MODELLING AND SIMULATION OF LOSSLESS DAMPING REDUCTION BY VECTOR CONTROLLED AC MOTOR DRIVE
WITH AN EFFICIENT LC FILTER

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Abstract:- In this paper Active damping technique is used to damp out the unwanted resonant frequency oscillations and proposed for lossless damping of vector-controlled ac drives with an efficient LC-Filter. This paper mainly concentrated on protection of Induction motor and Synchronous motor under any balanced or unbalanced load conditions and this proposed technique is simulated with the combination of Voltage Source Inverter (VSI), LC Filter and AC Drives. However, the LC-Filter created unwanted oscillations due to internal resistance at system resonant frequency. This resistance drop is emulated by controlling terminal voltage. The proposed technique neither affects the dynamic response of the drive nor changes the design of the standard vector control loops. This proposed technique is carried out in three phase domain for better accuracy of control. This paper has been implemented and simulated by using MATLAB/SIMULINK 7.8 (R2009a) version.

I. INTRODUCTION

Voltage source inverters are used to regulate the speed of three-phase drives by changes the frequency and the voltage. The voltage-source-inverter (VSI)-fed alternating-current (ac) drive topology is standard in the market. Due to high \( \frac{dv}{dt} \) of the VSI output voltages, bearing failure, insulation failure of the motor windings, and issues related to electromagnetic compatibility/interference are common. Passive \( \frac{dv}{dt} \) filters, common-mode filters, and pulse width-modulation (PWM) techniques have been proposed to mitigate the aforementioned problems. 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 [1-3].

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 control of such a configuration, when the filter corner frequency is within the bandwidth of the current loops, has been addressed. Vector control of the induction machine with the LC filter is implemented by using four cascaded proportional-integral loops. Capacitor-voltage and inductor-current control loops are present, in addition to the main vector control loops. The active damping (AD) method provides a good alternative solution for this problem. To date, very little work has been reported on AD for VSI-fed adjustable speed drives for ac machines [4-7].

The AD technique has been also reported for LCL-filter based grid side converter current source inverter with CL filter, uninterruptable power supply application, and direct-current (dc) converter for good transient and steady-state performances. A simple and robust AD technique for the grid-side converter is proposed. In that paper, the anti-phase capacitor resonating voltages are subtracted from the voltage references in the synchronous reference frame [11-18]. In this paper, a simple AD technique is proposed for vector controlled VSI-fed ac motors.

**Important features of the proposed technique are:**

- The control action is taken in per-phase basis for accurate extraction of resonant-frequency signal
extraction, which, in turn, ensures appropriate damping.

The proposed technique emulates a virtual series resistance for AD of the LC resonance in the control.

The proposed technique corrects the delay in the damping signals caused by the switching action of the VSI.

The proposed technique damps out transient voltage oscillations during sudden speed and load change and minimizes steady-state resonant-frequency oscillation.

The proposed AD technique does not affect the main control loops of the field-oriented control.

II. POWER CONVERTER STRUCTURE AND CONTROL TECHNIQUE

A. Power Converter Structure Description

The power circuit of an ac machine connected to a VSI by an efficient LC filter is shown in Fig.1. \( L_f \) is the filter inductance, and \( C_f \) is the filter capacitance. \( v_{sr}, v_{sy}, \) and \( v_{sb} \) are the capacitor voltages; \( i_{sr}, i_{sy}, \) and \( i_{sb} \) are the machine currents; and \( i_{fr}, i_{fy}, \) and \( i_{fb} \) are the filter currents. Fig. 2(a) and (b) is the equivalent circuits of the ac motor. \( L_l \) is the leakage inductance of the machine. For an induction machine, \( L_l \) is the sum of the stator \( (L_{ls}) \) and rotor \( (L_{lr}) \) leakage inductances. For a synchronous machine, \( L_l \) is the synchronous inductance \( L_s \) of the machine. The equivalent resonating elements are the filter capacitor \( C_f \) and the parallel combination of the filter inductance \( L_f \) and \( L_l \). For a synchronous machine, the synchronous inductance \( L_s \) is large, as compared with the filter inductance \( L_f \). Therefore, the equivalent inductance \( L_{eq} \) for the synchronous machine is almost the same magnitude as \( L_f \).

