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Model Predictive Control of Bidirectional AC-DC Converter for Energy Storage System

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Abstract – Energy storage system has been widely applied in power distribution sectors as well as in renewable energy sources to ensure uninterruptible power supply. This paper presents a model predictive algorithm to control a bidirectional AC-DC converter, which is used in an energy storage system for power transferring between the three-phase AC voltage supply and energy storage devices. This model predictive control (MPC) algorithm utilizes the discrete behavior of the converter and predicts the future variables of the system by defining cost functions for all possible switching states. Subsequently, the switching state that corresponds to the minimum cost function is selected for the next sampling period for firing the switches of the AC-DC converter. The proposed model predictive control scheme of the AC-DC converter allows bidirectional power flow with instantaneous mode change capability and fast dynamic response. The performance of the MPC controlled bidirectional AC-DC converter is simulated with MATLAB/Simulink® and further verified with 3.0kW experimental prototypes. Both the simulation and experimental results show that, the AC-DC converter is operated with unity power factor, acceptable THD (3.3% during rectifier mode and 3.5% during inverter mode) level of AC current and very low DC voltage ripple. Moreover, an efficiency comparison is performed between the proposed MPC and conventional VOC-based PWM controller of the bidirectional AC-DC converter which ensures the effectiveness of MPC controller.

Keywords: Model predictive control (MPC), Bidirectional AC-DC converter, Unity power factor, Reactive power, Energy storage system

1. Introduction

Renewable energy sources are playing an indispensable role to satisfying the future energy demand. The power provided by renewable energy sources is interruptible and unpredictable because these energy sources depend on the weather conditions [1]. Hence, an energy storage system is necessary to use in renewable energy sources to provide a reliable power supply and make it dispatch-able on demand [2-4].

Fig. 1 shows an energy storage system which composes of a Li-ion battery bank, a bidirectional isolated DC-DC converter and a three-phase bidirectional AC-DC converter [5]. The three-phase bidirectional AC-DC converter is an essential part of the energy storage system due to its bidirectional-power-flow and synchronization capabilities [6]. This bidirectional AC-DC converter should to be highly efficient as it needs to prevent the problems of poor power quality such as high total harmonic distortion (THD), low power factor, ac voltage distortion, ripple in DC current and DC voltage pulsations [7-9]. Therefore, several topologies and control methods have been investigated to improve the efficiency and performance of this bidirectional AC-DC converter. The classical control of AC-DC converter is generally based on voltage-oriented control (VOC) scheme, which decomposes the active and reactive power in stationary α-β coordinate and synchronize the powers with rotating d-q reference frames by characterizing the current control loops using PI controllers [10]. Moreover, a virtual-flux-oriented control has been proposed in [11], which also uses the PI controllers. The major limitation of these control schemes is tuning the PI controllers which further affect the coordinate transform accuracy. Furthermore, direct power control (DPC) scheme [12, 13] has been applied for grid-tied AC-DC converter based on direct torque control (DTC) [14, 15] principle, which also uses the PI controllers.

In order to improve the performance of the converter, look-up table (LUT) based direct power control (DPC) scheme has been proposed in [16] and [17], in which the switching action of the converter is done with predefined switching state table on the basis of active and reactive power characteristics. This look-up table based DPC method has variable switching problem, which produces undesirable harmonic spectrums. To overcome this variable

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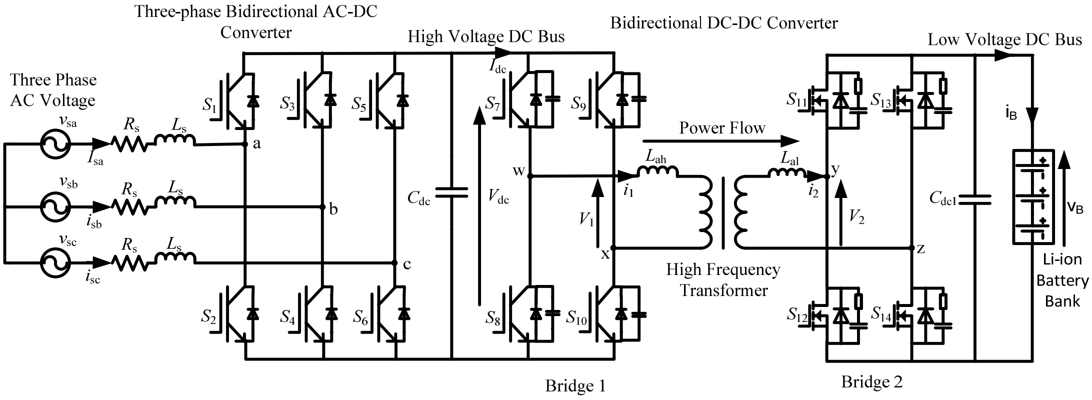

Fig. 1. An energy storage system [5]

switching, a fuzzy-logic based switching state selection criteria has been presented in [18] by avoiding predefined switching table. Although the active and reactive power are smoothed in fuzzy-logic based DPC algorithm compared with classical DPC, but its sampling frequency is little bit high. Therefore, a sliding mode nonlinear control approach has been investigated in [19] for active and reactive power regulation of grid connected DC-AC converter, which is very much dependent on variables.

