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# Active damping of output LC filter resonance for vector controlled VSI- fed AC motor drive

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**ABSTRACT**

*For longer life of alternating-current (ac) machines, it is desirable to feed them by sinusoidal voltages. This can be achieved by connecting an LC filter between the voltage source inverter and the motor. However, the LC filter creates unwanted oscillation at system resonant frequency. A resistance connected in series with the capacitor is a solution to damp out the resonant frequency oscillation, but this damping technique increases loss in the system. In this paper, a simple active damping technique is proposed for lossless damping of vector-controlled ac motor drives with an LC filter. In the proposed technique, the resistance drop is emulated in the control using the terminal motor voltages. The proposed technique is carried out in the three-phase domain for better accuracy of the control. The proposed technique neither affects the dynamic response of the drive nor changes the design of the standard vector control loops. Results from experimental ac motor drives are presented.*

***INDEX TERMS—****Active damping (AD), induction machine, LCfilter, synchronous machine, vector control.*

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## I. INTRODUCTION

The voltage-source-inverter (VSI)-fed alternating-current (ac) drive topology is standard in the industry. Due to high dv/dt of the VSI output voltages, bearing failure, insulation failure of the motor windings, and issues related to electromagnetic compatibility/interference are common [1]–[6]. Passive dv/dt filters, common-mode filters, and pulse width-modulation (PWM) techniques have been proposed to mitigate the aforementioned problems [7]–[11]. However, for longer life of the motor, it is always desirable to operate the machine with sinusoidal voltages. One common method is to connect an LC filter between the inverter and the machine. The LC filter smoothens the VSI output voltage and supplies sinusoidal voltage into the motor. However, when ac machines are driven by a VSI with an output LC filter, the motor terminal voltage oscillates at system resonant frequency. Although the magnitude of the resonant frequency voltage in the VSI is small, the LC filter does not offer any impedance at the resonant frequency. Therefore, a large amount of resonating current circulates between the VSI and the LC filter. The resonating current magnitude is restricted only by the filter resistance. Due to this circulating current, motor voltage also oscillates at the resonant frequency. The active damping (AD) method provides a good alternative solution for this problem. In this paper, a simple AD technique is proposed for vector controlled VSI-fed ac motors.

**Important features of the proposed active damping technique are:**
1) The control action is taken in per-phase basis for accurate extraction of resonant-frequency signal extraction, which, in turn, ensures appropriate damping.
2) The proposed technique emulates a virtual series resistance for AD of the LC resonance in the control, only by using the terminal voltage information.
3) The proposed technique corrects the delay in the damping signals caused by the switching action of the VSI.
4) The proposed technique damps out transient voltage oscillations during sudden speed and load change and minimizes steady-state resonant-frequency oscillation.
5) The proposed AD technique does not affect the main control loops of the field-oriented control; the design of current control loops is independent of the design of the AD controller.
This paper is organized in the following way: Section II describes the power structure and the brief overview of the proposed control technique. Section III describes the proposed AD technique.