For the induction machine

\[
L_{eq} = \frac{(L_l \times (L_{ls} + L_{lr}))/ (L_l + (L_{ls} + L_{lr}))}{(1)}
\]

For the synchronous machine

\[
L_{eq} = (L_l L_s)/(L_l + L_s) \approx L_f \quad (2)
\]

Equations (1) and (2) are derived by thevenizing the circuit, as shown in Fig. 2(a) and (b). The resonant frequency \( \omega_n \) of the system is decided by

\[
w_n = 1/\sqrt{L_{eq}C_f} \quad (3)
\]

Around 10% voltage drop is allowed across the filter inductor. The choice of the inductor value is made as a compromise between reduction of inductor current ripple amplitude and inductor size. The capacitor value can be chosen such that the system resonant frequency \( \omega_n \) is lesser than one third of the inverter switching frequency [3]. This is a tradeoff between the filter size and attenuation of the resonant frequency by the control action. In this case, at least three samples can be obtained to replicate the resonant frequency components. The filter details for an induction motor and a synchronous motor are given in Tables I and II.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DETAILS OF FILTER FOR INDUCTION MACHINE DRIVE WITH OPERATING SWITCHING FREQUENCY AT 2.4 AND 4.9 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Inductance</td>
<td>( L_f )</td>
</tr>
<tr>
<td>Total Machine Leakage Inductance</td>
<td>( L_{ls} + L_{lr} )</td>
</tr>
<tr>
<td>Filter Capacitance</td>
<td>( C_f )</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>( w_n )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>DETAILS OF FILTER FOR SYNCHRONOUS MACHINE DRIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Inductance</td>
<td>( L_f )</td>
</tr>
<tr>
<td>Synchronous Inductance</td>
<td>( L_s )</td>
</tr>
<tr>
<td>Filter Capacitance</td>
<td>( C_f )</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>( w_n )</td>
</tr>
</tbody>
</table>
B. 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 (2.4 kHz) is close to the resonant-frequency component (828 Hz) 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. In the proposed AD technique, compensation for the inverter delay can be also easily and accurately incorporated. However, when the inverter switching frequency is very low (around 500 Hz), the switching-frequency components in the capacitor voltage are higher in magnitude compared with the resonant frequency. Therefore, in these cases, suitable PWM techniques have to be adopted to reduce the switching-frequency harmonics in the capacitor voltages.

III. CONTROL TOPOLOGY

Exact and noise free, resonant-frequency capacitor voltages are essential for the control.

A. Resonant-Frequency Signal Extraction Block

Fig. 3 describes the resonant-frequency signal extraction block. At the steady state, the machine terminal voltages contain fundamental- (of) and resonant-frequency (on) 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 vr, vs, and vb are sensed to extract resonant capacitor voltages. The sensed voltages are transformed into the d-q domain. In the transformed d-q voltages vds and vsq, both the fundamental components vdsf and vsqf and the resonant components vrsd and vsrq are present. vdsf and vsqf are dc quantities and vrsd and vsrq are ac quantities that are close to the resonant frequency, i.e.,

\[ v_{sd} = v_{sdf} + \tilde{v}_{sd} \]  \hspace{1cm} (4)
\[ v_{sq} = v_{sqf} + \tilde{v}_{sq} \]  \hspace{1cm} (5)

vds and vsq are filtered using low-pass filters with cutoff frequencies at around 10 Hz. The outputs of the low-pass filters are vdsf and vsqf. They are subtracted from vsd and vsq to extract \( \tilde{v}_{sd} \) and \( \tilde{v}_{sq} \). The extracted resonant-frequency components \( \tilde{v}_{sd} \) and \( \tilde{v}_{sq} \) have frequency (of) due to the d-q transformation. The frequency of \( \tilde{v}_{sd} \) and \( \tilde{v}_{sq} \) varies with the variation of of. To get rid of this variation of of in \( \tilde{v}_{sd} \) and \( \tilde{v}_{sq} \), they are transformed back to the three-phase domain. The outputs of the reverse transform are \( \tilde{v}_{sr} \), \( \tilde{v}_{sq} \), and \( \tilde{v}_{sb} \). Due to the reverse transformation, the extracted per phase resonant frequency capacitor voltages \( \tilde{v}_{sr} \), \( \tilde{v}_{sq} \), and \( \tilde{v}_{sb} \) are exactly at on. Hence, the frequency of the extracted components lies at (on of). Therefore, a little frequency mismatch exists in these techniques.

