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Design and experimental verification of a dead beat power control strategy for low cost three phase PWM converters

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ABSTRACT

As a cost-effective and reliable alternative to standard three phase PWM converters, the low cost converters have attracted great attentions today. While the research trends mainly focused on using these converters for AC motor drives, some successful efforts in grid connected applications are also reported. These works use the voltage oriented technique to regulate the active and reactive power exchanges with the electric grid. This paper presents a dead beat direct power control strategy for grid integration of low cost three phase PWM converters. While keeping the advantages of fast and accurate power control associated to the VOC technique, the proposed strategy offers a considerably simpler algorithm. Extensive simulation and experimental results are provided which confirm the validity of the proposed technique.

1. Introduction

A standard three phase voltage source converter utilizes three legs, with a pair of complementary power switches per phase [1–3]. A low cost converter uses only two legs, with four switches, as shown in Fig. 1. Several articles report on this structure [4–25]. This topology is also widely employed in industrial applications. The circuit of Fig. 1 has two converter legs and the third phase is connected to the middle point of the DC link capacitor bank.

Compared to the standard converter, the low cost converter has a lot of advantages such as [4–25]; the number of power semiconductor switches and the fly-wheel diodes are reduced, resulting in cost and space savings. Besides, associated control and drive circuits are also eliminated, which itself brings more savings. On the other hand, due to a reduced number of switches, the conduction and switching losses in the semiconductor devices will also be decreased. Also, eliminating some semiconductor devices from the topology brings more reliability. Last but not least, DC link voltage is as twice as compared to a standard converter; although it is an advantage in rectifying operation, this may not be desired in some inverter applications. This topology also has some drawbacks; the third phase current flows through the DC link capacitors. So they are exposed to low frequency harmonics which calls for bigger DC link capacitors. Besides, the low cost converter does not eliminate the third-order harmonics automatically, so higher switching frequencies are expected.

During the two last decades, many works regarding the design and adaption of low cost converters in AC motor drives [11–17] are reported. In such an application, the converter acts as a controlled voltage source, where usually a SPWM or SVM modulation technique is utilized to generate sinusoidal voltages and currents for the motor or local load. A detailed analysis and performance comparison of these modulation strategies for the low cost four switch converters can be found in [4,18,19]. Some other works successfully employed this converter in the grid connected applications as an inverter for grid integration of distributed generation systems [20–22], and as a PWM voltage source rectifier to achieve the controlled power factor while allowing bidirectional power flow at the source side [23–25]. In the grid connected applications, PWM converters act as a controlled current source, where, as standard converters, the low cost converters also require sophisticated control of active and reactive power flows between the DC energy storage capacitors and the electric grid. The voltage oriented control (VOC), as a well-known indirect control method of active and reactive powers of standard converters, is also utilized for the grid connection of low cost converters [20–25]. In VOC, by decomposing the AC currents into active and reactive components, a decoupled power control is achieved, and at the same time a fast transient response and high static performance is ensured. With all its advantages, VOC mainly suffers from a complex structure including two PI controllers, a decoupling network, and reference frame transformations, and the performance is dependent on the applied current control strategy and the connected electric grid conditions.

This paper focuses on the control of active and reactive power flows of a low cost three phase voltage-source converter in grid

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connected mode of operation. The proposed technique is based on the dead beat direct power control strategy. In discrete-time control theory, the dead beat control is famous for its simplicity and fast dynamics performance. The main advantages that the proposed technique offers over the VOC method include: (1) very simpler algorithm, (2) no need for internal current controllers, therefore no control parameters to tune, and (3) better performance under non-ideal grid conditions. The effectiveness of the proposed method in providing fast and accurate control is confirmed through extensive simulations and experimental results.

2. Available control strategies

The control schemes commonly used for voltage source converters can be divided into direct and indirect control strategies. Although these control strategies can achieve the same main goals, such as accurate and fast power control and near-sinusoidal currents, their principles differ. The indirect control is characterized by a voltage modulator which computes the on/off times of converter switches along a switching period through the evaluation of the voltage reference. This reference is produced by the current controllers, which idealizes the converter as a continuous voltage source. On the other hand, the direct control technique is aimed to control the instantaneous active and reactive powers and establishes a direct relation between the behavior of the controlled variable and the state of the converter switches.

2.1. Voltage oriented control (VOC)

VOC as a well-known method of indirect active and reactive power control is based on the current vector orientation with respect to the line voltage vector, which guarantees high dynamics and static performance via internal current control loops. As it can be seen in Fig. 2, the scheme decouples the converter currents into active and reactive power components. Control of the active and reactive powers is then achieved by controlling the decoupled converter currents using current controllers. The PWM signals can be generated according to a sinusoidal pulse-width modulation (SPWM) or space vector modulation (SVM) strategy [8,26,27]. These well-known modulation techniques for the four-switch converter topology are comprehensively addressed by the authors in another work [4]. The VOC scheme, except for the PWM generation block, is exactly the same for both low cost and standard converter topologies. The virtual flux oriented control (VFOC), which is an adaption of VOC to a virtual flux reference frame is recently developed and seems to be less sensitive against line voltage variations [27]. VOC provides good transient behavior and PI current controller ensures zero steady state error. Besides its complex algorithm, one main drawback of the control strategy depicted in Fig. 2 is that the performance is highly dependent on the applied current control strategy and the connected AC network conditions. The implementation of the rotating reference frame controller allows an