## I. DESCRIPTION OF THE POWER CONVERTER STRUCTURE AND THE PHILOSOPHY OF THE CONTROL TECHNIQUE

### A. Description of Power Converter Structure

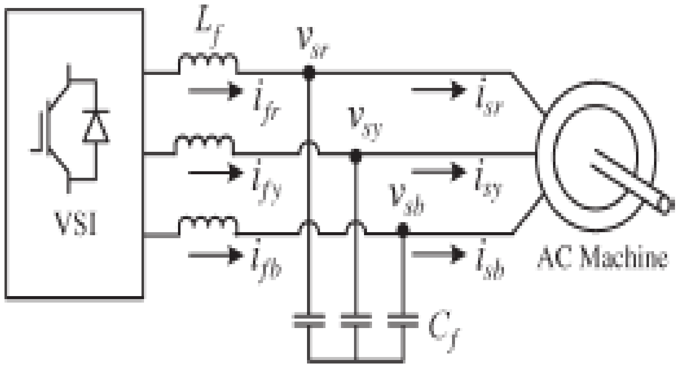


Fig 1.Power hardware

Fig. 1. Shows the power circuit of an ac machine connected to a VSI by an LC filter. Lf is the filter inductance, and Cf is the filter capacitance. vsr, vsy, and vsb are the capacitor voltages; isr, isy, and isb are the machine currents; and ifr, ify, and ifb are the filter currents. Fig. 2(a) and (b) is the equivalent circuits of the ac motor. Ll is the leakage inductance of the machine. For an induction machine, Ll is the sum of the stator (Lls) and rotor (Llr) leakage inductances. For a synchronous machine, $L_l$ is the synchronous inductance Ls of the machine.
The equivalent resonating elements are the filter capacitor Cf and the parallel combination of the filter inductance Lf and Ll. For a synchronous machine, the synchronous inductance Ls is large, as compared with the filter inductance Lf. Therefore, the equivalent inductance Leq for the synchronous machine is almost the same magnitude as Lf.

For the induction machine

$$L\mathrm{eq} = [Lf \times (L\mathrm{ls} + L\mathrm{lr})] / [Lf + (L\mathrm{ls} + L\mathrm{lr})] \ldots\ldots\ldots\ldots \quad (1)$$

For the synchronous machine

$$L\mathrm{eq} = (LfLs)/(Lf + Ls) \approx Lf . \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (2)$$

### B. Philosophy of the Control Technique

A resistance can be connected in series with the capacitor to damp out the *LC* resonance. This solution increases power loss in the system. To achieve lossless damping, an AD method is proposed. In the proposed AD technique, a fictitious resistance value is multiplied by the individual capacitor currents at the resonant frequency and subtracted from the source voltages. In this way, a damping effect of the resistance is emulated but in a lossless fashion. The difficulty in this method is that the capacitor current is noisy. The capacitor current consists of switching-frequency components, along with fundamental and resonant components. In cases where the resonant and switching frequencies are close by, it will be difficult to extract only the resonant-frequency component from the sensed capacitor currents. However, when the inverter switching frequency is high (more than 2 kHz), the capacitor *voltage* contains only the fundamental and resonant components. It does not contain the significant switching-frequency component. However, the capacitor *current* contains a considerable amount of switching-frequency components. The switching-frequency component is close to the resonant-frequency component with higher magnitude. These create serious difficulty in extracting only the resonant-frequency component from the sensed capacitor current, which is required for the control. Therefore, in this paper, it is proposed to emulate the resonant component of the capacitor currents with the help of signatures in the capacitor voltages when the inverter switching frequency is more than 2 kHz.

## II. DESCRIPTION OF CONTROL TOPOLOGY

Exact and noise free, resonant-frequency capacitor voltages are essential for the control. In Section III-A describes the proposed resonant-frequency signal extraction. III-B describes the procedure to generate compensating signals for the proposed AD technique.

