons and C. Montero, "Basic Principles of MPC for Power Converters: Bridging the Gap Between Theory and Practice," *IEEE Industrial Electronics Magazine*, vol. 9, no. 3, pp. 31-43, 2015.
- [14] S. Xiao, M. B. Shadmand, and R. S. Balog, "Model predictive control of multi-string PV systems with battery back-up in a community dc microgrid," in *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2017, pp. 1284-1290.
- [15] S. Xiao, M. Metry, M. Trabelsi, R. S. Balog, and H. Abu-Rub, "A Model Predictive Control Technique for Utility-Scale Grid Connected Battery Systems Using Packed U Cells Multilevel Inverter," presented at the IEEE Ind. Electron. Conf. (IECON), Florence, Italy, 24-27 Oct 2016, 2016.
- [16] J. Lu and R. Niu, "A state estimation and malicious attack game in multi-sensor dynamic systems," in *2015 18th International Conference on Information Fusion (Fusion)*, 2015, pp. 932-936.