Control Strategies for Voltage Control of a Boost Type PWM Converter

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Abstract. **This paper addresses the non-linear problem of regulating the DC link voltage, in a vector controlled three-phase boost type PWM converter with particular emphasis on applications in wind energy systems. The AC side current control is performed in a synchronously rotating reference frame. An analysis of the system is provided and several alternative DC link voltage controller designs are investigated and compared. Fuzzy controllers augmented using a feed-forward compensation technique are found to provide excellent performance. A 3kW experimental set up has been built and experimental results are provided to validate the control designs.**

I. INTRODUCTION

Boost type PWM converters provide a bi-directional DC-AC interface with high quality currents on the AC side and controllable displacement factor [1-4]. The converter finds most use as the "front end" in AC drive applications where it allows non dissipative regeneration capability and nearly sinusoidal input currents. This paper, however, concentrates on Wind Energy Conversion Systems (WECS), where the boost converter is used as the interface to the AC grid system.

When induction machines are used for grid connected variable speed WECS, for example, two back to back converters are required for squirrel cage machines [4,6,7] as well as for doubly fed induction machines [5-8]. Control of the AC side currents is usually carried out in a d-q synchronously rotating reference frame [1,2]. High bandwidth current response is then achieved and furthermore de-coupled control of the active and reactive power flow between the converter and the grid is possible. In a WECS, there may be a number of generation sources/loads connected to the DC link in general as shown in Fig. 1. The converter power flow must be controlled in order to regulate the DC link voltage E_{dc} according to a reference value E^*_{dc}.

This paper concentrates on control strategies to regulate the DC link voltage. The problems created by non-linear impedance on the DC side are addressed particularly when the characteristics of the DC side generation/load are unknown. A PI type fuzzy logic controller is proposed and feed-forward or load compensation is used to improve the performance of the controller to load disturbance rejection. State observers are used to estimate the load current needed for the feed-forward compensation. Experimental results obtained from a 3kW prototype are discussed and the performances of the control strategies are compared.

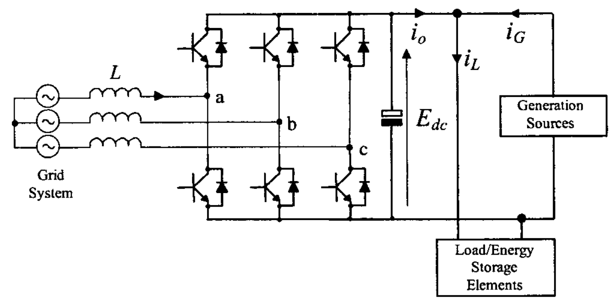

Fig.1. Boost type PWM Rectifier

II. SYSTEM MODELLING

The equivalent circuit of a three-phase boost converter in a d-q synchronous reference frame, rotating at ω_e, aligned with the supply voltage vector can be derived as shown in Fig. 2 [2].

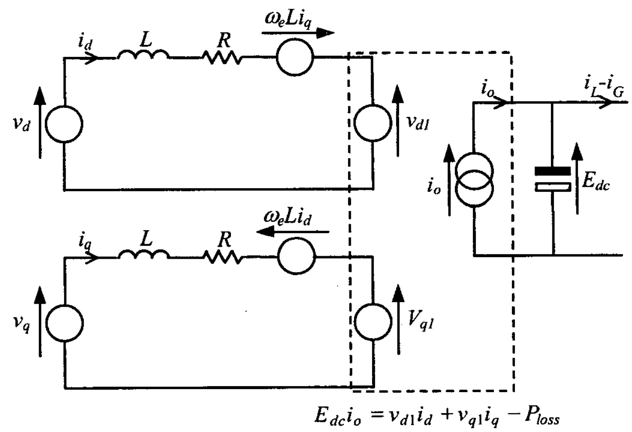

Fig. 2. Boost converter equivalent circuit in d-q co-ordinates

According to this figure, the energy balance can be written as:

$$E_{dc}(i_L - i_G) + \frac{1}{2}CpE_{dc}^2 + P_{loss} = E_{dc}i_0$$
$$= k\left[v_d i_d - R(i_d^2 + i_q^2) - \frac{1}{2}Lp(i_d^2 + i_q^2)\right] \quad (1)$$

Where v_d, v_q, i_d, i_q, v_{dl}, v_{ql} are the supply voltages, supply currents and converter voltages respectively, referred to the synchronous frames and k is a constant which depends on the transformation used. R and L are the input filter resistance and inductance respectively. P_{loss} represents the losses in the converter and i_L, i_G represent the load and generation connected to the DC link capacitor respectively.