### A. Signal extraction at resonant frequency

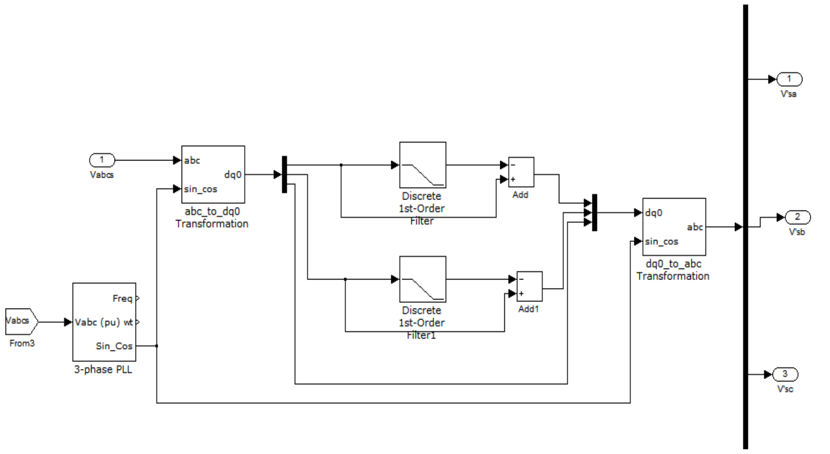


Fig2 signal extraction

At the steady state, the machine terminal voltages contain fundamental- (ωf ) and resonant-frequency (ωn) signals. When the switching frequency of the inverter is high (> 2 kHz), the switching-frequency component in the capacitor voltages are comparatively lower in magnitude than the resonant frequency components. Machine-per-phase voltages vsr, vsy, and vsb are sensed to extract resonant capacitor voltages. The sensed voltages are transformed into the d–q domain. In the transformed d–q voltages, both the fundamental components and the resonant components are present. *These sensed voltages* are filtered using low-pass filters with cutoff frequencies at around 10 Hz. The outputs of the low-pass filters are  are subtracted from *v*sd and *v*sq to extract ˜*v*sd and ˜*v*sq. The extracted resonant-frequency components ˜*v*sd and ˜*v*sq have frequency ($\omega n - \omega f$) due to the *d–q* transformation. The frequency of ˜*v*sd and ˜*v*sq varies with the variation of $\omega f$. To get rid of this variation of $\omega f$ in ˜*v*sd and ˜*v*sq, they are transformed back to the three-phase domain. The outputs of the reverse transform are ˜*v*sr, ˜*v*sy, and ˜*v*sb. Due to the reverse transformation, the extracted-per-phase resonant frequency capacitor voltages ˜*v*sr, ˜*v*sy, and ˜*v*sb are exactly at $\omega n$.

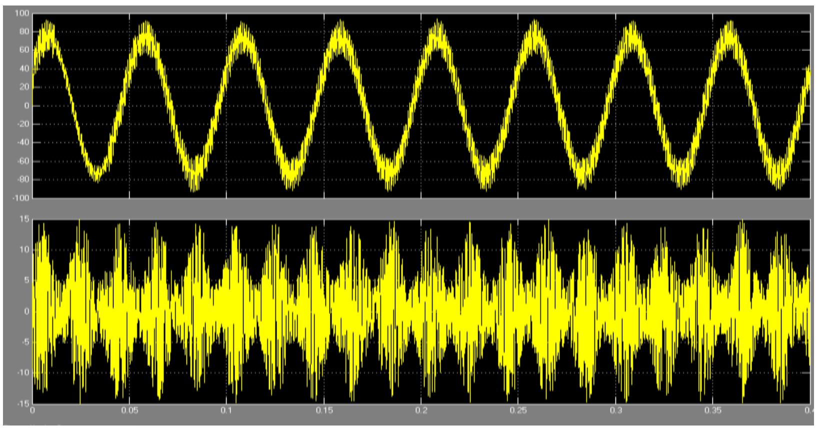

Fig 3.capacitor voltage at resonant frequency

### B. LC filter control block

A series *LC* circuit excited by a sinusoidal voltage source at the resonant frequency does not offer any impedance to the circuit. When a resistance is added in this *LC* circuit, then the current magnitude at the resonant frequency is damped by this resistance. The resistance can be placed in series or in parallel with the capacitor. However, this solution causes power loss in the circuit and reduces efficiency of the drive. Therefore, the AD technique is adopted to damp out the oscillation in lossless fashion without physically connecting any resistance in the circuit. In the proposed method of AD, a series resistance in the *LC* circuit is emulated in the control.