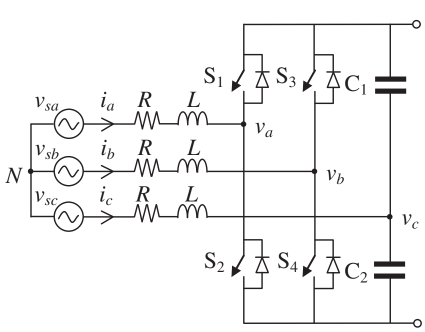

Fig. 1. Low cost three phase PWM converter.

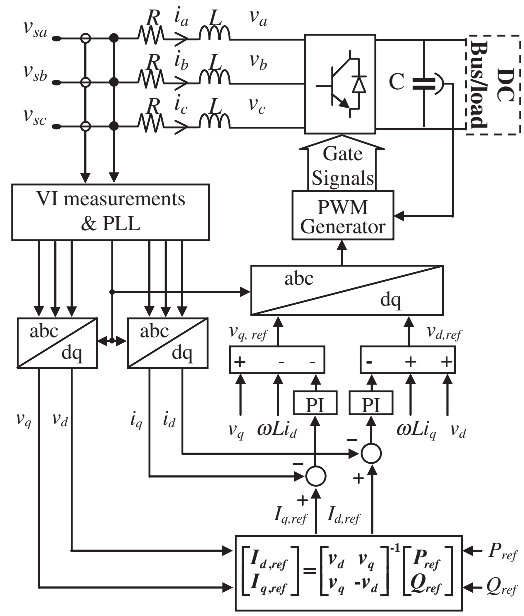

Fig. 2. VOC for three phase standard and low cost converters.

improved reference tracking capability of the PI regulator; however, this involves coordinate transformation and a decoupling feed-forward path between *d* and *q* components of reference currents [8,26,24].

2.2. Direct power control (DPC)

DPC is based on the instantaneous active and reactive power control. As it is shown in Fig. 3, in DPC, there are no internal current control loops and no PWM modulator block, because the converter switching states are appropriately selected by a look-up table based on the instantaneous errors between the commanded and measured values of the active and reactive powers. Compared to VOC, there is a simpler algorithm, no current control loops, no coordinate transformation and separate PWM voltage modulator, no need for decoupling between the control of the active and reactive components, and better dynamics performance. On the other hand, the variable switching frequency and some problems due to the high gain of the hysteresis controllers are the well-known disadvantages of the DPC scheme [27–32]. In the case of low cost converters, some essential requirements of DPC principle cannot be achieved. Mainly, due to unsymmetrical voltage vectors and reduced realizable switching states, as depicted in Fig. 4, it is impossible to develop an efficient switching table which is the heart of

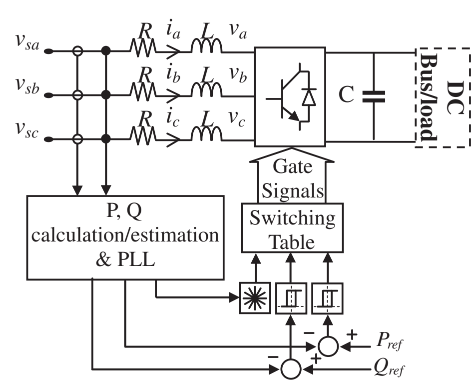

Fig. 3. DPC for three phase standard converters.

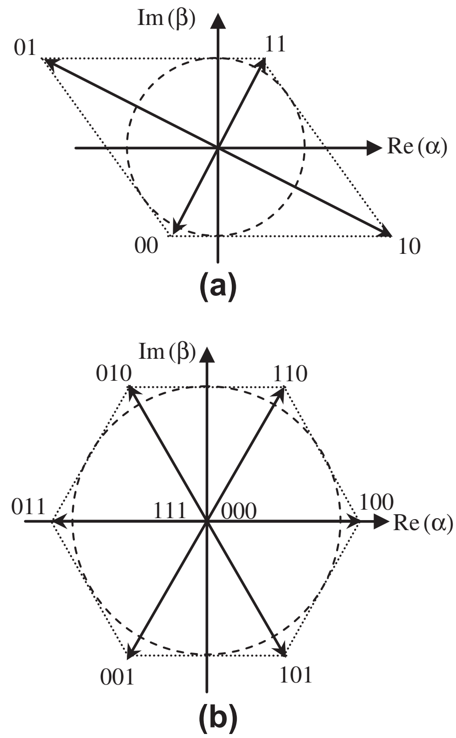

Fig. 4. Switching vectors for (a) low cost and (b) standard converter.

DPC scheme. So, the conventional switching table based DPC cannot be applied to the low cost converter topology.

