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Local Vector Control Applied to Current Control

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Abstract—Current control is the most basic control loop for a current controlled inverter-fed machine. Current controllers fall into two categories depending on the reference frames they operate in – rotating reference frame controllers, and stationary frame controllers. This paper introduces a novel current control technique for inverter controlled machines known as Local Vector Control (LVC). This control technique can be used for the current control loops as well as outer control loops, and can operate without alteration in a stationary or rotating reference frame. Due to its high gain properties it potentially offers excellent transient performance, minimises the effects of disturbances, and operates with varying system parameters. This paper is a preliminary investigation of this algorithm applied to power electronic applications.

Keywords—current control; inverter; grid connection

INTRODUCTION

The current control loop of variable speed drives is the most important loop of a drive system. The synchronous PI (SynPI) controller has been the most used control loop in inverter controlled machine systems for many years. The fact that it is easy to implement, can be intuitively tuned, and gives good to excellent performance has been the reason for its wide spread adoption. More recently the Proportional+Resonant (P+R) controllers [1], [2] have found favour in applications involving constant or near constant grid frequencies, since they allow zero steady state error in a stationary frame through the use of a generalised integrator to give near infinite gain at the grid frequency. The Predictive Current Controller (PCC) is another stationary frame controller that has been found to be useful in variable speed drive systems [3], [4].

The control strategy to be investigated in this paper is called Local Vector Control. It is a control strategy first published in 1989 [5]. The theoretical analysis of this controller is complex and outside the scope of this paper. The interested reader can find a thorough analysis of its properties in [6]. Hitherto LVC, as far as the authors know, has not seen any application. Figure 1 shows the structure of the algorithm. As can be seen it has two control loops – one around the Behaviour Reference System (R) and a second loop involving the system to be controlled (S) and the Behaviour Reference Controller (BRC).

A cursory look at the control structure indicates similarities with high gain control [7]. However, LVC is different in that it has system state feedback into the behaviour reference system, which itself not related to the plant model at all.

The main properties of this algorithm that may make it relevant to power electronic applications are:

Figure 1. Block diagram of LVC controller.

- It makes no distinction between linear or non-linear systems.
- It tolerates substantial parameter changes to the system S without changes to the controller gain (provided the gain chosen can cope with the full parameter range).
- Non-linearities due to control saturation are handled since they are seen as a system non-linearities.
- Due to its high bandwidth nature it can operate in a stationary reference frame without resorting to resonant feedback. This means that it can operate over a wide output frequency range.

With these possible advantages one may ask “*why hasn’t this controller seen application?*” The main reason is probably that the algorithm depends on derivatives for its operation, and has therefore been deemed too prone to noise for practical implementation. Having said that, the PCC algorithm [4], [8] is also dependent on derivatives for its operation, and by careful organisation of the sampling has been successfully implemented in a variety of power electronic systems.

The purpose of this paper is to carry out a preliminary investigation of the operation of the LVC algorithm in power electronic applications. Power electronic systems are notorious for producing noisy measurements, so they will be a good test of the ability of the LVC algorithm to operate successfully with noisy measurements. Furthermore, the bandwidths required are high. The testing of the algorithm will be mainly carried out in simulation using realistic representations of the noise on the signals (including quantisation noise). Variable speed drive systems and grid connected applications will be investigated.

Figure 2. Evolution of the state-time trajectories of S and R .

LVC ALGORITHM BASICS

In this section we shall conceptually understand how the LVC algorithm works. The following discussion is with reference to Figures 1 and 2.

The plant S in Figure 1 can have linear or non-linear dynamics. The R system has the dynamics that we want S to have, and is called the Behaviour Reference System (BRS). This is usually some ‘nice’ system such as a unity gain, 2nd order, critically damped differential equation. The simple controller around R is to ensure that it will follow some desired output. The $\dot{y}_R$ state from R is fed to a controller which calculates a control to apply to S to make it follow the state trajectories of R . The state resetting resets the states of R to those of S at each control time.

This action can be further understood from Figure 2, which shows the state trajectories of the S and R systems. Point 1 is at time $t(k)$ and at this point $(y_S(k), \dot{y}_S(k), t(k)) = (y_R(k), \dot{y}_R(k), t(k))$. Point 2 is on the next plane at time $t(k+1)$, this state-time point being $(y_S(k+1), \dot{y}_S(k+1), t(k+1))$. Point 3 is where R evolves to if its states are set to S ’s at $t(k)$ and it is being driven by $u_R(k)$ from the trajectory system controller.

If no control is applied then S will propagate to Point 2 at $t(k+1)$ from Point 1 at $t(k)$. System R starts from the same Point 1 as it has been reset to this by the state resetting process, and propagates to Point 3 at $t(k+1)$. The dashed trajectory is the desired trajectory, and the control is applied so that the trajectory of S is mapped onto that of $R \forall t$.