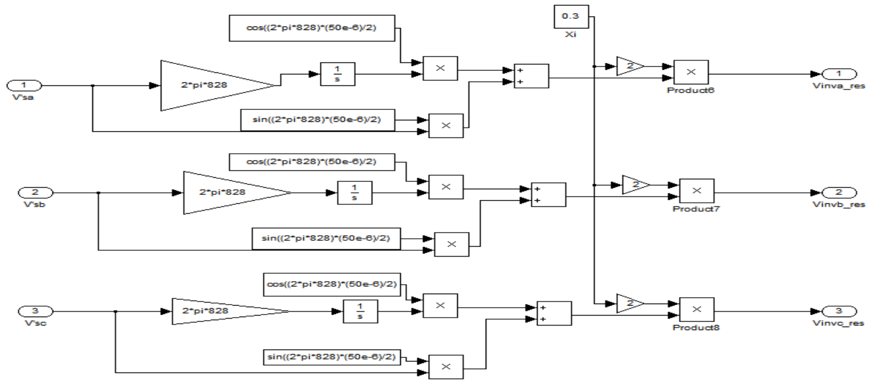


Fig 4. LC filter block

The extracted resonant capacitor voltages ˜Vsr, ˜Vsy, and ˜Vsb mainly contain the resonant-frequency components and they lag by 90◦ from the resonating capacitor currents. The extracted resonant capacitor voltages ˜vsr, ˜vsy, and ˜vsb are integrated to obtain ˜vsr_int, ˜vsy_int, and ˜vsb_int signals (see Fig. 5). Instead of a pure integrator, a low-pass filter is used to generate ˜vsr_int, ˜vsy_int, and ˜vsb_int signals to avoid dc drift problems. The cutoff frequencies of these low-pass filters are kept at around 50 Hz, which are far below the resonant frequency $\omega n$. Therefore, these low-pass filters do not cause any phase shift to the ˜vsr_int, ˜vsy_int, and ˜vsb_int signals. These signals lag by 180◦ out of phase from the resonant capacitor currents. ˜vsr_int lags by 90◦ from ˜vsr In below Fig5. phasor relationships for ˜vsr, ˜vsr_int, and vr_comp are elaborated for an induction motor drive with the inverter switching frequency kept at 4.9 kHz.

INVERTER DELAYS GENERATED AT DIFFERENT EXPERIMENTAL CONDITIONS

| *Experimental Conditions* | *Inverter Delay* ($\omega_n T_s/2$) |
|---|---|
| Induction Machine, switching freq.=2.4 kHz, Resonant freq.=828 Hz. | 61.1° |
| Induction Machine, switching freq.=4.9 kHz, Resonant freq.=828 Hz. | 30.6° |
| Synchronous Machine, switching freq.=4.9 kHz, Resonant freq.=503 Hz. | 18.6° |

TABLE1

**Obtained output waveform of integrated signal, compensating signal and resonant inverter voltage are shown below**

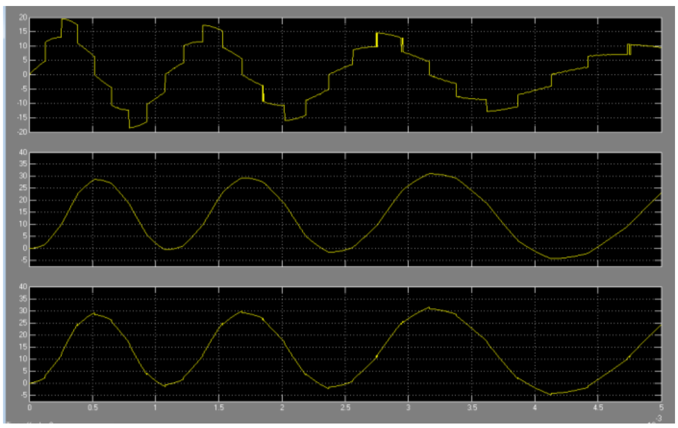

**Fig5.capacitor voltage, integrated voltage and compensated signal**

When the inverter switching frequency is close to the resonant frequency, the inverter introduces a considerable amount of phase delay to the compensating signals $\tilde{v}_{sr\_int}$, $\tilde{v}_{sy\_int}$, and $\tilde{v}_{sb\_int}$. Therefore, it is essential to advance the phase of $\tilde{v}_{sr\_int}$, $\tilde{v}_{sy\_int}$, and $\tilde{v}_{sb\_int}$ to compensate the inverter phase lag. Table I elaborates the phase delay ($\omega_n T_s/2$) generatedby the inverter for the experiments carried out in this paper. The phase delay is predicted from the system resonance and switching frequencies of the inverter.