3. Proposed dead beat control

This paper presents a new dead beat power control strategy for low cost three phase PWM converters. Fig. 5 shows the block diagram of the proposed method. In this technique, the required converter voltage in each sampling period is directly calculated based on reference and measured values of active and reactive powers, system parameters, and the measured voltage of the AC source, through simple mathematical operations. Then, a PWM generator synthesizes the reference voltage and generates the switching pulses for the voltage source converter. Compared to VOC, the proposed technique has a simple algorithm and current control loops are eliminated, also, there is no need for decoupling between the control of active and reactive components. These advantages are achieved for the standard converters by DPC technique. The proposed strategy for the low cost converter, besides having the conventional DPC method advantages, offers many unique features such as fixed switching frequency and no need for hysteresis controllers.

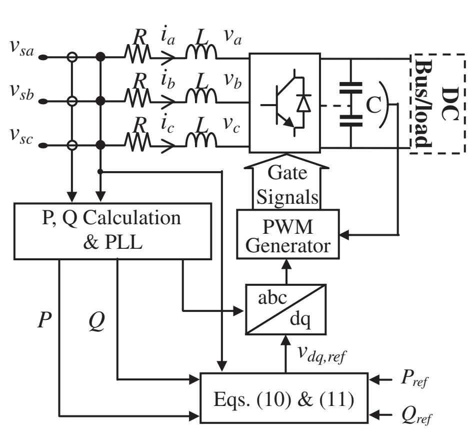

Fig. 5. Proposed dead beat control strategy.

Table 1
Parameters of the system under study.

Parameter	Value
Sampling frequency (kHz)	10
Switching frequency (kHz)	5
Inductance of reactors (mH)	10
DC Link capacitor (μF)	1000
Line to ground AC voltage (V rms)	50
AC Voltage frequency (Hz)	50

4. Controller equations

In discrete-time control theory, the dead beat control problem consists of finding what input signal must be applied to a system in order to bring the output to zero in the smallest number of time steps. For such an evaluation, an accurate discrete model of the system under study should be developed. So, we start with the Eq. (1) which describes the circuit of Fig. 1:

$$L\frac{d}{dt}\vec{i}_{abc} = -R\vec{i}_{abc} + \vec{v}_{sabc} - \vec{v}_{abc} \tag{1}$$

where v is the converter voltage, v_s is the AC source voltage, i is the line current, R, and L are equivalent resistance and inductance of the smoothing filter, respectively. In the synchronous reference frame, the Eq. (1) can be discretized in each small sampling period (T_{sp}) and decoupled to d and q components as shown by Eqs. (2) and (3), where the small volt-drop on the filter resistance is neglected.

$$i_d(k+1) = i_d(k) + T_{sp}\omega i_q(k) + \frac{T_{sp}}{L}(v_{sd}(k) - v_d(k)) \tag{2}$$

$$i_q(k+1) = i_q(k) - T_{sp}\omega i_d(k) + \frac{T_{sp}}{L}(v_{sq}(k) - v_q(k)) \tag{3}$$

On the other hand, the active and reactive powers in the rotating reference frame are:

$$P(k+1) = v_{sd}(k+1)i_d(k+1) + v_{sq}(k+1)i_q(k+1) \tag{4}$$

$$Q(k+1) = v_{sq}(k+1)i_d(k+1) - v_{sd}(k+1)i_q(k+1) \tag{5}$$

By substituting (2) and (3) in (4) and (5), and ignoring the AC source voltage variations during a sampling period, i.e. $v_{sd}(k+1) = v_{sd}(k)$ and $v_{sq}(k+1) = v_{sq}(k)$, we obtain:

$$\begin{aligned} P(k+1) = {} & i_d(k)v_{sd}(k) + i_q(k)v_{sq}(k) + T_{sp}(\omega i_q(k)v_{sd}(k) \\ & - \omega i_d(k)v_{sq}(k)) \\ & + \frac{T_{sp}}{L}\left(v_{sd}^2(k) - v_{sd}(k)v_d(k) + v_{sq}^2(k) - v_{sq}(k)v_q(k)\right) \end{aligned} \tag{6}$$

$$\begin{aligned} Q(k+1) = {} & i_d(k)v_{sq}(k) - i_q(k)v_{sd}(k) + T_{sp}(\omega i_q(k)v_{sq}(k) + \omega i_d(k)v_{sd}(k)) \\ & + \frac{T_{sp}}{L}(v_{sd}(k)v_{sq}(k) - v_{sq}(k)v_d(k) - v_{sd}(k)v_{sq}(k) \\ & + v_{sd}(k)v_q(k)) \end{aligned} \tag{7}$$

Assuming that by using a PLL, the control system will be synchronized with the AC source voltage, i.e. $v_{sq}(k) = 0$, the above equations for the instantaneous powers can be simplified as:

$$\begin{aligned} P(k+1) &= i_d(k)v_{sd}(k) + T_{sp}\omega i_q(k)v_{sd}(k) + \frac{T_{sp}}{L}\left(v_{sd}^2(k) - v_{sd}(k)v_d(k)\right) \\ &= P(k) - T_{sp}\omega Q(k) + \frac{T_{sp}}{L}\left(v_{sd}^2(k) - v_{sd}(k)v_d(k)\right) \end{aligned} \tag{8}$$

$$\begin{aligned} Q(k+1) &= -i_q(k)v_{sd}(k) + T_{sp}\omega i_d(k)v_{sd}(k) + \frac{T_{sp}}{L}(v_{sd}(k)v_q(k)) \\ &= Q(k) + T_{sp}\omega P(k) + \frac{T_{sp}}{L}v_{sd}(k)v_q(k) \end{aligned} \tag{9}$$