In order to understand how this process works a few equations must be introduced. Note that this is a conceptual continuous time explanation. LVC is capable of controlling n th order dynamic plant models, but we shall only consider 2nd order plants of the form:

$$\ddot{y}_S = f_S(\dot{y}_S, y_S, t) + g_S(\dot{y}_S, y_S, t)u_S \quad (1)$$

where f_S, g_S can be non-linear functions. We can write the BRS in a similar way to 1. Using $\tilde{f}_{S,R} = f_{S,R}(\dot{y}_{S,R}, y_{S,R}, t)$

and $\tilde{g}_{S,R} = g_{S,R}(\dot{y}_{S,R}, y_{S,R}, t)$ we can write the S and R models as:

$$\ddot{y}_{S,R} = \tilde{f}_{S,R} + \tilde{g}_{S,R}u_{S,R} \quad (2)$$

Let $\hat{u}_S$ be the input that generates $\hat{\dot{y}}_S$ from the system. That is:

$$\hat{\dot{y}}_S = \tilde{f}_S + \tilde{g}_S \hat{u}_S \quad (3)$$

Let us initially consider the algorithm in continuous time. The LVC algorithm works by making the states of the system S follow the states of the system R . This means that:

$$\ddot{y}_S = \ddot{y}_R \forall t \quad (4)$$

and consequently:

$$\ddot{y}_R = \tilde{f}_S + \tilde{g}_S u_S \quad (5)$$

Rearranging this gives:

$$u_S = \frac{\ddot{y}_R - \tilde{f}_S}{\tilde{g}_S} \quad (6)$$

Similarly (3) can be rearranged to give:

$$\hat{u}_S = \frac{\hat{\dot{y}}_S - \tilde{f}_S}{\tilde{g}_S} \quad (7)$$

One can subtract these two expressions to get the difference between the two controls. This expression can then be rearranged to give the augmented control to the S system:

$$u_S - \hat{u}_S = \frac{\ddot{y}_R - \hat{\dot{y}}_S}{\tilde{g}_S} \quad (8)$$

$$\Rightarrow u_S = \hat{u}_S + \frac{\ddot{y}_R - \hat{\dot{y}}_S}{\tilde{g}_S} \quad (9)$$

where the $\ddot{y}_R$ value required is determined from the reference system R as:

$$\ddot{y}_R = \tilde{f}_R + \tilde{g}_R u_R \quad (10)$$

If this u_S is applied to the system S then its 2nd derivative follows that of the reference system, and therefore it behaves dynamically as if it is the reference system. This can be simply seen by substituting the above control (9) into the system equation (3):

$$\ddot{y}_S = \tilde{f}_S + \tilde{g}_S \left(\hat{u}_S + \frac{\ddot{y}_R - \hat{\dot{y}}_S}{\tilde{g}_S} \right) \quad (11)$$

$$= \underbrace{\tilde{f}_S + \tilde{g}_S \hat{u}_S}_{\hat{\dot{y}}_S} + \ddot{y}_R - \hat{\dot{y}}_S \quad (12)$$

$$\therefore \ddot{y}_S = \ddot{y}_R \quad (13)$$

which implies that the dynamics of S are now the same as those of R . This means that the state trajectories of S follow those of R . Therefore if the output of R converges to the reference, then so does the output y_S of S .

Remark 1: There are some regularity conditions on the plant S . For example it is assumed that the plant order is known and at least equal to the BRS model, that there is smoothness of f and g with respect to input and output, and smoothness of f and g with respect to time – i.e. Lipschitz continuous with

respect to time, and the relative degree is constant. These and other conditions are discussed in [6].

The discrete implementation of the algorithm is discussed in [5], [9].

SIMULATION STUDIES

In order to test the operation and versatility of the LVC algorithm in several relevant situations for Power Electronics, the following simulation scenarios were set up:

- Induction machine control
 - using firstly LVC operating in a stationary reference frame;
 - and secondly LVC operating in a rotating reference frame with currents sampled with 12bit A/D converters with 3 bits of additive noise.
- Grid connected application with a poorly damped LCL line side filter and a variable grid inductance simulating a weak grid.

The simulations were implemented with Wolfram SystemModeler[®] which is a Modelica based simulator. The LVC is implemented digitally. The first simulation is of a inverter-fed induction machine. The simulation uses a standard triangular wave carrier sinusoidal PWM generator, and the current controllers are implemented as three stationary frame controllers using LVC. The control frequency is 5kHz and the sampling frequency is 10kHz.

In order to operate in a stationary reference frame, a 2nd order, unity DC gain BRS is set with $\omega_n = 10000$ r/s, and the damping of the system to $\zeta = 1.0$ – i.e. it is critically damped. In the digital form of the LVC algorithm the $\tilde{g}_S$ is replaced with a constant, which effectively sets the gain of the control. The value in this case was set to 600×10^6 . If this is set too small then the control chatters.

The speed control loop is also implemented with an LVC controller, but in this case the 1st order form since the rotating load dynamics are essentially 1st order. The time constant of the unity DC gain 1st order BRS was $\tau = 0.002$ sec. The output of this controller was then used as the torque reference to the vector current controller. The output was limited to 50Nm. The reference currents are derived from a traditional vector control algorithm.