In order to regulate E_{dc} it is necessary to control the real power flow via i_d. The quadrature current i_q is normally close to zero implying close-to-unity displacement factor operation. Using (1), neglecting the inverter losses and assuming i_q=0, a small signal transfer function can be obtained between E_{dc} and i_d for an operating point (E_{dc0}, i_{d0}, $(i_L-i_G)_0$) as follows:

$$\frac{\Delta E_{dc}}{\Delta i_d} = \frac{k\left[v_d - 2Ri_{d0} - i_{d0}Ls\right]}{E_{dc0}\left[\frac{(i_L - i_G)_0}{E_{dc0}} + \left.\frac{\partial(i_L - i_G)}{\partial E_{dc}}\right|_{E_{dc0}i_{do}} + Cs\right]} \quad (2)$$

Equation (2) may be used to design a linearised controller. However, the transfer function is dependent on the operating point. Moreover, the pole of (2) is strongly dependent on the disturbance current (i_L-i_G). In general either i_G or i_L may be a function of E_{dc}. For example, a static load could be placed across the DC link and/or i_G may be supplied from a generator operating a constant power. Given the variation of (2) over the operational range and the generally unknown load and generating conditions, a fixed classical controller is inappropriate.

The approach taken in this paper to account for the non-linearity and uncertainty in (2) is to derive a PI type fuzzy controller augmented by a feed-forward compensation technique [9].

III. DC LINK VOLTAGE CONTROLLER

A. *PI Type Fuzzy Controller.*

The scheme for the fuzzy logic controller is shown in Fig. 3. The inputs to the controller are the DC voltage error, *e(k)* and the change of voltage error, Δ*e*(*k*). The output of the fuzzy controller is the change in the d-axis reference current Δi_d. The updated d-axis reference current is then calculated from:

$$i_d^*(k) = i_d^*(k-1) + \Delta i_d^*(k) \quad (3)$$

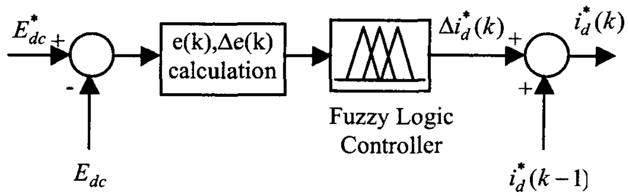

Fig. 3. Fuzzy logic controller scheme.

For the fuzzification process, seven fuzzy levels are selected with the following fuzzy-set values for *e*(*k*) and Δ*e*(*k*): NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS(positive small), PM (positive medium), and PB (positive big). Triangular-type fuzzy-set values are used with 50% overlap. The control rules are shown in Table I. The inferred output of each rule is obtained using Mamdani's min fuzzy implication [10].

TABLE I.
CONTROL RULES.

Voltage Error e(k) \ Change in Voltage Error Δe(k)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	NZ
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

For the defuzzification process, seven triangular membership functions are also used, again with 50% overlap. A crisp value for Δi_d is calculated using the high - weighted method [10]. Tuning of the fuzzy controller was initially done off-line using a guided-search algorithm [11]. Minor adjustments of the controller parameters were subsequently done on-line to improve the response to step changes in DC link voltage reference.

B. *Feed-forward Compensation.*

In order to improve the DC link voltage regulation feed-forward compensation is used. This is based on the parametric model of the system and relates the disturbance current (i_L-i_G) to i_d. Neglecting the energy variation in L because the input filter inductance is small and considering that the energy variation in *C* is also negligible because the voltage is kept relatively constant by the controller action then the steady state equation may be used to derive the feed forward compensation term. From (1) the steady state power balance for unity-power factor operation, i_q^*=0, is then given by:

$$E_{dc}(i_L - i_G) + P_{loss} = k(v_d i_d - R i_d^2) \quad (4)$$

From which the feed-forward term is given by:

$$i_{d,comp} = \frac{v_d - \sqrt{v_d^2 - 4R\left(Ri_q^2 + \frac{1}{k}\left(E_{dc}(i_L - i_G) + P_{loss}\right)\right)}}{2R} \quad (5)$$

Equation (5) can be calculated in real time using a look up table. However, a simpler expression can be obtained by neglecting the inductor copper losses which yields:

$$i_{d,comp} = \frac{\frac{1}{k}\left(E_{dc}(i_L - i_G) + P_{loss}\right)}{v_d} \quad (6)$$