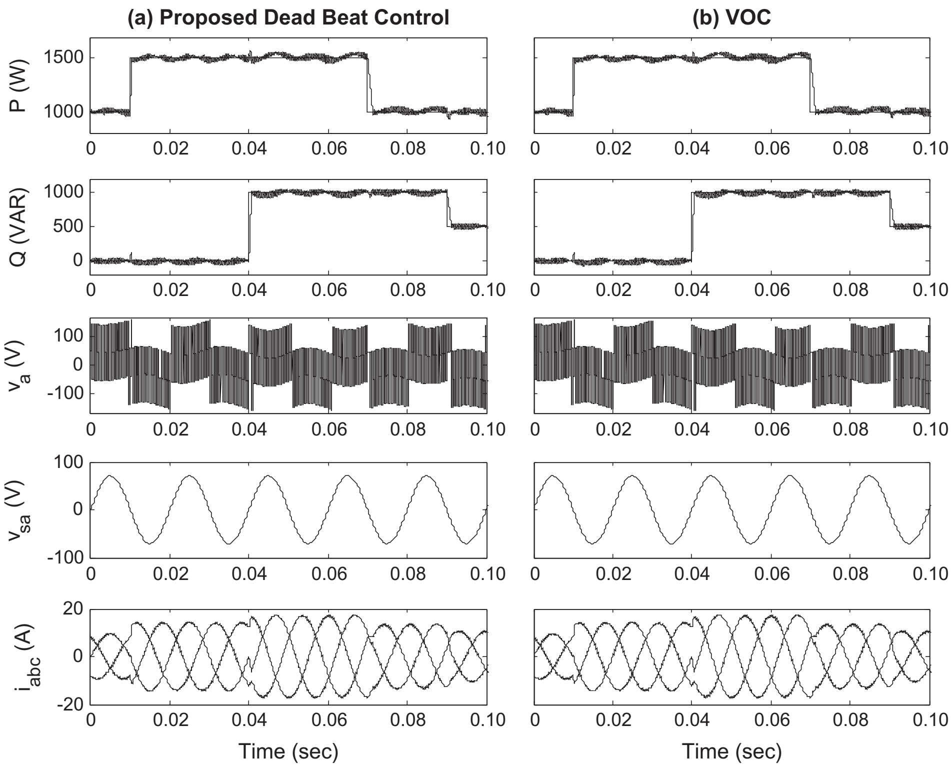

Fig. 6. Simulated waveforms; step changes of active and reactive power reference values.

Table 2
Comparison of dynamic performances.

Parameter	Proposed method	VOC
Active power rise time (ms)	0.4	0.45
Active power fall time (ms)	1.8	1.8
Reactive power rise time (ms)	0.6	0.6
Reactive power fall time (ms)	1.1	1.1

The target of the control is to make the load active and reactive powers at the sampling point ($k + 1$), equal to the reference active and reactive power values currently available at the sampling point (k), i.e. $P(k + 1) = P_{ref}(k)$ and $Q(k + 1) = Q_{ref}(k)$. These two control rules are substituted in (8) and (9). By rearranging the results we will have the following equations for $v_d(k)$ and $v_q(k)$:

$$v_d(k) = v_{sd}(k) + \frac{L}{T_{sp}}\left(\frac{P(k) - P_{ref}(k)}{v_{sd}(k)}\right) - L\omega\frac{Q(k)}{v_{sd}(k)} \tag{10}$$

$$v_q(k) = -\frac{L}{T_{sp}}\left(\frac{Q(k) - Q_{ref}(k)}{v_{sd}(k)}\right) - L\omega\frac{P(k)}{v_{sd}(k)} \tag{11}$$

The above equations are the d and q components of the converter voltage in the rotating reference frame which will satisfy the control criteria. The gating signals of the low cost PWM converter will then be produced according to these d and q voltage components using one of the well-known modulation techniques mentioned in [4] in order to achieve high efficiency and good harmonics performance.

Regarding the structures demonstrated in Figs. 2 and 5, one of the greatest advantages of the proposed control technique (Fig. 5) when compared with the VOC (Fig. 2), is its simplicity. As one can see, the two PI controllers and the decoupling network are eliminated and the control action just includes evaluating two simple algebraic equations in each sampling period.

Table 3
THD (%) as a function of inductance mismatch, 5th harmonic, and imbalance (P_{ref} = 1000 W, Q_{ref} = 0).