Fig6 shows the phasor relationships of important signals at the resonant frequency. The inverter source voltage $v_{res}$ and the resonant capacitor current $i_{res}$ are in the same phase. The capacitor voltage $\tilde{v}_{sr}$ lags them by 90◦. $\tilde{v}_{sr\_int}$, $\tilde{v}_{sy\_int}$, and $\tilde{v}_{sb\_int}$ are at the opposite phase with $i_{res}$. $\tilde{v}_{sr\_int}$, $\tilde{v}_{sy\_int}$, and $\tilde{v}_{sb\_int}$ signals are phase advanced by $\omega_n T_s/2$ to construct the per-phase compensating signals $v_{r\_comp}$, $v_{y\_comp}$, and $v_{b\_comp}$. This phase advancement compensates the delay of $\omega_n T_s/2$ introduced by the inverter.

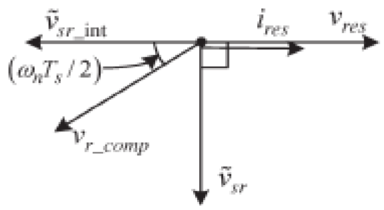


**Fig6. Phasor diagram**

The inverter switching frequency is $f_s$, and the inverter time constant is $T_s/2$, where$T_s = 1/f_s$. $v_{r\_comp}$ is obtained from

$v_{rcomp} = \tilde{v}_{sr\_int}\cos(\omega_n T_s/2) + \tilde{v}_{sr}\sin(\omega_n T_s/2)$

As $\cos(\omega_n T_s/2)$ and $\sin(\omega_n T_s/2)$ are fixed numbers, the compensation for the inverter delay can be easily and accurately introduced. For the proposed AD, $v_{r\_comp}$, $v_{y\_comp}$, and $v_{b\_comp}$ signals are multiplied by the scaling factor $K_{damp}$ to emulate the resistance drop, i.e., $v_{invr\_res} = K_{damp} \times v_{r\_comp}$.

$v_{invr\_res}$, $v_{invy\_res}$, and $v_{invb\_res}$ signals are directly added to the inverter voltage references $V^*_{invr}$, $v^*_{invy}$, and $v^*_{invb}$ generated from the standard vector control block. The corrective action is instantaneous as the correcting signals are directly added to the inverter voltage references. Moreover, the proposed AD technique does not hamper the main vector control loops.

$K_{damp}$ can be expressed in terms of the damping factor $\xi$, i.e.,

$$K_{damp} = R_{fvir}\,|i_{res}(t)/v_{r\_comp}| = 2\xi$$

Where $\xi = (R_{fvir}/2)\sqrt{c_f/L_{eq}}$

It is experimentally observed that, for $\xi$ varying from 0.2 to 0.4, the system most effectively works. For the lower damping factor, the damping effect is not prominent, and for the higher damping factor, the compensating signals cause distortion to the actual voltage signals.

The complete block diagram of the proposed AD technique is shown in Fig 7. The block diagram is valid for both induction and synchronous machines.