The principle feature of the model predictive control (MPC) scheme is to predict the future behavior of the control variables. This MPC algorithm has become an attractive mode of control technique for bidirectional AC-DC converter comparing with all the classical solutions due to its simple and intuitive concept with fast dynamic responses [20-22]. Moreover, MPC algorithm is very easy to configure with constraints and non-linearity and also for practical implementation. The fast and powerful microprocessors are available today to implement the predictive control algorithm very easily as it requires higher number of calculations compared with all the classical controls [6, 20]. Till to date, this algorithm is proposed for an active front-end rectifier [23-25], indirect matrix converter [26-28] and voltage source inverter [22]. Although model predictive algorithm is an attractive alternative for controlling the power converters, it has been used very limitedly to control power flow of a bidirectional AC-DC converter.

This paper proposes a model predictive control (MPC) algorithm that is applied in a bidirectional AC-DC converter for energy storage system. The system configuration and working principle of the bidirectional AC-DC converter are elaborately described in section 2. The formulation of MPC method with discrete time model, the cost function used for selection of switching states and a detailed explanation of control scheme and algorithm are in section 3. The performance of the proposed MPC method for bidirectional AC-DC converter is tested with MATLAB/Simulink and the simulation results are presented in section 4. The simulation results are further verified with a 3.0 kW experimental configuration, which are discussed in section 5. Section 6 describes the efficiency comparison between the proposed MPC and conventional VOC-based PWM controller of the bidirectional AC-DC converter. Finally section 7 draws the conclusion of the proposed MPC controlled bidirectional AC-DC converter for energy storage system.

2. Bidirectional AC-DC Converter Topology

2.1 System configuration

Fig. 2 shows the three-phase bidirectional AC-DC converter topology which transfers power between the three-phase AC voltage supply and the DC voltage bus. The bidirectional AC-DC converter consists of six IGBT-Diode switches (S_1-S_6), which is connected with three-phase AC voltage supply through series filter inductance (L_s) and resistance (R_s). A DC capacitor (C_{dc}) is connected across DC voltage bus to keep the voltage (V_{dc}) constant. The bidirectional AC-DC converter operates in two modes. The first mode is rectifier mode, in which the bidirectional AC-DC converter operates as a front end rectifier and allows power transfer from the three-phase AC voltage end to the DC voltage bus. The second mode is inverter mode, where the power flows from DC voltage bus to three-phase AC voltage end and the converter acts as a voltage source inverter.

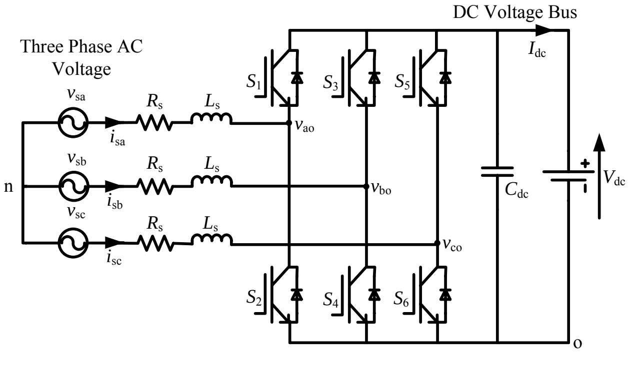

Fig. 2. Three-phase bidirectional AC-DC converter topology

2.2 Working principle

Model predictive control (MPC) algorithm is applied to control the power flow of the three-phase bidirectional AC-DC converter. The working principle of MPC scheme is based on a finite number of possible switching states, which utilizes the discrete behavior of a static power converter. In the case of three-phase bidirectional AC-DC converter, MPC algorithm utilizes the discrete nature of filter inductances (L_s) to control the power flow by appropriate switching action. In order to select the appropriate switching state to be applied for firing the converter switch, a selection criterion must be defined with a cost function which measures the error between references and predicted values. Then, the state that minimizes the cost function is selected for the next sampling interval.

In order to avoid short circuit, the two switches in each leg of the bidirectional AC-DC converter should be operated in a complementary mode. Hence, the gating signals S_a, S_b and S_c determine the switching states of the three-phase bidirectional AC-DC converter as follows:

$$S_a = \begin{cases} 1, & S_1 \text{ is on and } S_2 \text{ is off} \\ 0, & S_1 \text{ is off and } S_2 \text{ is on} \end{cases} \tag{1}$$

$$S_b = \begin{cases} 1, & S_3 \text{ is on and } S_4 \text{ is off} \\ 0, & S_3 \text{ is off and } S_4 \text{ is on} \end{cases} \tag{2}$$

$$S_c = \begin{cases} 1, & S_5 \text{ is on and } S_6 \text{ is off} \\ 0, & S_5 \text{ is off and } S_6 \text{ is on} \end{cases} \tag{3}$$

Therefore, the switching function vector ($\vec{S}$) of the bidirectional AC-DC converter can be expressed as,

$$\vec{S} = \frac{2}{3}(S_a + \vec{\omega} S_b + \overrightarrow{\omega^2} S_c) \tag{4}$$

where, $\vec{\omega} = e^{j2\pi/3}$, is the unity vector.

