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Optimal PAM Control for a Buck Boost DC-DC Converter with a Wide-Speed-Range of Operation for a PMSM

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ABSTRACT

A pulse width modulation-voltage source inverter (PWM-VSI) is used for variable speed permanent magnet synchronous motor (PMSM) drives. The PWM-VSI fed PMSM has two major disadvantages. Firstly, the PWM-VSI DC-link voltage limits the magnitude of the PMSM terminal voltage. As a result, the motor speed is restricted. Secondly, in a low speed range, the PWM-VSI modulation index declines. This is caused by a high DC-link voltage and a low terminal voltage ratio. As a result, the distortion of the voltage command and the stator current are increased. This paper proposes an optimal pulse amplitude modulation (PAM) control which can adjust the inverter DC-link voltage by using a buck-boost DC-DC converter. At a low speed range, the proposed system can reduce the distortion of the voltage command, which improves the stator current waveform. Also, the allowable speed range is extended. In order to verify the proposed method, experimental results are provided to confirm the simulation results.

Key Words: Buck boost DC-DC converter, PAM control, PMSM drive

I. INTRODUCTION

In recent years, variable speed controlled permanent magnet synchronous motors (PMSMs) have been developed by evolving power electronics technology and by utilizing rare-earth magnets. PMSMs are widely applied in industry due to their high energy density, high torque to ampere ratio, robustness and high efficiency. A PMSM does not required rotor winding. As a result, the performance of PMSMs is better than induction motors [1].

Generally, PWM voltage source inverters (PWM-VSI) have been used for variable speed PMSM drives [2]–[4]. However, PWM-VSI fed PMSMs have two main disadvantages. Firstly, the PWM-VSI DC-link voltage limits the magnitude of the PMSM terminal voltage. Consequently, the motor speed is also limited because it is necessary for the terminal voltage to be increased proportional to the motor speed. In order to overcome this problem, flux-weakening control [5], [6] or boosting [7] the PWM-VSI DC-link voltage according to the motor driving conditions have been proposed. Secondly, in a low speed range, the PWM-VSI modulation index decreases due to a high DC-link voltage and a low terminal voltage ratio. This problem causes distortion in the stator currents and produces torque. As a result the speed control performance deteriorates.

So far, for control performance in a low speed range, it seems that there are few approaches which focus on the PWM-VSI DC-link voltage. Improving these disadvantages is important in applications that require high performance in a wide speed range,such as electrical vehicles (EVs) [8].

This paper proposes an optimal PAM control system for PMSMs, in order to overcome the above disadvantages. Furthermore, the proposed system allows for a bi-directional energy flow. The system has a bi-directional buck boost DCDC converter [9] on the primary side of the PWM-VSI. This paper also describes the determination of an optimal DC-link voltage command and the duty factors of the converter.The bi-directional buck-boost DC-DC converter adjusts the motor DC-link voltage with respect to the speed of the motor. As a result, it generates a variable DC-link voltage instead of a constant DC-link voltage at the side of the PWM-VSI. The effectiveness of the proposed method is verified by simulation and experimental results. This paper is organized as follows. In Section II, an optimal DC-link voltage is considered. Section III roughly explains the operating principle of the bi-directional buck boost DC-DC converter. The proposed system is shown in Section IV. This section also explains the switching control of the DC-DC converter. The simulation and experimental results are presented in Section V and Section VI shows the conclusions.

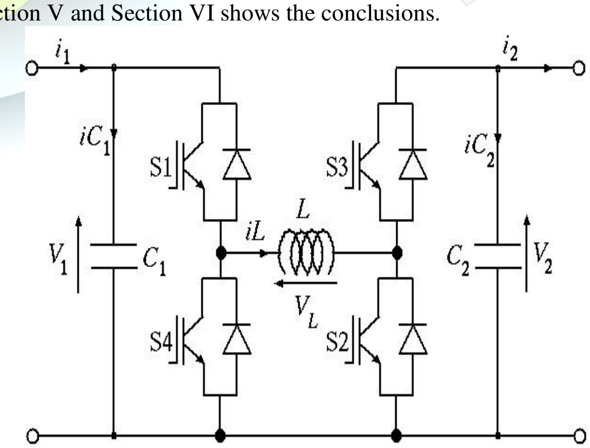

Fig. 1. Bi-directional buck boost DC-DC converter.

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II. DETERMINATION OF THE OPTIMAL DC-LINK VOLTAGE COMMAND

The PMSM terminal voltage V_l is expressed as:

$$V_l = \sqrt{\frac{3}{2}} V_{amp} \qquad (1)$$

Where Vamp is the amplitude of the phase voltage. Since Vamp = VDC/2 in the triangular wave comparison method, V_l is imposed following a constraint by the DC-link voltage VDC:

$$V_l \leq \sqrt{\frac{3}{8}} V_{DC}. \qquad (2)$$

In order to make PMSMs drive in the constant torque region, VDC should be determined so that V_l does not exceed its constraint. However, too large a VDC reduces the PWM-VSI modulation index and then, it is difficult for the PWM-VSI to realize the required phase voltages.Further, the disturbance voltage related to the dead time of the switching devices increases in operation with a low modulation index. In order to maintain the maximum modulation index and the minimum disturbance voltages in any speed range, it is necessary for VDC to maintain an optimal value. Therefore, the commanded DC-link voltage VDC is calculated as follows, after calculation of the commanded d-q axis voltages:

$$V_{DC}^* \leq \sqrt{\frac{8}{3}} V_l^*$$

By the above calculation, VDCis determined on-line according to, and it can correspond to the load variation. It is important that V_l be greater than the nominal value because the PWM-VSI output voltage includes harmonic components due to several nonlinearities of the PWM-VSI. Furthermore, a boost voltage is required for it to start up stably. Therefore, VDCis finally determined as follows:

$$V_{DC}^* = \max(K_{PAM} V_l^*, V_{DC\,\min}) \qquad (3)$$

where KPAM and VDC min are the PAM coefficient and the lower limit of the DC-link voltage, respectively. In an ideal

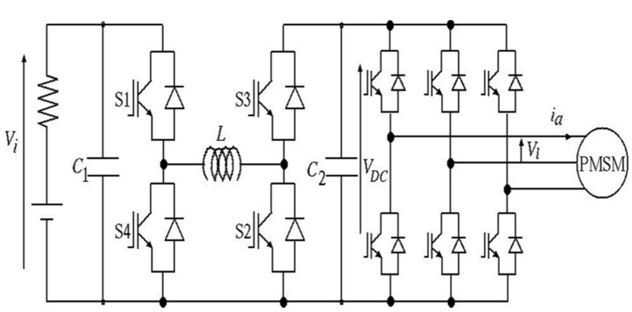

Fig. 2. Variable DC-link voltage circuit.

situation the value of KPAM is q 8 3 but in order to give a margin, KPAM is selected as 2.5.

III. BI-DIRECTIONAL BUCK BOOST DC-DC CONVERTER

In order to buck and boost the DC-link voltage, the proposed system uses a bi-directional buck-boost DC-DC converter [4] as shown in Fig. 1. The operation of each mode of this converter is presented in [4]. In this converter the terminal voltages v1 and v2 are expressed as:

$$\left.\begin{aligned} v_2 &= \frac{D_1}{1-D_2} v_1 \\ v_1 &= \frac{D_3}{1-D_4} v_2 \end{aligned}\right\} \qquad (4)$$

where $D_i\{i \in 1,2,3,4\}$ are respectively the duty factors for the switches $S_i\{i \in 1,2,3,4\}$. From (4), the bi-directional buck-boost operation can be achieved by using the switches S_1 and S_2 when the power flows from v_1 to v_2 and by using the switches S_3 and S_4 when the power flows from v_2 to v_1. The variables in Fig. 1, i_L,v_1 and v_2, are then expressed as the following differential equations:

$$\left.\begin{aligned} i_L &= \frac{v_L}{L} \\ v_1 &= \frac{i_{C1}}{C_1} v_2 \\ v_2 &= \frac{i_{C2}}{C_2} \end{aligned}\right\}. \qquad (5)$$

Note that the variables, v_L,i_{C1} and i_{C2}, are determined according to the switch states and the initial value of i_L.

IV. OPTIMAL PAM CONTROL

In this section, a control method for the bi-directional buckboost DC-DC converter will be explained. A variable DC-link voltage circuit is established as shown in Fig. 2 by using the circuit shown in Fig. 1. In this circuit, the input voltage V_i and PWM-VSI DC-link voltage VDC correspond to v_1 and v_2 inFor motoring mode, if $V_{DC^*} < V_i$ then the duty factors for each switch are determined as:

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$$\left.\begin{array}{l} D_1 = \frac{V_{DC}^*}{V_i} \\ D_2 = 0 \\ D_3 = 0 \\ D_4 = 0 \end{array}\right\}. \qquad (6)$$

The converter outputs the optimal V_{DC} by a step-down operation according to the motor speed. If $V_{DC^*} > V_i$ for motoring mode, then the duty factors for each switch are determined as:

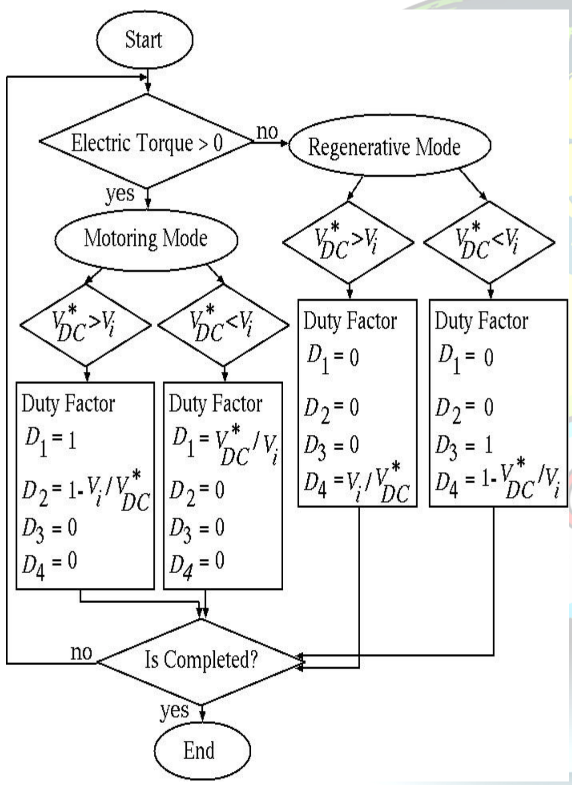


Fig. 3. Flowchart of PAM operation.