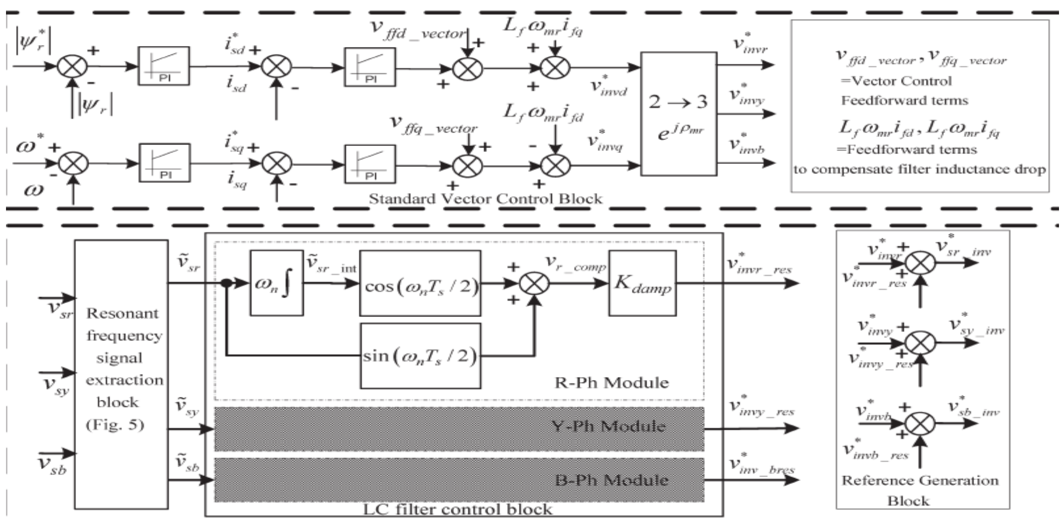


Fig7complete block diagram

**Simulation result at the 4.9-kHz Switching Frequency:**

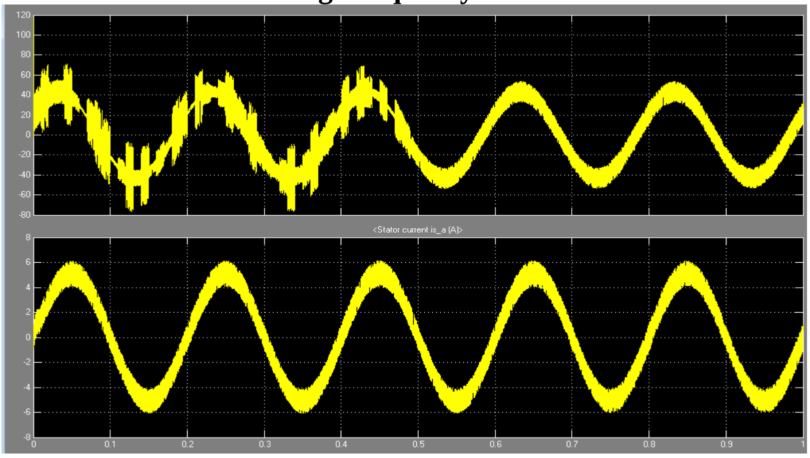

**Fig 8 shows R-phase capacitor voltage and machine current at 5hz with zeta value 0.3 with active damping at time o.5.**

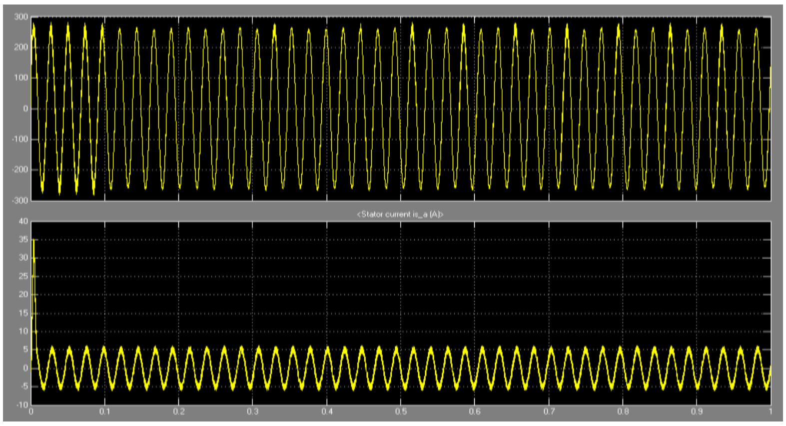

**Fig 9 shows R-phase capacitor voltage and machine current at 43hz with zeta value 0.3 with active damping at time 0.5.**