The output voltage space vector ($\vec{v}_{\text{conv}}$) of the AC-DC converter for both the rectifier and inverter mode can be presented with phase to neutral voltages (v_{ao}, v_{bo} and v_{co}) as,

$$\vec{v}_{\text{conv}} = \frac{2}{3}(v_{ao} + \vec{\omega} v_{bo} + \overrightarrow{\omega^2} v_{co}) \,. \tag{5}$$

This output voltage space vector ($\vec{v}_{\text{conv}}$) can also be related to the DC bus voltage (V_{dc}) and the switching function vector ($\vec{S}$) as,

$$\vec{v}_{\text{conv}} = \vec{S} \times V_{dc} \,. \tag{6}$$

There are eight possible voltage vectors can be obtained from the eight consequence switching states of the switching signals S_a, S_b and S_c. These eight voltage space vectors are listed in Table 1.

Table 1. Voltage space vectors of the bidirectional AC-DC converter

Switching states			Voltage space vector
S_a	S_b	S_c	$\vec{v}_{\text{conv}}$
0	0	0	$\vec{v}_1 = 0$
0	0	1	$\vec{v}_2 = -(1/3)V_{dc} - j(\sqrt{3}/3)V_{dc}$
0	1	0	$\vec{v}_3 = -(1/3)V_{dc} + j(\sqrt{3}/3)V_{dc}$
0	1	1	$\vec{v}_4 = -(2/3)V_{dc}$
1	0	0	$\vec{v}_5 = (2/3)V_{dc}$
1	0	1	$\vec{v}_6 = (1/3)V_{dc} - j(\sqrt{3}/3)V_{dc}$
1	1	0	$\vec{v}_7 = (1/3)V_{dc} + j(\sqrt{3}/3)V_{dc}$
1	1	1	$\vec{v}_8 = 0$

The energy storage system allows bidirectional power transfer between three-phase AC voltage side and energy storage device through the bidirectional AC-DC converter. Hence, the bidirectional AC-DC converter needs to be operated in two modes, which are specified as rectifier mode and inverter mode. The operating principle of the bidirectional AC-DC converter for both the rectifier and inverter modes are elaborately described in the following subsection.

2.2.1 Rectifier and inverter modes of operation

During the rectifier mode of operation, the bidirectional AC-DC converter acts as a front end rectifier that is connected to the three-phase AC voltage source through the input filter inductance L_s and resistance R_s as shown in Fig. 2. By applying Kirchhoff's voltage law at the ac side of the rectifier, the relationship between the three-phase AC voltage and rectifier input voltage vectors are,

$$\begin{aligned} \vec{v}_s = L_s \frac{d\vec{i}_s}{dt} + R_s \vec{i}_s + \frac{2}{3}\left(v_{ao} + \vec{\omega} v_{bo} + \vec{\omega}^2 v_{co} \right) \\ - \frac{2}{3}\left(v_{no} + \vec{\omega} v_{no} + \vec{\omega}^2 v_{no} \right). \end{aligned} \tag{7}$$

The space-vector model of three-phase AC voltage $\vec{v}_s$ and current $\vec{i}_s$ can be derived from phase voltage and current as,

$$\vec{v}_s = \frac{2}{3}(v_{sa} + \vec{\omega} v_{sb} + \vec{\omega}^2 v_{sc}) \tag{8}$$

and

$$\vec{i}_s = \frac{2}{3}(i_{sa} + \vec{\omega} i_{sb} + \vec{\omega}^2 i_{sc}) \,, \tag{9}$$

where v_{sa}, v_{sb}, and v_{sc} are phase voltages; i_{sa}, i_{sb}, and i_{sc} are phase currents of three-phase AC voltage source during the rectifier mode.

The input current dynamics of the bidirectional AC-DC converter during rectifier mode operation can be evaluated from (5) and (7) as,

$$\frac{d\vec{i}_{\mathrm{S}}}{dt}=\frac{1}{L_{\mathrm{S}}}\left(\vec{v}_{\mathrm{S}}-\vec{v}_{\mathrm{conv}}-R_{\mathrm{S}}\vec{i}_{\mathrm{S}}\right) \tag{10}$$

The bidirectional AC-DC converter works as a voltage source inverter during the inverter mode, which allows the power transfer from the DC voltage bus to the three-phase AC voltage end. Therefore, the load current dynamics of the converter remains same as in (10). However, it is 180$^{\mathrm{o}}$ out-of-phase with respect to the load voltage.

3. MPC Formulation

The formulation of model predictive control (MPC) algorithm for three-phase bidirectional AC-DC converter is described in the following section. The MPC controller is formulated in discrete time domain. Therefore, it is necessary to transform the dynamic system of bidirectional AC-DC converter for both rectifier and inverter mode of operation represented in (10) into discrete time model at a specific sampling time T_{s}.

3.1 Discrete time model for prediction horizon

A discrete time model is used to predict the future values of currents and voltages in the next sampling interval (k+1), from the measured currents and voltages at the k^{th} sampling instant. The system model derivative dx/dt from Euler approximation can be expressed as:

$$\frac{dx}{dt}\approx\frac{x(k+1)-x(k)}{T_{\mathrm{S}}} \tag{11}$$

Using the above approximation, the discrete time model of predictive currents and voltages for the next (k+1) sampling instant of the bidirectional AC-DC converter in rectifier and inverter mode can be derived.