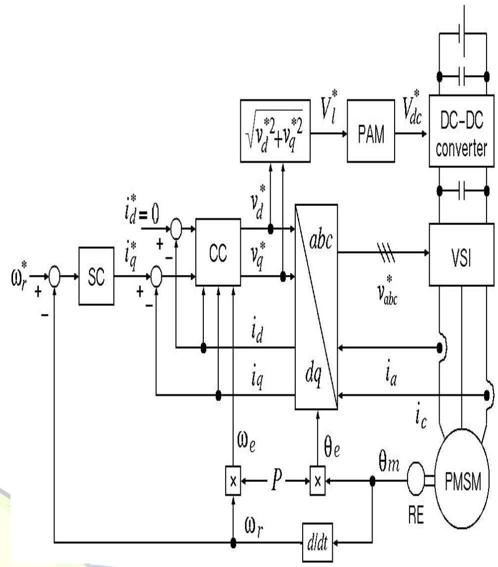
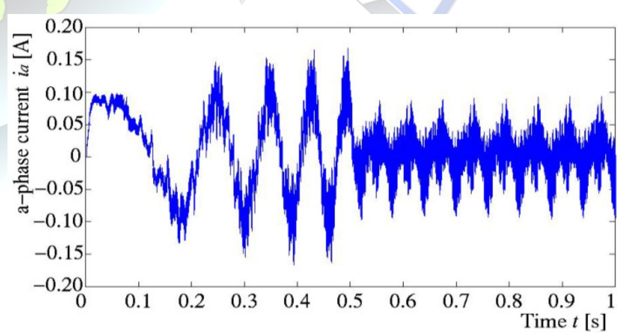


Fig. 4. PAM control system for PMSM drive.

$$\left.\begin{array}{l} D_1 = 1 \\ D_2 = 1 - \frac{V_i}{V_{DC}^*} \\ D_3 = 0 \\ D_4 = 0 \end{array}\right\}. \qquad (7)$$

In this case, the converter performs a step-up operation according to the motor speed.For regenerative mode, the battery charge current is controlled by boosting up VDC to over   for the regenerative mode, the duty factors for each switch will be determined as:

$$\left.\begin{array}{l} D_1 = 0 \\ D_2 = 0 \\ D_3 = 1 \\ D_4 = 1 - \frac{V_{DC}^*}{V_i} \end{array}\right\}. \qquad (8)$$



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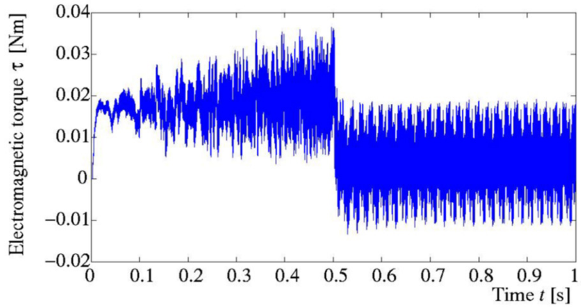

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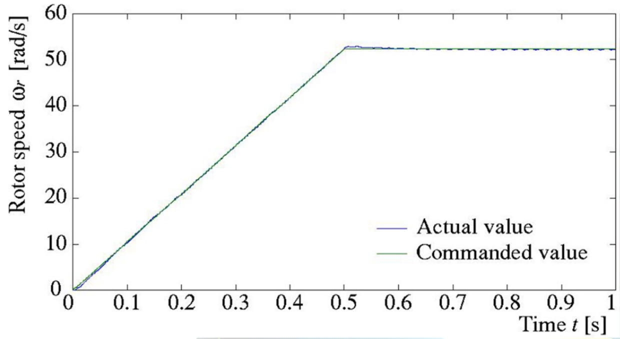

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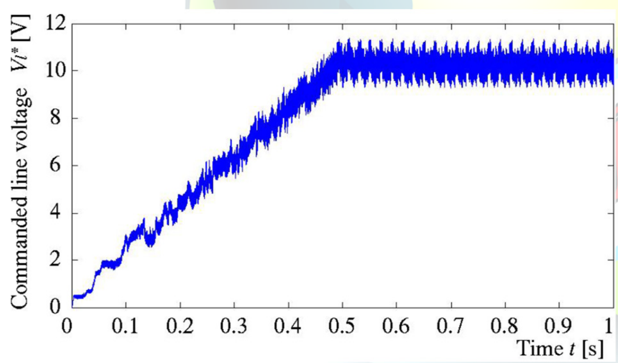