Effect	Proposed method	VOC
Ideal conditions	2.03	2.04
Inductance mismatch (ΔL = +50%)	2.05	2.04
Inductance mismatch (ΔL = −50%)	1.99	2.02
5th Harmonic distorted (3%)	3.55	3.57
5th Harmonic distorted (5%)	5.31	5.33
Imbalanced (3%)	3.59	3.61
Imbalanced (5%)	5.35	5.37

The operation of model-based controller depends on the system parameters, i.e. L. To eliminate the steady state error caused by the parameters mismatch and numerical errors, an integral controller with a large time constant can be used. In this way, the integration results of the active and reactive power errors will be added to $v_d(k)$ and $v_q(k)$, respectively. This integrator will ensure the accurate power tracking performance while by using a large time constant, its impact on system dynamic performance is negligible.

5. Simulation results

The system parameters are summarized in Table 1 and are the same for simulations and experimental tests. The performance of the proposed system will be verified by simulation and experimental results and will be compared with the results of VOC. To assure a valid comparison, both the proposed method and VOC utilize sinusoidal PWM (SPWM) with 5 kHz switching frequency to generate gate signals. The idea is similar to the SPWM for the standard converters with the only modification that the pattern of the reference signals are different. For the low cost converter, the phase shift between the reference signals does not obey the three phase symmetry. If the desired phase voltages for the converter of

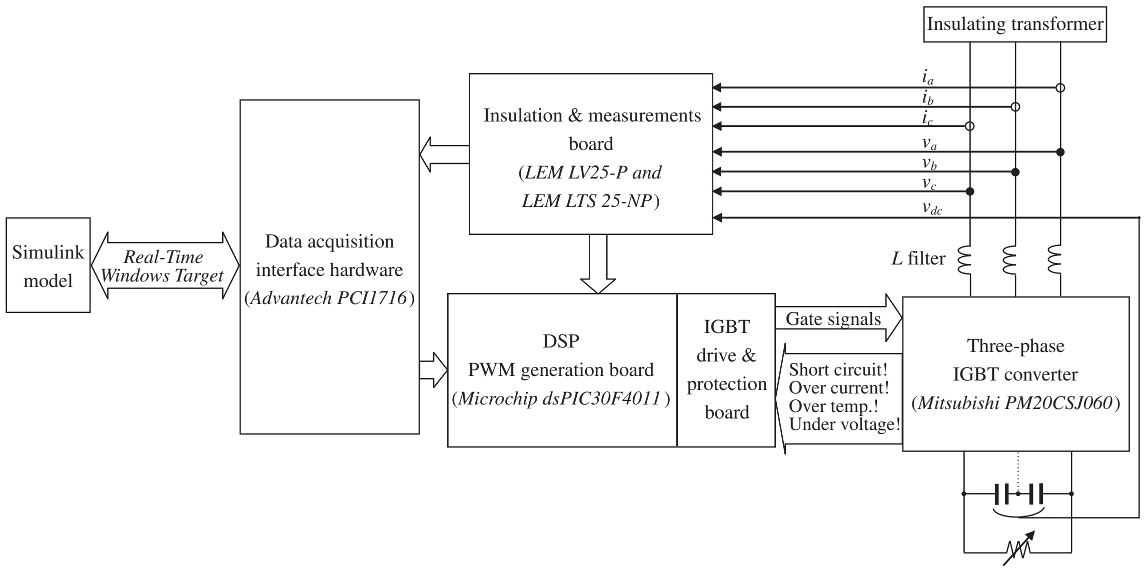

Fig. 7. Configuration of test rig.

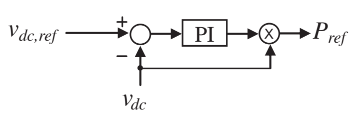

Fig. 8. DC link voltage regulator.

Fig. 1 are as $v_a = V_m \sin(\omega t)$, $v_b = V_m \sin(\omega t\text{-}120)$, and $v_c = V_m \sin(\omega t + 120)$, then the reference voltages for the two controlled legs will be $v_{an} = 3^{1/2}\ V_m \sin(\omega t\text{-}30)$, and $v_{bn} = 3^{1/2}\ V_m \sin(\omega t\text{-}90)$. More details can be found in [4].

Fig. 6 shows the response of the proposed controller and VOC schemes to various changes in commanded active and reactive powers. These waveforms confirm the proper operation of the proposed method. Both controllers provide precise current control with low distortion and harmonic noises (THD*i*) and at the same time, accurate regulation of output active and reactive powers. Indeed, the reference tracking capability as well as the steady state performance of the proposed controller is as good as a properly designed VOC. From Fig. 6, one can obtain the dynamic performance measures as summarized in Table 2. Clearly, both techniques provide a very fast power tracking capability while the proposed method exhibits a slightly faster performance to the active power step-up command.