The discrete time model of predictive input currents at the next sampling instant (k+1) for the rectifier and inverter mode of the bidirectional AC-DC converter can be evaluated from (10) with the help of Euler approximation as,

$$\vec{i}_{\mathrm{S}}(k+1)=\left(1-\frac{R_{\mathrm{S}}T_{\mathrm{S}}}{L_{\mathrm{S}}}\right)\vec{i}_{\mathrm{S}}(k)+\frac{T_{\mathrm{S}}}{L_{\mathrm{S}}}\left\{\vec{v}_{\mathrm{S}}(k)-\vec{v}_{\mathrm{conv}}(k)\right\}. \tag{12}$$

3.2 Cost function

The main objective of model predictive control algorithm is to minimize the error with fast dynamic response between the predicted and reference values of the discrete variables. To achieve this objective, an appropriate cost function (e) is defined with a measurement of predicted input error. Hence, the cost function for the rectifier and inverter can be expressed with the absolute error between the predictive and reference values of input and load current for both the rectifier and inverter mode of operation as,

$$\vec{e}=\left|\vec{i}_{\mathrm{ref}}(k+1)-\vec{i}_{\mathrm{p}}(k+1)\right| \tag{13}$$

where, e is the cost function. The reference input and predicted current are $\vec{i}_{\mathrm{ref\_rec}}(k+1)$ and $\vec{i}_{\mathrm{p\_rec}}(k+1)$, and $\vec{i}_{\mathrm{ref\_inv}}(k+1)$ and $\vec{i}_{\mathrm{p\_inv}}(k+1)$ for the rectifier and inverter modes, respectively.

3.3 Control scheme

Fig. 3 shows the proposed control strategy of model predictive control (MPC) algorithm. At first, the operating mode of the bidirectional AC-DC converter is selected depending on charging state of the energy storage device, which is determined by the DC bus voltage V_{dc}. If the charging state (determined by DC voltage) is less than threshold level, then it is operated in rectifier mode, otherwise it is operated in inverter mode.

During the rectifier mode of operation, three-phase input AC current $\vec{i}_{s}(k)$ is measured and the future value of this current $\vec{i}_{s}(k+1)$ is predicted by using the discrete time Eq. (12) for each one of eight possible switching vector ($\vec{S}$) of

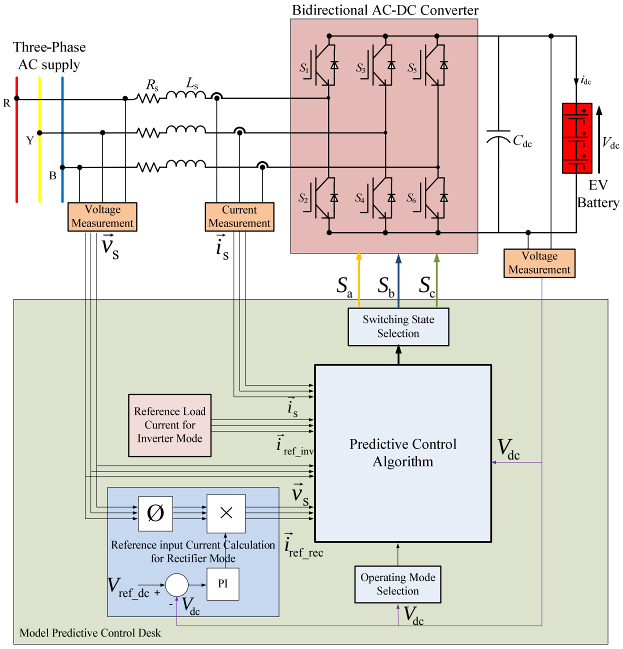

Fig. 3. Proposed MPC control scheme

the converter. This future value of three-phase input AC current $\vec{i}_s(k+1)$ is compared with the reference current $\vec{i}_{\mathrm{ref\_rec}}(k+1)$ of the rectifier mode by utilizing the cost function (*e*) of Eq. (13). The reference current $\vec{i}_{\mathrm{ref\_rec}}(k+1)$ of the converter in rectifier mode is calculated from the three-phase input AC voltage vector ($\vec{v}_s$) and DC bus voltage (V_{dc}) by using PI controller. Finally, the switching states of the bidirectional AC-DC converter which minimizes cost function, is selected for next sampling time.

Similarly, in inverter mode of operation, the future value of the three-phase AC load current ($-\vec{i}_s(k+1)$) is predicted by using the discrete time Eq. (12). Hence, the optimizing switching states are selected for firing the switches by using cost function (13).

3.4 Control algorithm

Fig. 4 presents the control algorithm of MPC method for the three-phase bidirectional AC-DC converter. The whole predictive control process completes the following steps for selecting the optimized switching state of the converter in the next sampling interval (k+1).