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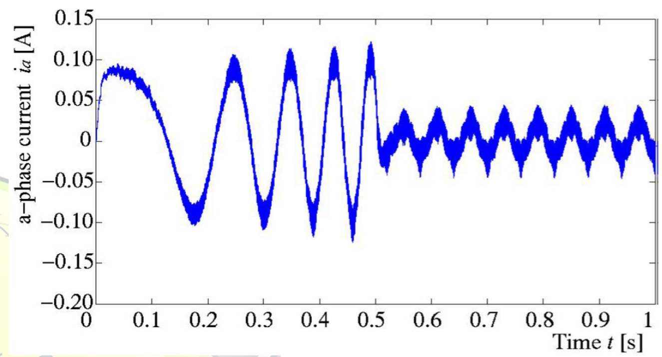
5. Simulation results: low speed operation for fixed DC-link voltage(V_{dc}=100v)

$$\left.\begin{array}{c} D_1 = 0 \\ D_2 = 0 \\ D_3 = \frac{V_1}{V_{DC}^*} \\ D_4 = 0 \end{array}\right\}. \quad (9)$$

Fig. 3 shows the gate duty factor and the operation mode of the converter.

V. SIMULATION AND EXPERIMENTAL RESULTS

The proposed control system is shown in Fig. 4. The PMSM control system is composed of speed and current control loops, and it assumes that the actual rotor position and the three phase currents can be obtained by a rotary encoder and current sensors [10].V_1 is calculated after the calculation of the commanded dq-axis voltage. Then, using the calculated V_1, the DC-DC converter controller determines the duty factors based on Section IV.



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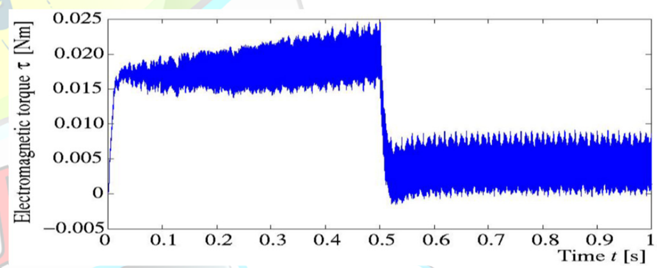

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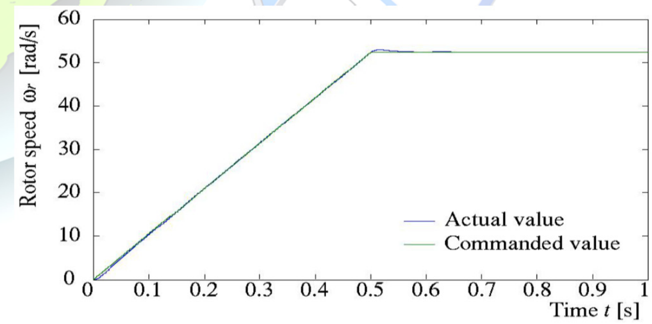

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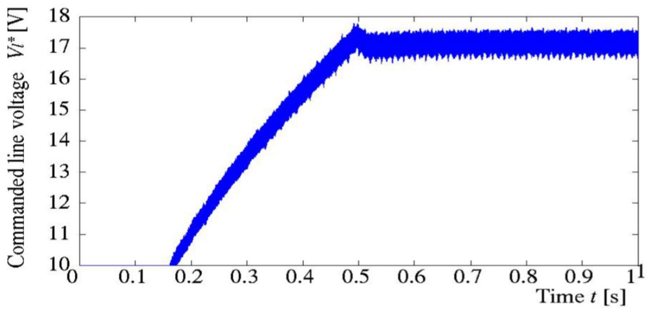

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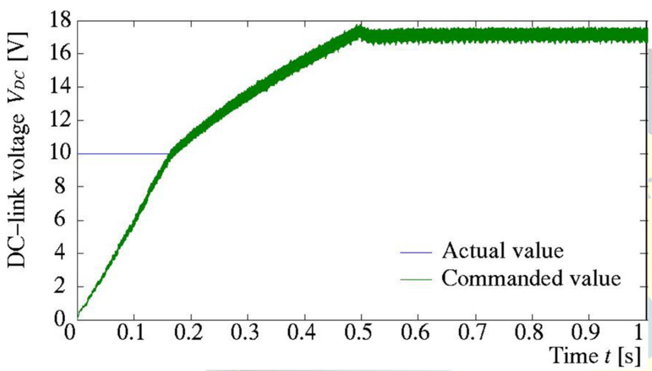

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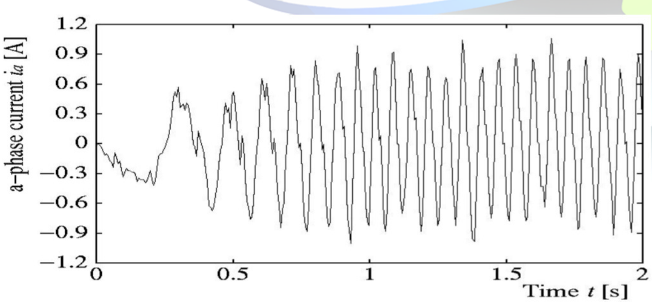
Fig. 6. Simulation results: low speed operation for variable DC-link voltage.