Figure 3 shows the Modelica simulation diagram. Parameters typical of a 7.5kW induction machine are used. Figure 4 shows the performance of the controller under this condition. As can be seen the current is accurately tracking the reference with approximately one sampling interval delay. The transient torque performance is excellent, and the speed is accurately tracking the reference showing that the outer speed loop, which is also implemented with LVC, is also working well. Figure 5 shows zoomed views of the current demonstrating the tracking and transient performance. Note that there is no feedforward of the back-emf in this controller.

The next diagrams show the performance of an LVC vector controlled induction machine in the presence of measurement noise. In this case the current control is implemented in a rotating frame, and 12 bit A/D converters are included for

current measurements. The bottom 3 bits of the A/D measured currents are randomized with uncorrelated noise to simulate noise in a real system. Figure 6 shows that despite the fact that the algorithm uses derivatives, it can be made to work successfully. This is to some degree counter intuitive, but it bodes well for practical implementations of the algorithm.

To show the versatility of the LVC strategy, and its ability to cope with dynamic systems that are underdamped and whose parameters are varying we shall consider a single phase grid connected inverter. The switching frequency is 10kHz. The filter parameters are (from [10]) : $L_{fc} = 0.7\text{mH}$, $L_{fg} = 0.37\text{mH}$, $C_f = 10\mu\text{F}$. There is a resistance of $R_f = 0.01\Omega$ in series with the capacitor. The grid inductance varies from $0 < L_g \leq 6\text{mH}$, and the grid resistance is $R_g = 0.1\Omega$. The current sensing is on the grid side of the filter. Figure 7 shows the Modelica block diagram for the simulation. Note that the grid inductance is variable. The current reference is in-phase with the system voltage.

Figure 8 shows the current performance and the inductance variation during the simulation. There is a step change in the demanded current at 0.15 secs. The filter has very little damping, and therefore will resonate if there are any frequencies near its 3.2kHz resonant frequency. The resonant frequency can be calculated using:

$$f = \frac{1}{2\pi} \sqrt{\frac{L_{fg} + L_g + L_{fc}}{C_f L_{fc} (L_{fg} + L_g)}} \quad (14)$$

and therefore the resonant frequency moves from 3.2kHz with $L_g = 0$ to just below 2kHz with $L_g = 6\text{mH}$. Normally the current through or voltage across the capacitor has to be measured in order to keep these filters stable during operation, especially given the variation in the grid inductance, but there is no capacitor current or voltage feedback in this example. As can be seen given these conditions the performance of the control is OK but not excellent. Note that it handles the changes of inductance with very little change in the output current.

Remark 2: The tracking performance of this case is not that good – there is about 12° phase error, meaning that the maximum power factor is about 0.97. This is due to the natural phase error due to digital PWM delay, coupled with the phase shift due to the 2nd order BRS. The parameters in this case were: $\omega_n = 40000$ r/s, $\zeta = 0.7$, and the control gain factor of 300×10^6 . Note that the LVC is effectively operating as a stationary frame controller, as there is no rotating frame transformations involved.

CONCLUSIONS

In conclusion the simulation studies have shown that the LVC controller can operate successfully in a stationary frame, a rotating frame, and under variable system parameter situations. Furthermore, its ability “modify the behaviour” of the system being controlled has been demonstrated with a resonant LCL filter connected to a variable grid inductance.

The main purpose and contribution of this paper is to introduce the hitherto unused LVC algorithm to current control

Figure 3. Block diagram of LVC stationary frame current control.

(a) Current and reference

(b) Shaft speed and torque

Figure 4. The current, torque and speed performance of the stationary frame controlled LVC system.

(a) Close-up of current and reference

(b) Current transient with reference

Figure 5. Zoomed current and reference for stationary frame LVC.

(a) Current and current reference

(b) Torque and shaft speed

Figure 6. LVC used for current control of a vector controlled drive. Bottom 3 bits of the current measurements are noise.

in power electronic systems, and to carry out a preliminary investigation of its performance. In order to do this several case studies were set up, namely

- Control of an induction machine using stationary frame current controllers without any noise in the measurements.
- Control of an induction machine using a rotating frame controller, with the current measurements using 12 bit A/D converters, and the bottom three bits are noise.
- A single phase PV grid inverter using an LCL filter was implemented. The grid inductance was varied from 0 to 6mH to simulate a grid changing from strong to weak.

Current was measured on the grid side of the LCL filter. The LVC technique applied to current clamp minimisation has recently been experimentally implemented and results recently presented [9]. These results confirmed that this algorithm works in a practical environment.

What is the overall conclusion from this study? The LVC algorithm works reasonable well in electrical machine current

control applications, even when there is substantial noise on the measurements. It does not work as well as P+R controllers in stationary frame applications, although the factor that it does work without any changes in structure is an interesting that without any change in structure that it works at all. In the single phase grid connected inverter application LVC was used without to any other stabilising capacitor current or voltage feedback and with a large variation in grid impedance. However in this case its performance was not very good compared to established techniques.

Tuning of the LVC is a problem. Finding the control gain factor in the digital version was difficult (the denominator in (9)), and was carried out by trial and error. This is not a very satisfactory for real engineering applications.

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