Fig. 3. Resonant-frequency signal extraction circuit.
current signal, but the extracted resonant capacitor
voltages ˜vr, ˜vsy, and ˜vsb mainly contain the
resonant-frequency components, and they lag by 90°
from the resonating capacitor currents. The extracted
resonant capacitor voltages ˜vr, ˜vsy, and ˜vsb are
integrated to obtain ˜vsr_int, ˜vsy_int, and ˜vsb_int
signals. Instead of a pure integrator, a low-pass filter
is used to generate ˜vsr_int.

When the inverter switching frequency is close
to the resonant frequency, the inverter introduces a
considerable amount of phase delay to the
compensating signals ˜vsr_int, ˜vsy_int, and ˜vsb_int.
Therefore, it is essential to advance the phase of
˜vsr_int, ˜vsy_int, and ˜vsb_int to compensate the
inverter phase lag. Table III elaborates the phase
delay (onTs/2) generated by the inverter for the
simulations carried out in this paper. The phase delay
is predicted from the system resonance and switching
frequencies of the inverter.

Phasor relationships of important signals at the
resonant frequency is shown in Fig. 5. The inverter
source voltage vres and the resonant capacitor current
ires are in the same phase. The capacitor voltage ˜vr
lags them by 90°. ˜vsr_int, ˜vsy_int, and ˜vsb_int are
at the opposite phase with ˜ires. ˜vr_int, ˜vsy_int, and
˜vsb_int signals are phase advanced by onTs/2 to
construct the per-phase compensating signals
vr_comp, vy_comp, and vb_comp. This phase
advancement compensates the delay of onTs/2
introduced by the inverter. The inverter switching
frequency is fs, and the inverter time constant is Ts/2,
where Ts = 1/fs. vr_comp is obtained from

\[ v_{r\_comp} = \sqrt{v_{sr\_int}} \cos \left( \omega_n T_s / 2 \right) + \sqrt{v_r} \sin \left( \omega_n T_s / 2 \right) \]  

(6)
### TABLE III
INVERTER DELAYS GENERATED AT DIFFERENT CONDITIONS

<table>
<thead>
<tr>
<th>Simulation Conditions</th>
<th>Inverter Delay ((\omega_n T_s/2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction Machine, switching freq. = 2.4 kHz, Resonant freq. = 828 Hz.</td>
<td>61.1°</td>
</tr>
<tr>
<td>Induction Machine, switching freq. = 4.9 kHz, Resonant freq. = 828 Hz.</td>
<td>30.6°</td>
</tr>
<tr>
<td>Synchronous Machine, switching freq. = 4.9 kHz, Resonant freq. = 503 Hz.</td>
<td>18.6°</td>
</tr>
</tbody>
</table>

### TABLE IV
VARIATION OF \(f_n\) AND \(\xi\)

<table>
<thead>
<tr>
<th>(f_n) (Hz)</th>
<th>((L_{ls} + L_{lr})) (3.24 mH)</th>
<th>+20% ((L_{ls} + L_{lr}))</th>
<th>-20% ((L_{ls} + L_{lr}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>828</td>
<td>802</td>
<td>894</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>0.29</td>
<td>0.324</td>
<td></td>
</tr>
</tbody>
</table>

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.,

\[
v_{inver\_res} = K_{damp} \times v_{r\_comp}
\]

\(v_{inver\_res}, v_{invy\_res}, \text{and } v_{invb\_res}\) signals are directly added to the inverter voltage references \(v_{inver}, v_{invy}, \text{and } v_{invb}\) 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.,

\[
K_{damp} = \frac{R_{fivr}|i_{res}(t)|/v_{r\_comp}}{2\xi}
\]  

(8.a)

Where

\[
\xi = (R_{fivr}/2) \sqrt{\frac{C_f L}{L_{eq}}}
\]  

(8.b)

It is 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. 6. The block diagram is valid for both induction and synchronous machines.

![Block Diagram](image-url)
C. System Robustness

The values of the stator and rotor leakage inductances may vary with time, or there may be error in the measurements. To account these changes, ±20% variation of the total stator and rotor leakage inductances is considered. Due to these variations, following changes in the system will happen: 1) The resonant frequency will change. 2) Damping factor $\xi$ will change.