- The control algorithm starts with measuring and sampling the three-phase AC current $\vec{i}_s(k)$ for the k^{th} sampling period.
- After sampling this three-phase AC current, the future value of this current $\vec{i}_s(k+1)$ is predicted by using the discrete time equation of the converter in next $(k+1)^{\mathrm{th}}$ sampling period.
- Then the reference currents for the rectifier mode ($\vec{i}_{\mathrm{ref\_rec}}$) and inverter mode ($\vec{i}_{\mathrm{ref\_inv}}$) are calculated and set to correspond with the amount of desired power flow.
- Therefore, the cost function (*e*) of the three-phase bidirectional AC-DC converter is calculated with the predicted and reference values of grid current.
- Finally, the switching state associated with the minimum cost function is finally selected for firing the converter in the next sampling time period (k+1).

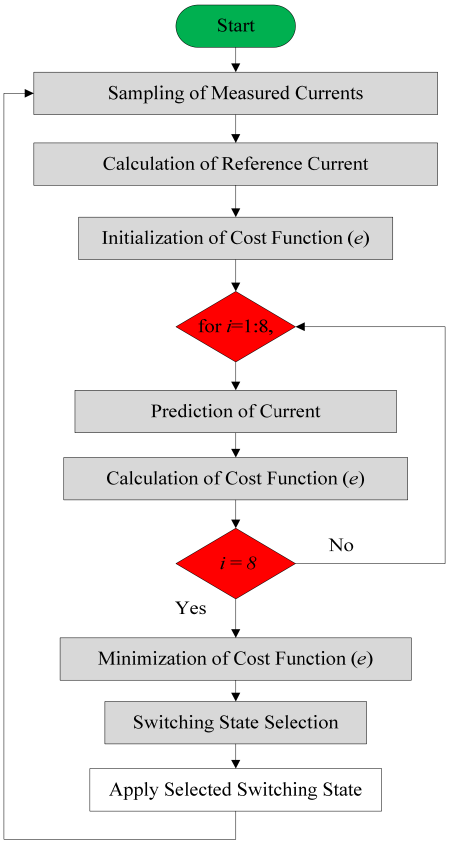

Fig. 4. Proposed MPC control algorithm

4. Simulation Results

The proposed MPC algorithm is carried out by using MATLAB/Simulink to validate the feasibility of the control method. To verify the proposed control method of bidirectional AC-DC converter for energy storage system, both the rectifier and inverter mode of operations have been investigated for power transfer between three-phase AC voltage side and DC voltage bus. The parameters shown in Table 2 are used in the simulation of the rectifier and inverter modes with the sampling time of 50 µs.

Fig. 5 shows the three-phase AC (phase-neutral) voltage and current of the bidirectional AC-DC converter in both the rectifier and inverter modes with instant mode changing capability. During the rectifier mode, the converter is operated as a front end rectifier. Therefore, the reference current is fixed with PI controller to transfer power from three-phase AC voltage source to DC bus by controlling the input current, in which the output DC voltage is fixed at 270 V. Results in Fig. 5(a) show that, the AC phase voltage and current are exactly in phase, which ensure the unity power factor. Again in inverter mode, the bidirectional AC-DC converter allows power transfer from DC voltage bus to AC voltage end by keeping the phase voltage and current in 180° phase shift. Therefore, the unity power factor is also maintained very accurately during this operating mode.

Fig. 5(b) shows the phase-to-phase AC voltage generated by the converter. On the other hand, the three-

Table 2. Simulation and experimental parameters

Parameters values and unit		
Variables and Parameters	*Values*	*Unit*
Power Rating (P)	3.0	kW
Three-phase Grid Voltage (v_g)	110	V (rms)
Grid Frequency (f_s)	50	Hz
DC bus Voltage (V_{dc})	270	V
Input Filter Inductance (L_s)	5	mH
Input Filter resistance (R_s)	0.1	Ω
Sampling Time (T_s)	50	µs
Load resistance (R_{Load})	50	Ω
DC link Capacitor (C_{dc})	1000	µF