**Experimental Results at the 2.4-kHz Switching Frequency:**

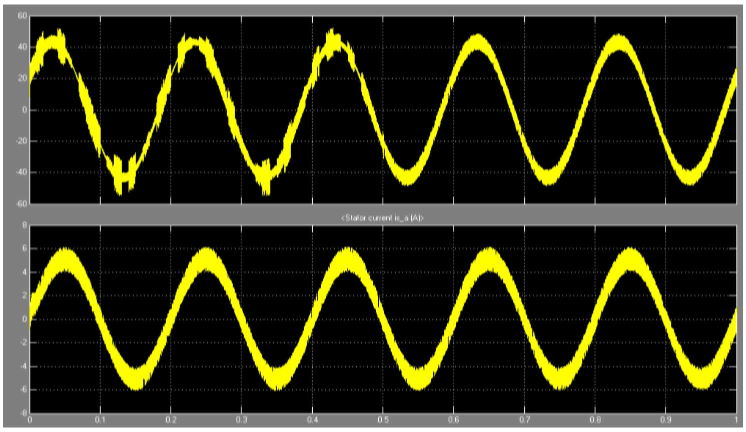

**Fig10. R-phase capacitor voltage and machine current at 43hz with zeta value 0.4 with active damping at time 0.5.**

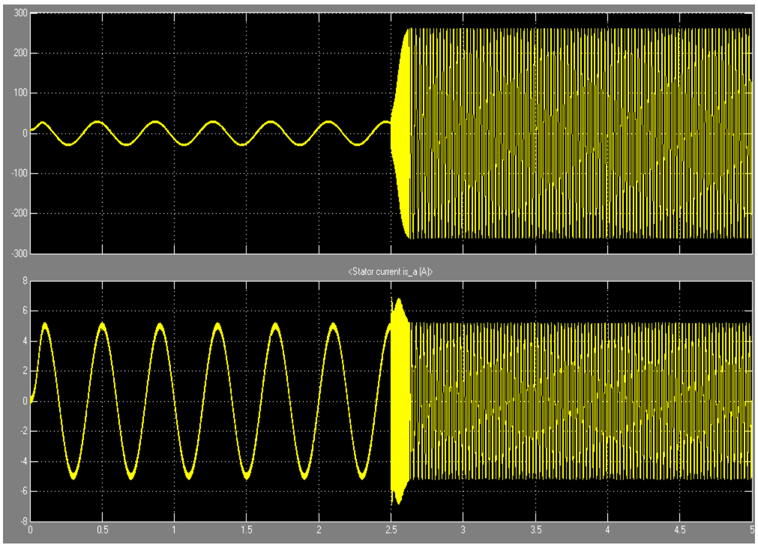


**Fig. 11 demonstrates the capacitor voltage and machine current waveform for a sudden speed change of the machine from 2.5 to 43 Hz with AD.**

## CONCLUSION

An Active Damping technique has been proposed for vector-controlled VSI-fed ac machine drives with output LC filters. This technique uses virtual resistor concept which significantly reduces resonant-frequency oscillation in motor terminal voltages and line currents. The proposed technique independently works from the vector control loops. The AD technique uses capacitor voltages to construct compensating signals. It acts on a per phase basis for better accuracy of the control. This active damping technique can be extended to any three-phase LC-filter-based system, namely, LCL-filter-based front-end converters or shunt active filters, and Active damping can also be done by using State-space based method.

## APPENDIX

1. **Induction Machine Details**

1.1. Machine details: 1.5-kW 220-V 11-A 1440-r/min four-pole Y-connected 50-Hz induction machine;

1.2. Machine parameters: Rs = 0.66 Ω Rr= 0.21 Ω ,Llr =1.62 mH, Lls = 1.62 mH, Lm = 38.8 mH;

1.3. Filter parameters: Lf = 2 mH, Cf = 30μF, and fn =828 Hz.

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