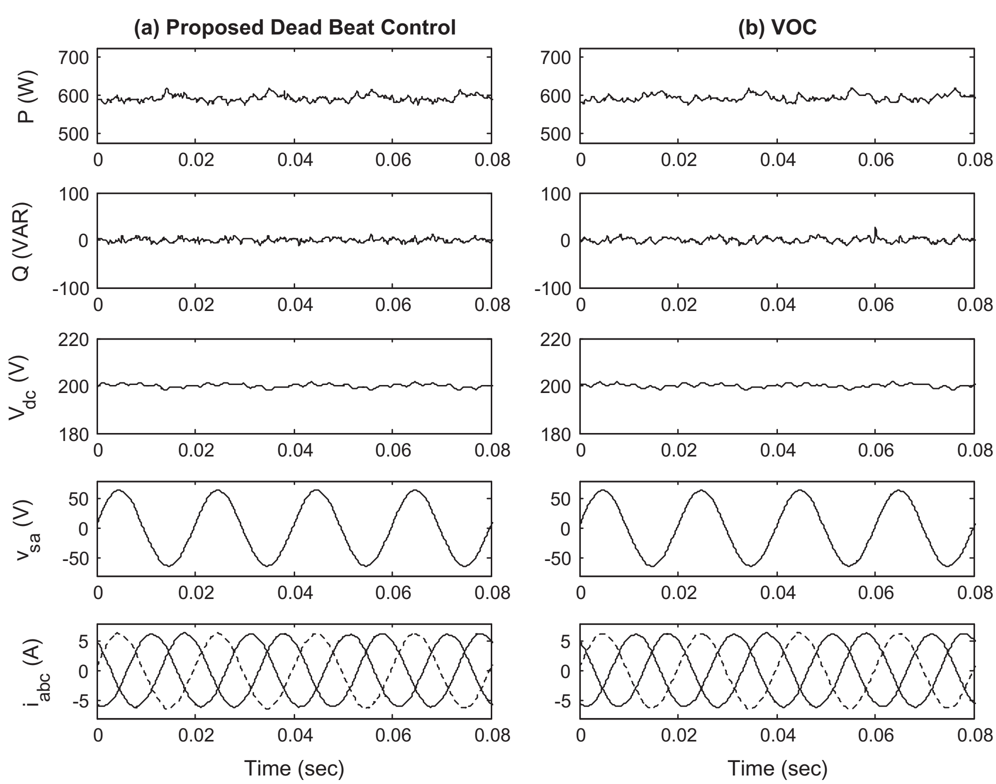

Fig. 9. Experimental waveforms; steady state operation.

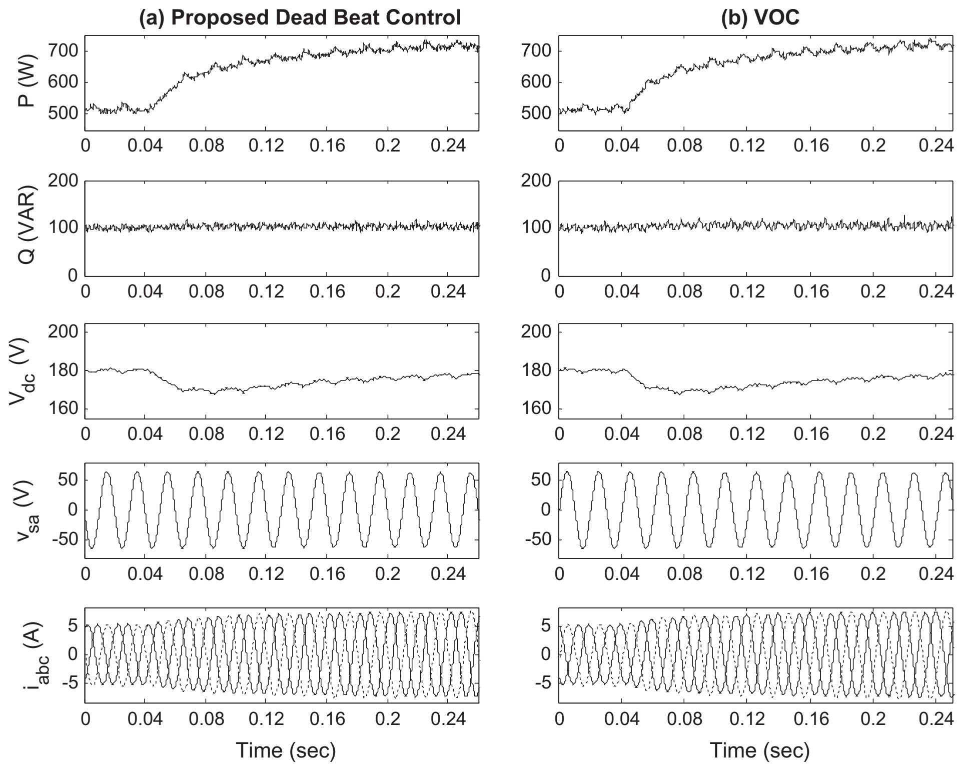

Fig. 10. Experimental waveforms; step jump of load power.