Fig. 5 and Fig. 6 show the simulation results for low speed operation. In this simulation, the PMSM is accelerated from 0 to 500rpm. For comparison, the simulation result for fixed DClink voltage operation (VDC = 100V) is shown in Fig. 5. From this figure, the pulsation of the stator current,the pulsation of the torque and the pulsation of the commanded line voltage are



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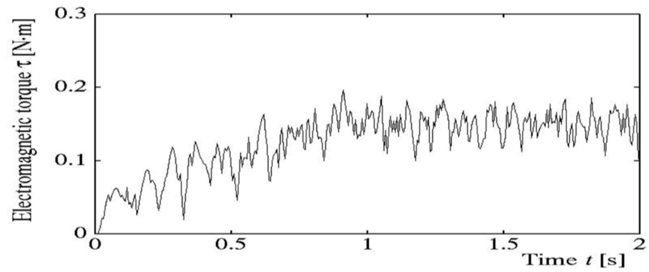

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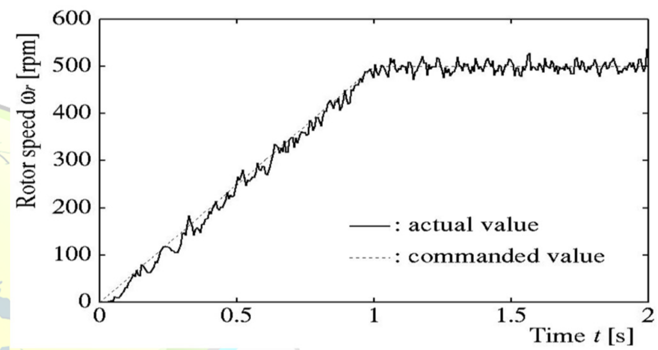

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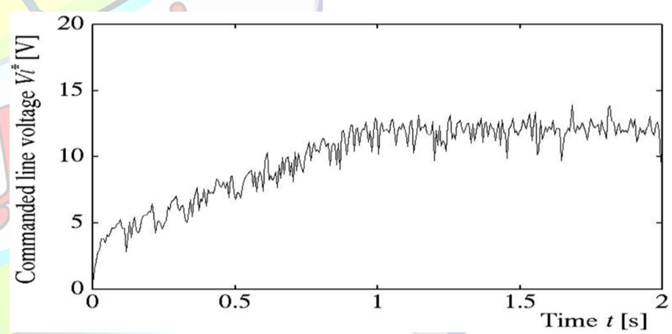

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Fig. 7. Experimental results: low speed operation for fixed DC-link voltage (V_{dc}=100v).

significantly increased. It can be confirmed from Fig. 6 that the desired commanded voltage is produced by the proposed method, and that the distortion of the stator currents, the pulsation of the torque and the pulsation of the commanded line voltage are improved. As a result, the proposed method is shown to have smoother operation than the fixed DC-link voltage operation.Further, it can be confirmed from the bottom figure of Fig. 6 that the DC-link voltage is controlled according to the driving condition.

Fig. 7 and Fig. 8 show the experimental results for low speed operation. In this experiment, the PMSM is accelerated from 0 to 500rpm. Fixed DC-link voltage operation is shown in

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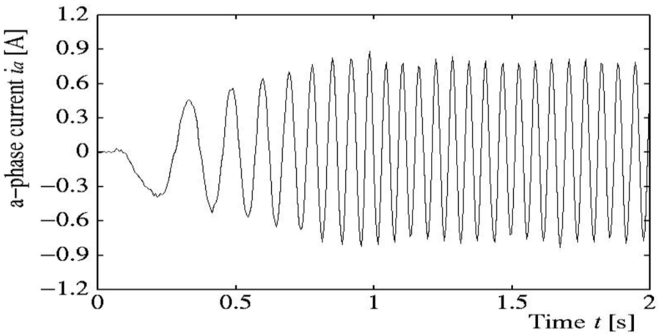

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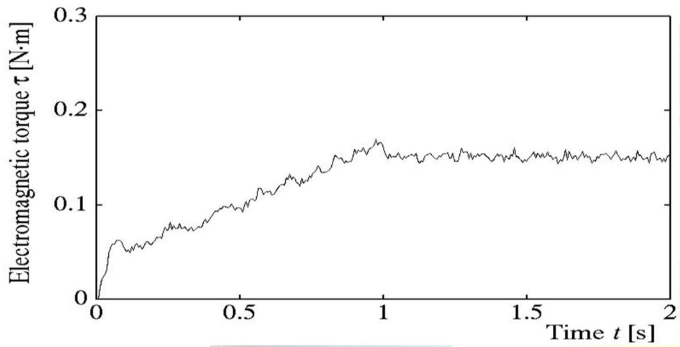

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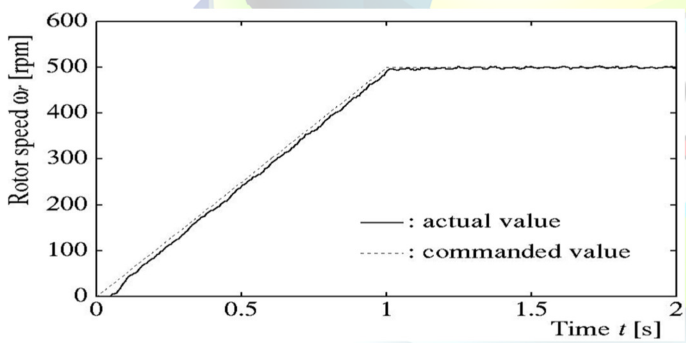