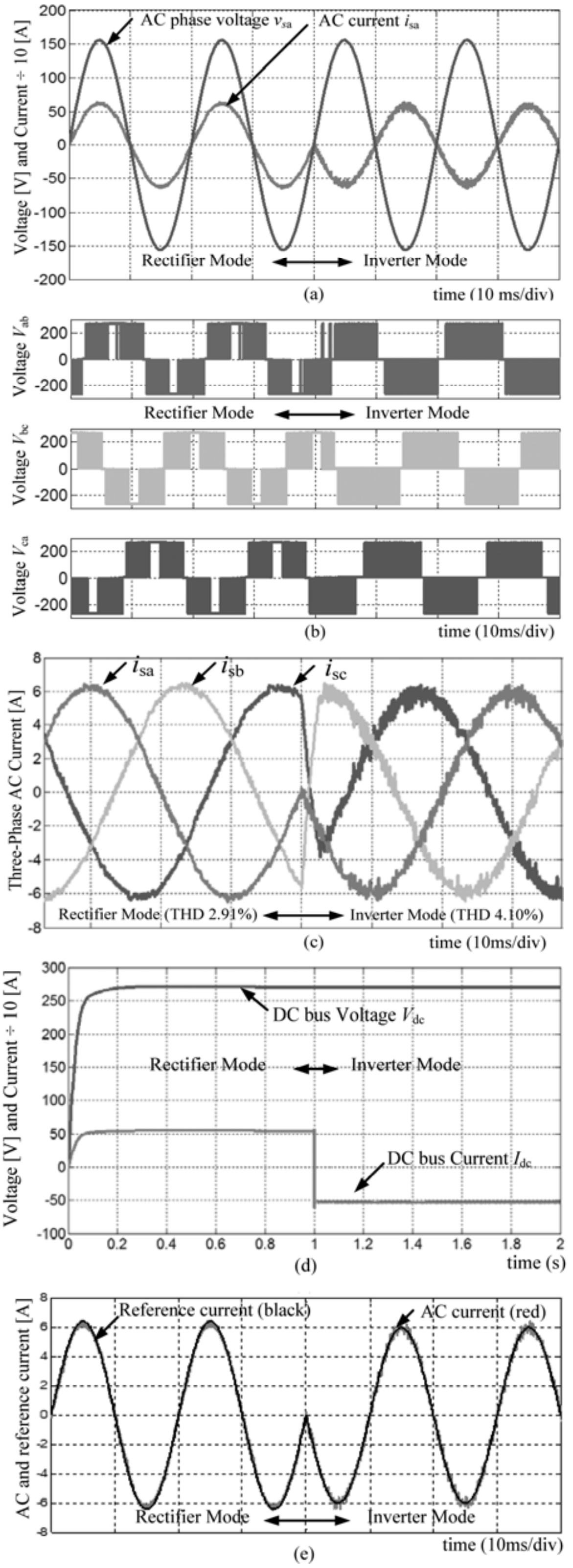

Fig. 5. Simulation results of the bidirectional AC-DC converter for both rectifier and inverter mode: (a) AC phase voltage and current; (b) phase to phase AC voltage generated by the converter; (c) three-phase AC current; (d) DC bus voltage and current and (e) AC current tracking with reference.

phase AC current drawn by the converter in rectifier mode and injected by the converter in inverter mode, is presented in Fig. 5(c). During the rectifier mode, the current drawn by the converter is controlled using PI controller at a value of 6 A (peak) for each phase current. Fig. 5(c) shows that, each phase AC current is accurately tracking the reference value, which verifies the feasibility of the model predictive control method. In inverter mode, the reference current is also fixed at a value of 6 A (peak) per phase. Therefore, the output current corroborates the accuracy of the proposed control method by accurately tracking the reference current. Furthermore, the MPC algorithm effectively reduces the THD of AC current by accurately tracking the sinusoidal reference current, which is presented in Fig. 5(e).

The DC bus voltage and current are depicted in Fig. 5(d). The DC voltage pulsations are very low in both the operating modes. The instantaneous operating-mode changing capability is one of the most attractive advantages of the converter with model predictive control method. The positive value (5.10 A) of DC current means that, the bidirectional AC-DC converter is working in rectifier mode and the power is transferring from three-phase AC source to energy storage device. On the other hand, the DC current goes to negative value (–5.05 A) during the inverter mode of operation.

5. Experimental Verifications

A 3.0 kW scaled down laboratory prototype of the bidirectional AC-DC converter that has been developed for the energy storage system. The experimental setup is presented in Fig. 6. The same parameters as in Table 2 are employed. During the experimentation, a three-phase portable power supply [KOSIJAYA, MODEL: KA19530] was used for voltage supply and STMICROELECTRONICS - STGW20NC60VD – IGBT, 600V, 20A was used as power devices. Moreover, inductor [SMP, MODEL: 9936.1, S:0004] was used as filter inductor and resistor [TERCO, MODEL: MV1100] was used as a resistive load.

The experimental verification of the proposed model

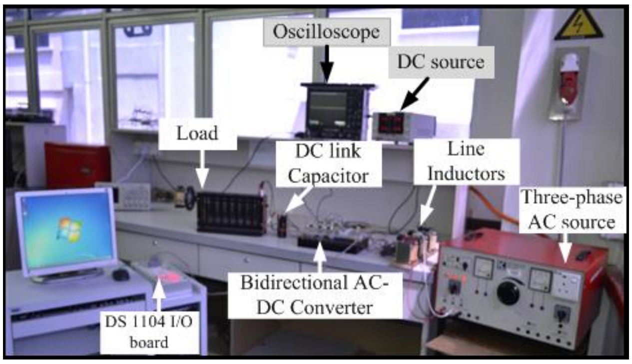

Fig. 6. Experimental system of the bidirectional AC-DC converter with model predictive control