Either (5) or (6) can be used to implement feed-forward compensation, but in any case, knowledge of the current (i_L-i_G) is necessary. This can be obtained either through direct measurement or an observer can be used. Both techniques have been implemented, although an observer is preferable, since it avoids the need for a transducer and the associated electronics. Finally, the d-axis reference current $i_{d,ref}$ including the feed-forward compensation term is given by:

$$i_{d,ref} = i_d^* + i_{d,comp} \quad (7)$$

IV LOAD OBSERVER FOR FEED-FORWARD COMPENSATION

The discrete state equation for the observer, assuming that the load current does not change during one sampling period, is given by:

$$\begin{bmatrix} \hat{E}_{dc}(k+1) \\ \Delta\hat{i}_L(k+1) \end{bmatrix} = \begin{bmatrix} \hat{E}_{dc}(k) \\ \Delta\hat{i}_L(k) \end{bmatrix} + \frac{T}{C}\begin{bmatrix} i_o(k) - \Delta\hat{i}_L(k) \\ 0 \end{bmatrix} + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}\left[E_{dc} - \hat{E}_{dc}\right] \quad (8)$$

$$\Delta\hat{i}_L(k) = (\hat{i}_L(k) - \hat{i}_G(k))$$

Where i_o is the current supplied by the converter into the DC link and $\Delta\hat{i}_L(k) = (\hat{i}_L(k) - \hat{i}_G(k))$ is the estimation of disturbance or load current in the DC link. T is the sampling time, C is the DC link voltage capacitor and l_1, l_2 are the observer coefficients.

The current supplied by the converter to the DC link is obtained by using the signals from the PWM and the currents i_d^* and i_q^*. This is obtained as:

$$i_0 = \begin{bmatrix} S_a & S_b & S_c \end{bmatrix} \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} \cos\lambda & -\sin\lambda \\ \sin\lambda & \cos\lambda \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \quad (9)$$

Where λ is the voltage vector position in the synchronous reference frame. The values [S_a, S_b, S_c] are the duty cycles of the three top switches of the converter. By using the i_d^*, i_q^* currents in (9) the switching noise of the i_a, i_b, i_c measurements is avoided.

When the PWM signals are not available, the load observer can still be implemented using a parametric model of the converter. Neglecting the losses and the variation of the energy stored in the filter inductance, i_0 can derived from (1) as:

$$i_0 = k\frac{v_d i_{d,comp}}{E_{dc}} \quad (10)$$

Equation (9) gives a better estimation of i_o than (10) which is more sensitive to variation in the parameters and noise on the signals. Moreover, it requires the determination of P_{loss}. The observer gains are obtained from classical observer design and for the system parameter of the Appendix, gain values of l_1=0.45218 and l_2= -0.17028 give and observer dynamic natural frequency of about 400rad/s.

A schematic of the overall control scheme employing the fuzzy PI with feed-forward compensation is shown in Fig. 4. The block labelled "Non linear gain" can implement either equation (5) or (6).

V. EXPERIMENTAL SET-UP AND RESULTS

A schematic of the experimental rig used to validate the control strategy is shown in Fig. 5. A commercial 7.5kW PWM inverter is used which is connected to the grid via three 12mH line inductors. The DC link voltage E_{dc} is regulated at 550V with a supply voltage that has been set to 250V using a three-phase variac. This gives a nominal modulation depth for the converter of about 0.75, which provides enough latitude during transients to avoid overmodulation problems. A chopper controlled resistive load has been used to extract current transients from the DC link to study the performance of the DC link voltage controllers to step load impacts. A PWM switching frequency of 1kHz (regular sampling asymmetric PWM) is used. A 0.5ms sampling period is used for voltage and current measurement and for calculation of the d-q axis current controllers and load observer. DC link voltage control is carried out every 5ms. The experimental rig uses two T800 floating point Transputers, although the computational burden is not great and could be met by most DSP devices.