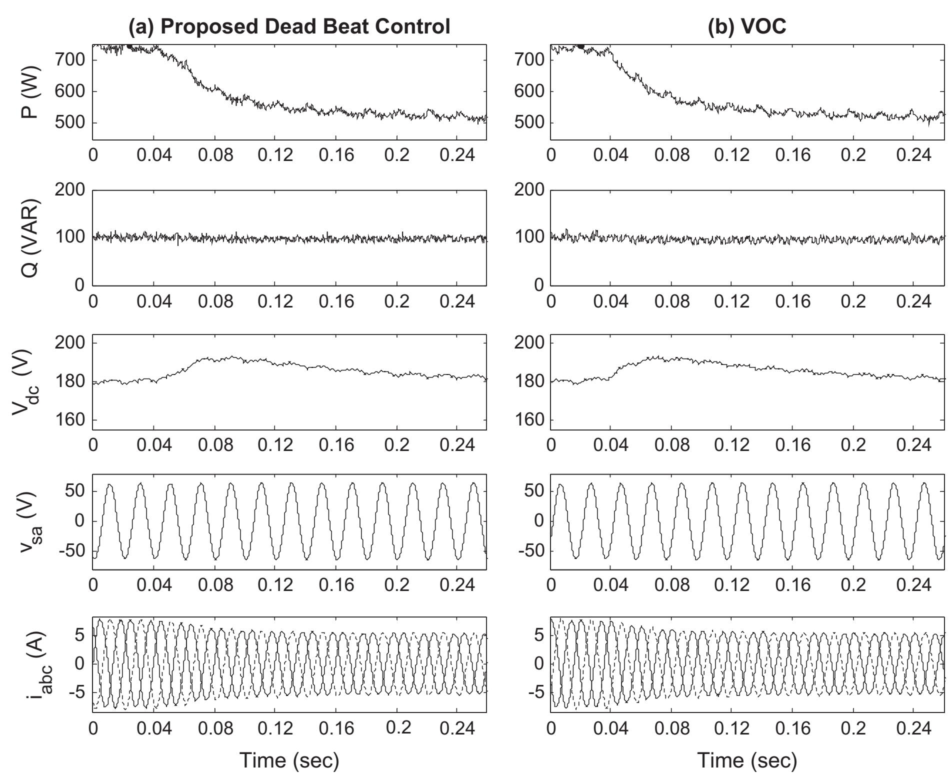

Fig. 11. Experimental waveforms; step drop of load power.

The correct operation of the proposed dead beat controller as well as the VOC technique depends on an exact estimation of the filter inductance. Eqs. (10) and (11) clearly show the effect of L on the equations of the proposed method, while Fig. 2 depicts that the L appears in the decoupling network of the VOC structure. The performance of the proposed and the VOC techniques considering mismatch in the inductance value is investigated and results are reported in Table 3. It can be seen that the THD is almost unaffected, however for smaller values of L the current ripple is slightly reduced.

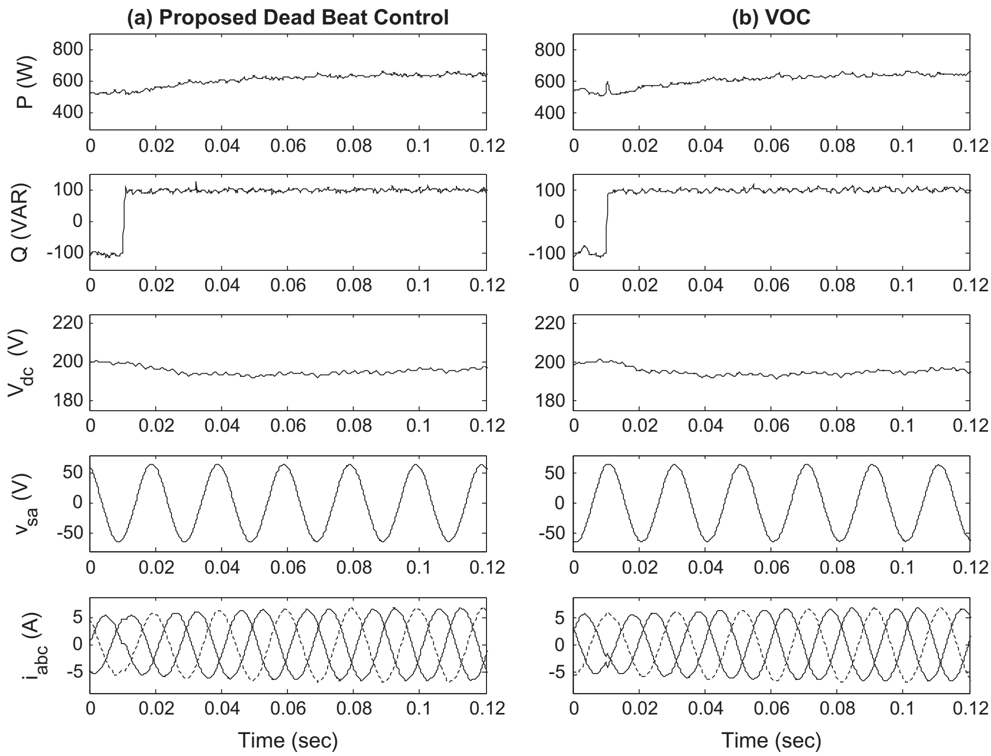

Fig. 12. Experimental waveforms; step jump of reactive power reference value.