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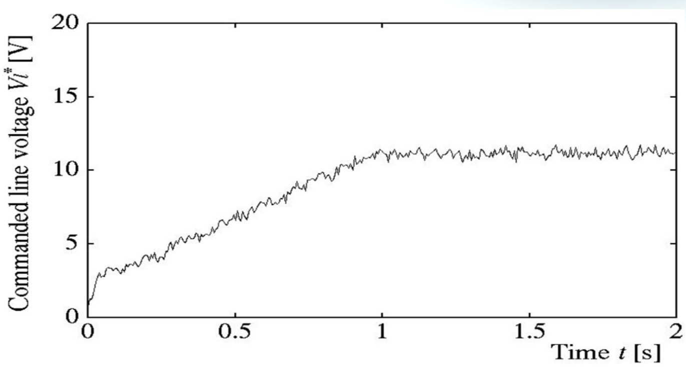

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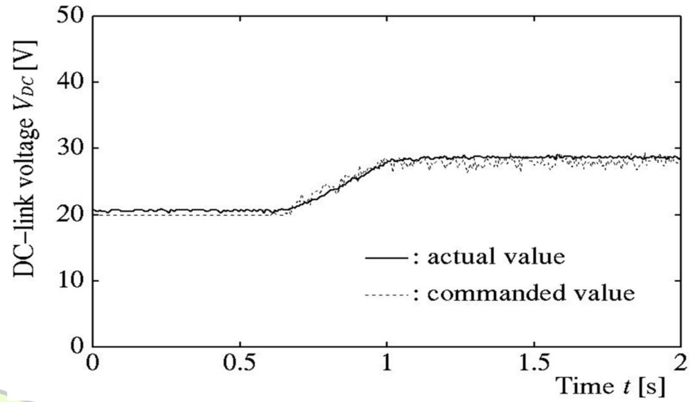

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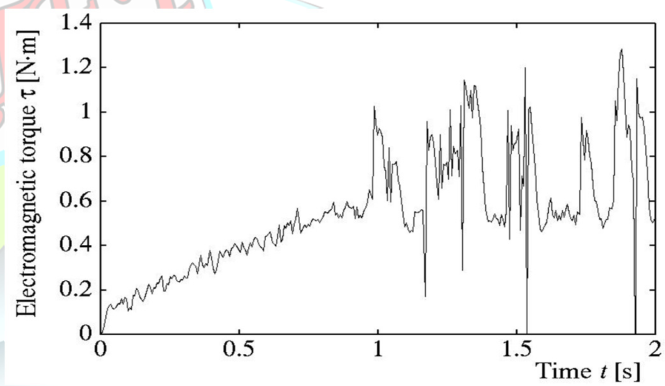
Fig. 8. Experimental results: low speed operation for variable DC-link voltage.

Fig. 7 and the proposed method (i.e. variable DC-link voltage operation) is shown in Fig. 8. From Fig. 7, the pulsation of the stator current, the pulsation of the torque and the pulsation of the commanded line voltage are drastically increased. On the other hand, from Fig. 8, the distortion of the stator current, the pulsation of the torque and the pulsation of the commanded line voltage are improved. From the bottom figure of Fig. 8 , it can be seen that the DC-link voltage is controlled according to the driving condition.



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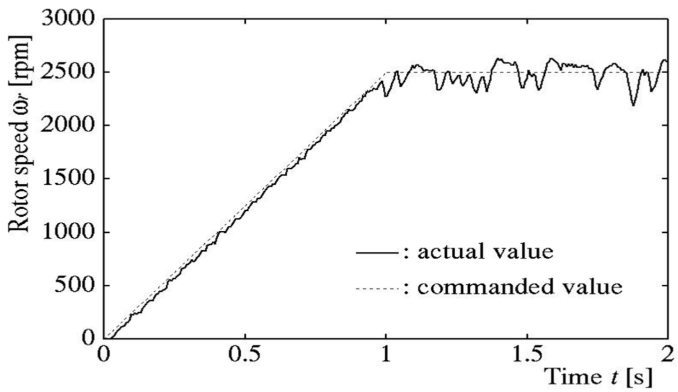

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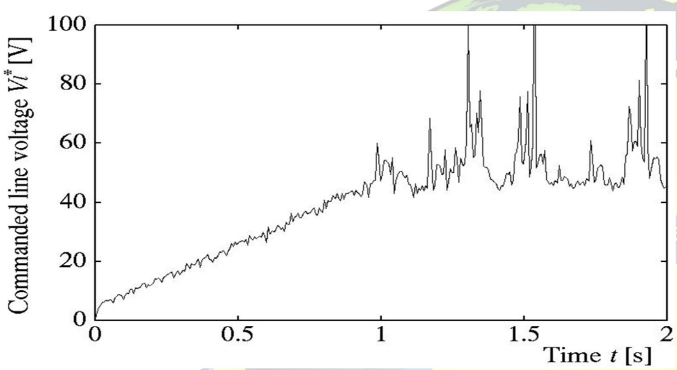