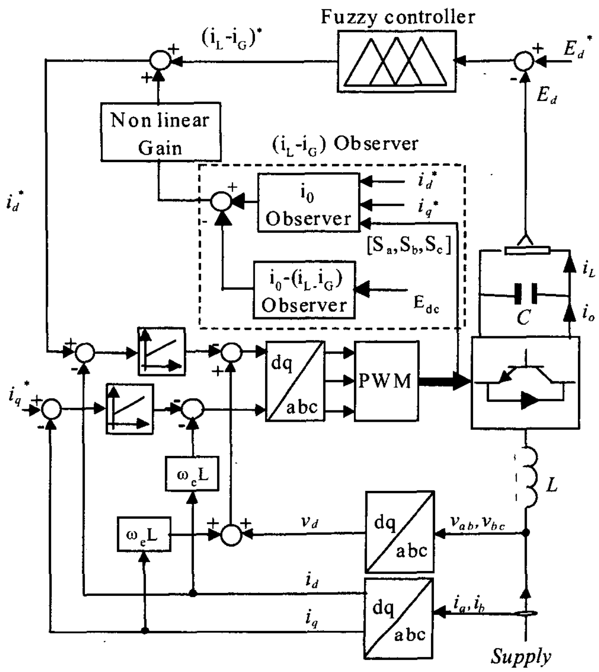

Fig. 4. Schematic of the proposed control system.

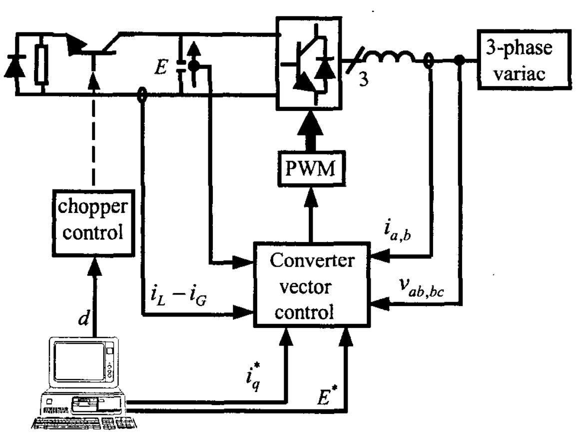

Figure 5. Experimental set-up.

Fig. 6 illustrates the performance of the controller, showing the response of E_{dc} and i_d for step changes in the DC link voltage reference from 500V to 550V. A voltage response with no overshoot is obtained with minor on-line adjustment of the fuzzy controller.

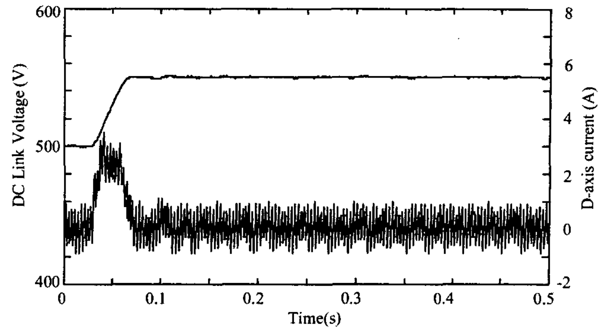

Fig. 6. Controller performance for step change in the reference voltage.

Figure 7 (a)→(d) shows the results for load disturbance rejection for the following controllers:

(a) Fuzzy controller.
(b) Fuzzy controller with feed-forward compensation and (i_L-i_G) measured using a hall effect current transducer.
(c) Fuzzy controller with feed-forward compensation with (i_L-i_G) estimated using the currents i_d^*, i_q^* and the PWM signals [S_a, S_b, S_c].
(d) Fuzzy controller with feed-forward compensation. The current (i_L-i_G) is observed with a parametric model of the power converter.

In each figure a load step impact of 2.5kW is applied at t=25ms and removed at t=275ms. The performance of the controllers is summarised in Table II

TABLE II.
CONTROLLER PERFORMANCE FOR DISTURBANCE REJECTION

Controller	Overshoot	Undershoot	Settling time
(a)	37.8V	37.8V	72ms
(b)	9.0V	7.3V	28ms
(c)	13.5V	13.4V	29ms
(d)	17.0V	15.2V	54ms

Taking the performance of the fuzzy controller alone as the basis for comparison (Fig 7a), Fig. 7b demonstrates the effectiveness of the feed-forward compensation term when the current is measured directly. The settling time is reduced by 60% and dip and the overshoot are reduced by 80%. Using a current observer for (i_L-i_G) with i_o estimated from the PWM signals (Fig 7c) still yields significant improvement, with a reduction in settling time of 60% and dip/overshoot of 64% Finally, the response when (i_L-i_G) is observed using a parametric model of the converter (Fig 7d) shows a reduction in settling time of 25% and dip/overshoot of 58%. Whilst the performance is not as good when an observer is used in place of direct current measurement, there is still a very worthwhile improvement over the case without feed-forward compensation.