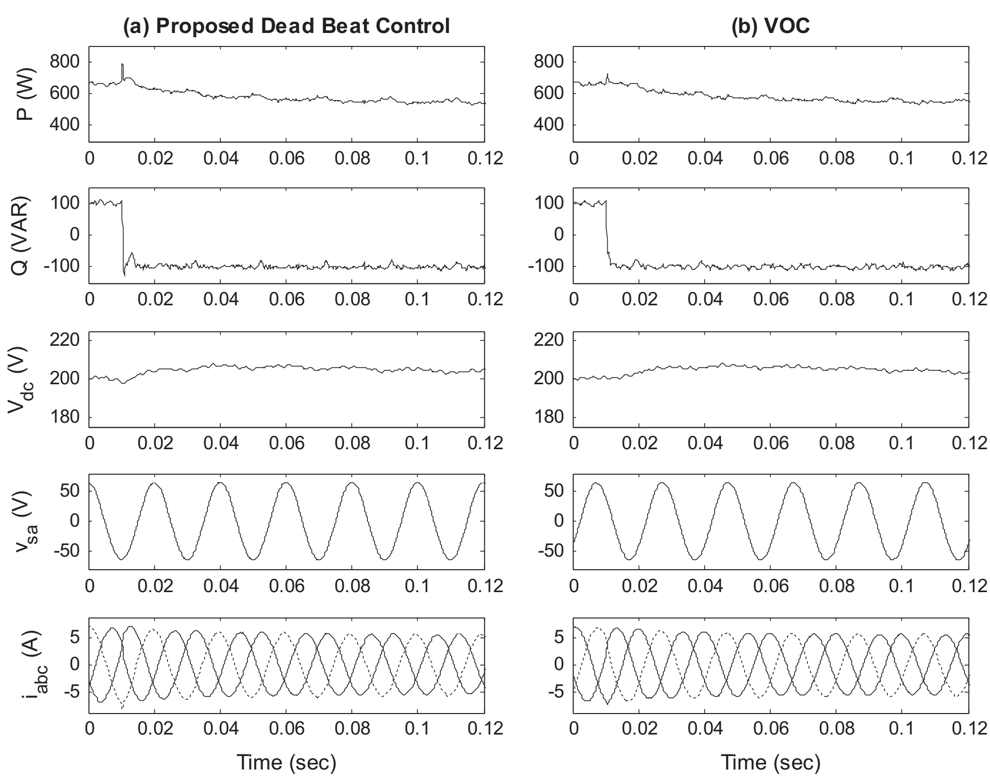

Fig. 13. Experimental waveforms; step drop of reactive power reference value.

In another study, the performance under harmonically distorted and imbalanced grid voltages is evaluated and the results are summarized in Table 3. Though both techniques still provide sinusoidal AC currents with low distortions, one can see that under such conditions, the THD values for the proposed strategy are slightly lower than those for the VOC method.

6. Experimental results

Fig. 7 shows the experimental setup of the proposed scheme. As depicted, the prototype IGBT converter includes a power circuit module, an interfacing and sensing module, PWM generator system and IGBT driver modules. The converter is equipped with software and hardware protections including over-voltage, over-current and over-temperature protections. The control strategy is developed using MATLAB/SIMULINK Real Time Windows Target and the interface between the model and the converter module is provided by using a high speed data acquisition interface card. The sampling frequency for experimental implementation was chosen as 10 kHz, and experimental results are obtained with the same parameters used in the simulations except that the value of input inductance is 15 mH. The DC side of the converter is connected to a resistive load and the active power flow is controlled indirectly through a DC-link voltage regulator as shown in Fig. 8.

Experimental results for the proposed dead beat controller in the case of closed loop control of DC link voltage are presented in Figs. 9–13. The experimental and simulated results show good agreement. The steady state operation, which confirms the proper operation of the proposed method, is presented in Fig. 9. The quality of practical converters is normally evaluated in terms of total harmonic distortion (THD). Based on the IEEE standard this value should be less than 5%. This value for the proposed strategy and VOC is 1.87% and 1.85%, respectively, which is much bellow the standard limit. The dynamic of the PWM converter with the proposed scheme as well as the VOC structure is fast and there is no coupling between the active and reactive powers. Figs. 10 and 11 show the measured waveforms during load changes. When the load current is jumped (dropped), the DC link voltage decreases (increases) to compensate for the real power supplied by source. Figs. 12 and 13 prove the fast and accurate tracking of reactive power reference value. Obviously, in the case of step changes of reactive power reference the active power also changes a little. This is because that as a result of reactive power changes, the AC current amplitude and as a consequence the converter losses have been changed. So the active power exchange with the grid varies accordingly to compensate for these losses and to maintain the DC link voltage.

7. Conclusions

Based on the discrete model of a four switch three phase PWM converter, a dead beat power control strategy is proposed. The control method is very simple to design and implement; however it is established on a strong mathematical approach. Simulation and experimental results confirm the effectiveness of the proposed method in providing precise power control with low distortion and harmonic noises (THD), and at the same time, small oscillations in active and reactive powers. The proposed strategy besides having the VOC's advantages, offers many unique features such as: no hysteresis or linear PI controller are required and reference values in each sampling period are directly computed based on measurements and system parameters through simple mathematical operations, decoupled control of active and reactive powers, no need for evaluation of any quality function or any other optimization which are time consuming calculations, simple algorithm besides strong theoretical background, finally, it operates at constant switching frequency thanks to the PWM generator, which makes the use of advanced modulation techniques possible.

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