The variation of the resonant frequency $f_r$ and the damping factor $\xi$ due to the variation of the values of the stator and rotor leakage inductances are shown in Table IV.

The extraction of the resonant-frequency signal is not decided by any predetermined resonant-frequency value. Therefore, small changes in the resonant frequency will not hamper the control action. The variation of $\xi$ will change the value of the damping resistance to be added in the system. However, this small change, as shown in Table IV, will not cause much variation in the proposed damping. Simulation results in Fig. 16(a) and (b) demonstrate the robustness of the proposed damping technique.

IV SIMULATION RESULTS

A. Simulation Results for an Induction Machine (Steady State)

The simulations are carried out using a two-level insulated gate- bipolar-transistor (IGBT) based VSI with an efficient LC filter, and the control algorithm is implemented in MATLAB/SIMULINK is shown Fig. 7. A high pass filter (HPF) is integrated in the control system for better performance. Machine and filter details are given in the Appendix and in Table I. The inverter switching frequency is kept for these experiments at 2.4 and 4.9 kHz. The system resonant frequency is fixed at 828 Hz. The current controller bandwidths are fixed at 100 Hz. The analog-to-digital converter (ADC) sampling frequency is kept at the switching frequency of the inverter. Anti-aliasing filters with 30-kHz bandwidth are used before the ADC section to remove high-frequency noises from the sensed signals.

Fig. 7. Simulation diagram of an ac machine connected to a VSI by an efficient LC filter.

Simulation Results at the 4.9-kHz Switching Frequency:

Figs. 8 and 9 are the waveform for the damping factor $\xi = 0.3$. The damping factor decides the magnitude of the resistance to be included in the circuit. Phase advancement given to compensate the inverter delay is 30.6° (as shown in Table III). It is clearly observed from the waveforms that, after activation of the AD loop in the control, the capacitor voltage waveforms become oscillation free.

Fig. 8. $R$-phase capacitor voltage and machine current at 5 Hz ($\xi = 0.3$) with and without AD.
B. Simulation Results for a Synchronous Machine
(Steady State)

The Simulation is carried out using a three-level IGBT based VSI, and the control algorithm is implemented in MATLAB. Figs. 12 and 13 are the Simulation results on a synchronous machine. The machine and filter details are provided in the Appendix and in Table II. The inverter is switched for these experiments at 4.9 kHz, and the system resonant frequency is at 503 Hz. The phase advancement given to compensate the inverter delay is 18.6º (as shown in Table III); results are given for the damping factor $\zeta = 0.3$. The result demonstrates the effectiveness of the method to reduce the resonant-frequency components in the synchronous machine terminal voltages.
C. Simulation Results for an Induction Machine (Dynamic Waveform)

Fig. 14 demonstrates the waveform for a sudden speed change of the machine from 2.5 to 43 Hz with AD. Fig. 15 demonstrates the waveform for a sudden load change at 43 Hz. From these waveforms, it is clear that the AD loop does not affect the dynamic operation of the normal vector control. This technique only removes the resonant-frequency oscillation from the waveforms. These Simulation results on an induction machine during dynamic condition demonstrate that the presence of the proposed AD technique does not affect the normal functioning of the field-oriented control.

D. Simulation Results for an Induction Machine (Robustness)

Fig. 16(a) and (b) is the capacitor voltage waveforms for the damping factor $\zeta$ at 0.25 and 0.35, respectively. It can be observed from the Simulation results that the small variations of $\zeta$ due to the variation of leakage inductance do not disturb the system operation (see Fig. 6).

Fig. 14. R-phase capacitor voltage and machine current during the sudden speed change from 2.5 to 43 Hz with AD.

Fig. 15. R-phase capacitor voltage and machine current during the sudden application of the 1-kW load at 43 Hz with AD.

Fig. 16. (a) R-phase capacitor voltage and machine current at 20 Hz ($\zeta = 0.25$) with and without AD. (b) R-phase capacitor voltage and machine current at 20 Hz ($\zeta = 0.35$) with and without AD.
V. CONCLUSION

In this paper Active damping technique is used to damp out the unwanted resonant frequency oscillations and proposed for lossless damping of vector-controlled ac drives with LC-Filter. This technique 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 and instantly acts. The proposed AD technique does not work well for very low inverter switching frequency. Simulation results verified the robustness of the proposed damping technique.

REFERENCES

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