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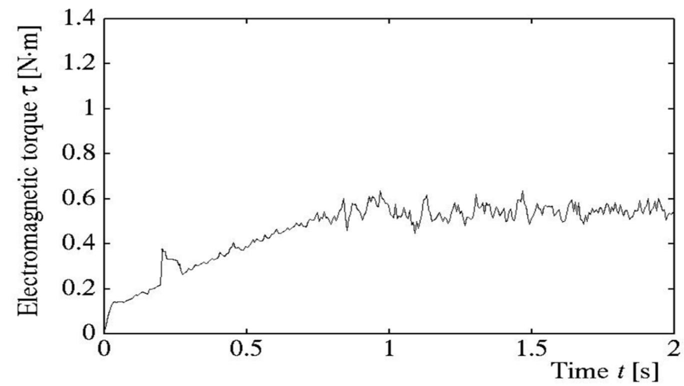
Fig. 9. Experimental results: high speed operation for fixed DC-link voltage (V_{dc}=100V).

During low speed, in the case of a fixed voltage the operation of the DC-link voltage is very high and the motor terminal voltage is very low. As a result, the modulation index is decreased and pulsations occur. However, in variable DClink voltage operation, the DC-link voltage is controlled by the Buck Boost DC-DC converter and it maintains the maximum modulation index. This is why, it can generate smooth output. According to the simulation and experimental results, the aphase current is different in the steady state operation of the motor drive. In the simulation, the motor load is zero but in the experiment, the motor is connected to a generator. As a result, some load appears. This is why, there are some differences between the experiment and simulation results.

The experimental results in the high speed range of operation are shown in Fig. 9 and Fig. 10. In this experiment, the PMSM is accelerated from 0 to 2500rpm. Fig. 9 shows the fixed DC-link voltage operation and Fig. 10 shows the



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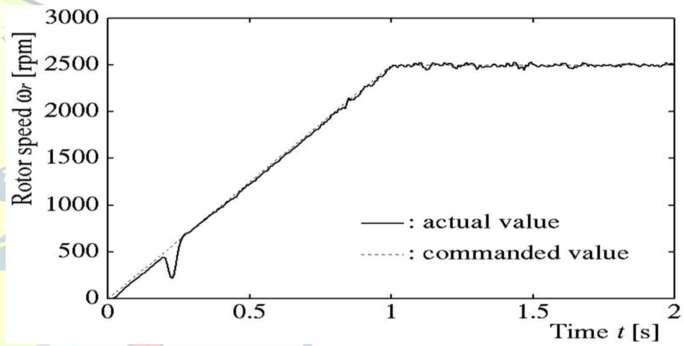

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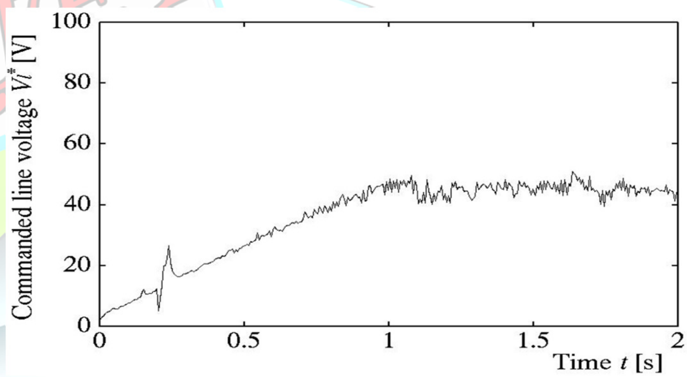

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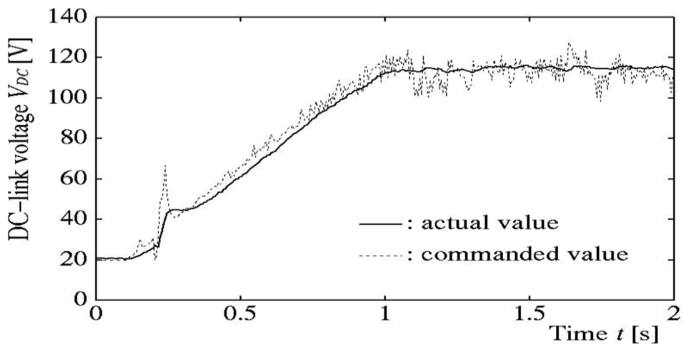

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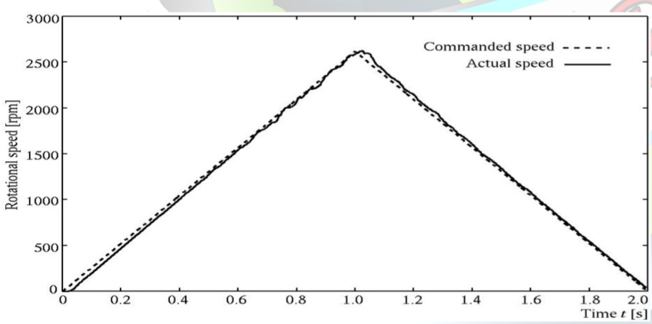
Fig. 10. Experimental results: high speed operation for variable DC-link voltage.

variable DC-link voltage operation. From Fig. 9, it can be seen that the electric torque, rotor speed and commanded voltage become unsteady and that the motor does not operate properly. This is due to the lack of motor terminal voltage. Fixed DClink voltage can provide a certain level of terminal voltage. However, in high speed operation, it does not get sufficient voltage to operate and therefore limits the motor speed.