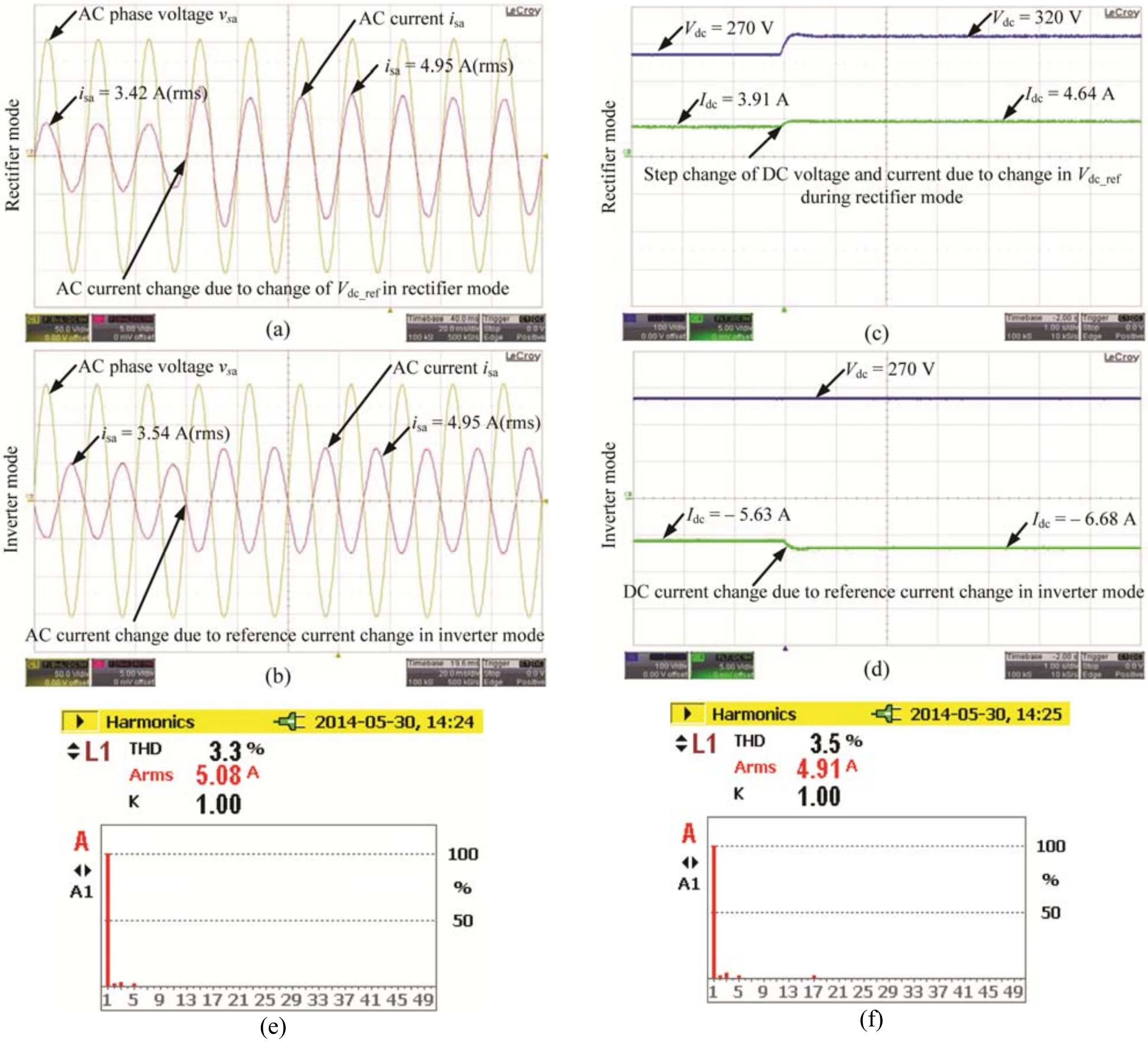

Fig. 7. Experimental results: (a) AC phase voltage and current at rectifier mode; (b) AC phase voltage and current at inverter mode; (c) DC bus voltage and current at rectifier mode; (d) DC bus voltage and current at inverter mode; (e) THD of AC current at rectifier mode, and (f) THD of AC current at inverter mode.

predictive controlled bidirectional AC-DC converter is carried out by using the rapid prototyping and real-time interface system dSPACE with DS1104 control card which consist of Texas Instruments TMS320F240 sub-processor and the Power PC 603e/250 MHz main processor. This dSPACE control desk works together with Mathwork MATLAB/Simulink R2011b real-time workshop and real-time interface (RTI) control cards to implement the proposed MPC algorithm.

The voltage is measured with differential probe [PINTEK DP-25] and the current with current transducer [LEM LA 25-NP]. Fig. 7(a) shows that the three-phase AC phase voltage and current are exactly in phase during the rectifier operation mode, which ensures the unity power factor. Again in the inverter mode, the converter allows power transfer with unity power factor from the DC voltage bus to AC voltage end by keeping the phase voltage and current with an 180^o phase shift, as presented in Fig. 7(b).

The DC bus voltage and current for both operating modes are depicted in Figs. 7(c) and 7(d). The results illustrate that the DC voltage ripple and the pulsation in DC current are very low during both operating modes.

During rectifier mode, the DC-link reference voltage (V_{dc}) is varied from 270 V to 320 V to check the stability and transient responsiveness of the MPC control algorithm. Figs. 7(a) and 7(c) show the experimental results of AC phase current, DC bus voltage and current that have been changed and reached its steady state level within very short time (less than 20 ms). This rapid step change confirms the fast response of the PMC method. Fig. 7(c) also shows that the steady state output of DC-link voltage and current remain linear in wide range of time with very low voltage and current ripple, which ensure the stability and good performance of the proposed MPC algorithm. Similarly, the stability and responsiveness of the proposed MPC method for AC-DC converter have been tested with Figs. 7(b) and 7(d) by varying the AC reference current (i_{ref_inv}), during the inverter mode of operation.