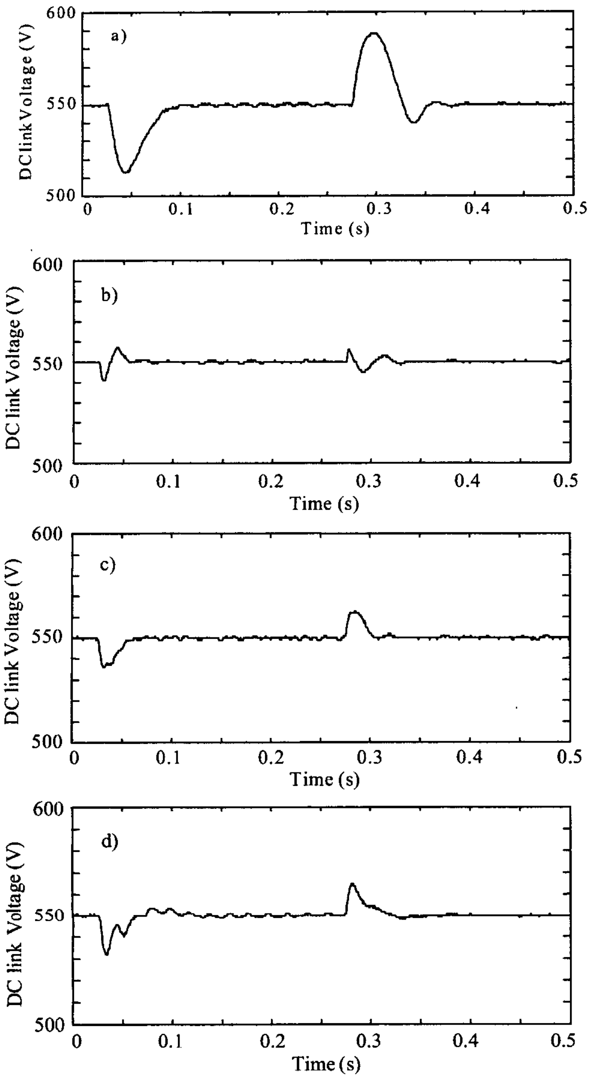

Fig. 7. Performance of various controllers for load disturbance rejection

Finally, the proposed DC link voltage control scheme has been verified on a variable speed wind energy system emulation [12]. Two back-to-back PWM converters are used to interface a cage induction generator to the grid supply. The induction generator is driven with a DC drive that emulates the wind turbine characteristic and is controlled using vector control [8]. Figure 8 shows the AC side converter current, the associated phase voltage and the DC link voltage for steady state operation. The system is operating at the optimum operating speed with the wind turbine emulation system setting a wind velocity of 8 m/s. Because i_q^* is set to zero the phase displacement between the phase voltage and current is 180^0 as expected.

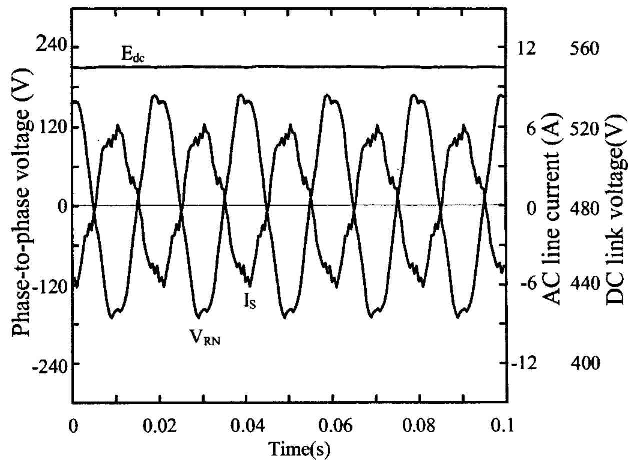

Fig. 8. Steady state performance in a wind energy system emulation

VI. Conclusions

In this paper a new improved control structure for regulating the DC link voltage of a boost type front-end converter in wind energy systems has been presented. Because of the non-linear and variable DC side characteristics, a PI type fuzzy logic controller has been proposed. An improvement in regulation has been obtained using feed-forward mapping of the net dc-link disturbance current with the direct axis (real power) current component of the power converter. To avoid the need to measure the current, a load/disturbance estimator has been used to obtain the feed-forward compensation term.

The experimental results show that excellent regulation can be achieved even without direct measurement of the DC side current. Finally, the scheme has also been validated in an experimental system emulating a wind turbine driven induction generator with a back to back converter interface to the grid.

Acknowledgments

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APPENDIX.

System parameters:

AC Filter inductance L=12mH

AC filter resistance R=0.1Ω

DC link filter capacitance C=1200μF