Fig. 10 shows the experimental results for high speed operation with a variable DC-link voltage. From these experimental results, it can be seen that the electric torque, rotor speed and commanded voltage become stable. From the bottom figure of Fig. 10 it can be seen that the DC-link voltage is controlled according to the driving condition. During the high speed



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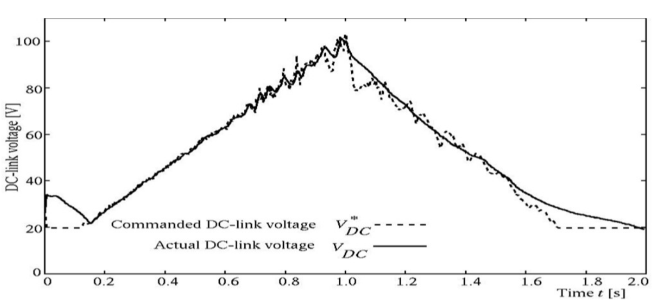

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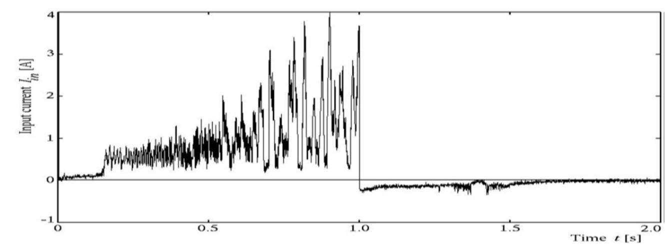

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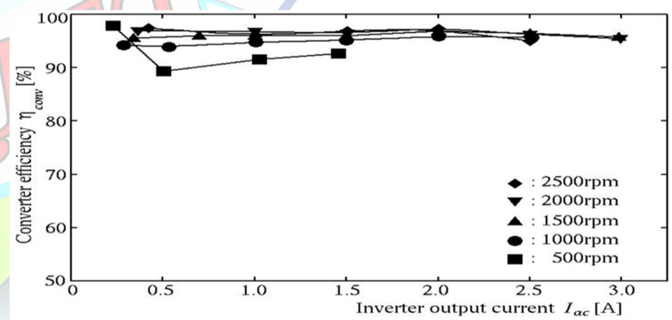
Fig. 11. Experimental results: during braking operation for variable DC-link voltage.

range of operation, the DC-DC converter is operated in boost mode. From the bottom figure of Fig. 10, it can be seen that the DC-link voltage moves up to 120V due to the boost mode operation of the DC-DC converter. As a result, the motor gets enough voltage to operate in the high speed range of operation.

Fig. 11 shows the experimental results for the proposed method in the case of a dynamic braking of operation. From this figure, it is observed that the rotational speed, the DClink voltage and the input current of the converter respond properly during this mode of operation. The input current of the converter is negative during the braking mode of operation, which means that the converter is working as a buck converter.



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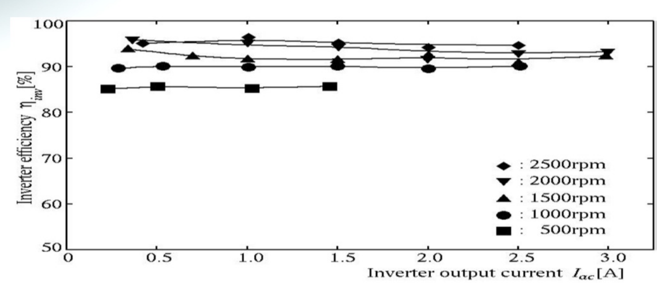

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Fig. 12. Experimental results: Converter and Inverter efficiency for variableDC-link voltage.

Fig. 12 shows the experimental results of the converter and inverter efficiency for the proposed method under different load conditions. From this figure, it can be seen that the efficiency does not depend on the load condition. It depends on the different rotational speeds. Table II and Table III also represent the efficiency of the converter and inverter at different speeds, values of KPAM and DC-link voltages. From these tables, it is observed that the efficiency is almost unchanged when the DC-link voltage and the KPAM are changed. However, when the rotational speed is changed, the efficiency varies.

VI. CONCLUSIONS

This paper proposes an optimal PAM control system for PMSM drives which can adjust the PWM-VSI DC-link voltage according to the driving condition in a range from low to high speed. This system uses a bi-directional buck boost DC-DC converter and this paper describes the determining methods for an optimal DC-link voltage and the converter duty factors. It can be confirmed that the commanded voltages, the armature currents and the produced torque are improved in the low speed range and that the allowable driving range is extended.

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