Finally, the harmonic analysis of three-phase AC current for both rectifier and inverter mode is illustrated in Figs. 7(e) and 7(f), which show that the total harmonic distortion (THD) is 3.3% and 3.5% in the rectifier and inverter modes, respectively. The THD of grid current is measured with FLUKE 1735 Power Logger. The accuracy of this power logger is ±0.2% of its full scale.

6. Efficiency Comparison

The efficiency of MPC controlled bidirectional AC-DC converter is measured with FLUKE 1735 Power Logger. The accuracy of this power logger is ±0.2% of its full scale. The efficiencies of AC-DC converter are measured in MPC method against the power transfer ranges from 0.5 kW to 3.0 kW. In order to confirm the effectiveness of MPC algorithm, the efficiencies of MPC controlled bidirectional AC-DC converter are compared with conventional VOC-based PWM controlled bidirectional AC-DC converter for both the rectifier and inverter mode of operation, presented in Fig. 8 and Fig. 9. The VOC-based PWM method is applied in the 3.0 kW bidirectional AC-DC converter topology with employing the same parameters and measurement techniques as in MPC algorithm. Although, MPC algorithm has variable switching frequency problem, the efficiencies associated with the MPC control are higher compared to the VOC-based PWM control method due to the elimination of reactive power, minimized DC voltage ripple and low THD level. Fig. 8 shows the efficiency comparison of the converter in rectifier mode. The maximum efficiency is 96.8% using the MPC method and it is 95.6% using the VOC-based PWM method, at the power transfer of 2 kW. On the other hand, Fig. 9 describes the efficiency comparison of proposed MPC controlled AC-DC converter with the conventional VOC-based PWM controlled converter during the inverter mode. The maximum efficiency associated with the MPC control algorithm is 96%, while the highest efficiency associated with VOC-based PWM controller is 95% during the inverter mode of operation at 2.0 kW. It can be seen that the efficiencies of the bidirectional AC-DC converter decrease with the increase of the power transfer. The flow of current increases with the power transfer which results the increase of conduction and switching loss. But, still the MPC algorithm shows the better efficiency than the VOC-based PWM control method for the whole ranges of power transfer.

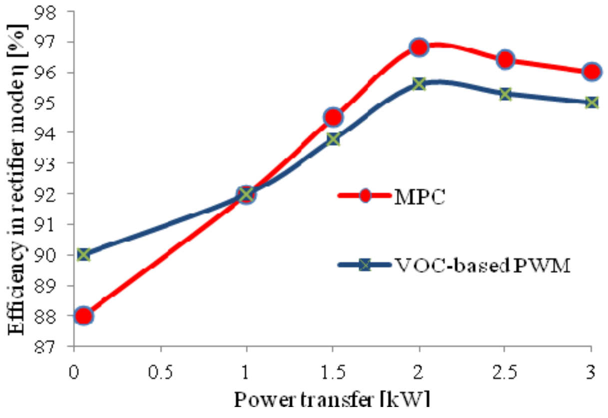

Fig. 8. Efficiency comparison between MPC and VOC-based PWM control method during rectifier mode of operation.

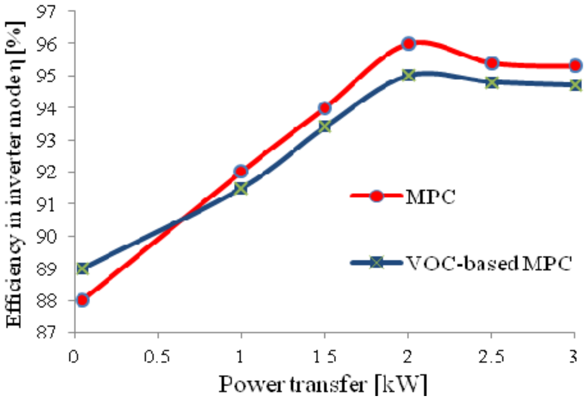

Fig. 9. Efficiency comparison between MPC and VOC-based PWM control method during inverter mode of operation.

7. Conclusion

In this paper, a model predictive controlled bidirectional AC-DC converter is presented for energy storage system to transfer power between three-phase AC voltage source and DC voltage bus. MPC is a powerful control algorithm in the field of bidirectional AC-DC power converters which provides bidirectional power flow with instantaneous mode changing capability and fast dynamic response. The most important outcomes of this investigation are as follows:

- The three-phase bidirectional AC-DC converter is operated with unity power factor in both the rectifier and inverter modes of operation.
- The total harmonic distortions (THD) are 3.3% and 3.5% during the rectifier and inverter operating modes, respectively, which are within the accepted limit.
- The DC voltage and current ripples are very low during both operating mode.
- Higher efficiency achieved compared to the VOC PWM method.

The results associated in this investigation are very much encouraging and will continue to play a strategic role in the improvement of modern high performance bidirectional AC-DC converter in energy storage system and will open a new prospect in the power electronics research.

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