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Minimization of Resonant Frequency Oscillations in Terminal Voltages of AC Motors Using Active Damping Technique

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Abstract:- This paper presents the detailed simulation of comparison between Induction Motor and Synchronous Motor with reduction of resonant frequency oscillations in their terminal voltages by using Active damping technique. 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 (I.M&S.M). However, the LC-Filter created unwanted oscillations due to internal resistance at system resonant frequency. This resistance drop is emulated by controlling terminal voltage. 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. 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 7.8 (R2009a) / SIMULINK version. Simulation results have been compared successfully with Induction motor and Synchronous motor in steady state, transient state and robustness conditions.

Index terms:- Active Damping technique (AD), Induction Machine (I.M), LC-Filter, Synchronous Machine (S.M).

I. INTRODUCTION

The voltage source inverter (VSI) fed alternating current (ac) drive topology is Standard in the industry. Ac motor drives (I.M and S.M) are commonly effected by sudden Change of loads, sudden change in speeds and high dv/dt ratings hence it causes to insulation failure of the motor windings, bearing failure and issues related to electromagnetic compatibility or interference are Common [1]-[6]. So consequently shorten the motor service life. To avoid afore mentioned

Problems AC drives are always operated with sinusoidal voltages. To achieve pure sinusoidal voltages of motors, an LC filter inserted between the inverter output terminals and ac motor terminals. In this system, an LC filter filtering the output voltages of VSI and supplies this output voltages to the motor. The entire process of the proposed system able to damp out the resonance frequency oscillations for lossless damping of vector-controlled ac motor drives with an LC-Filter by using simulation process. Passive dv/dt filters, common-mode filters and pulse width-modulation (PWM) techniques also have been proposed to mitigate afore mentioned problems [7]-[11]. 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 huge 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 control of such a configuration, when the filter corner frequency is within the bandwidth of the current loops has been addressed [12]–[15]. The active damping (AD) method provides a good alternative solution for reducing resonance frequency oscillations problem. Active damping technique operated with ac drives. However, AD with direct torque control has been proposed [16]. The AD technique has been reported for LCL-filter based grid side converter also [17]–[21], [25], [27], [29]–[32] and current source inverter with CL filter [21], [22], [26], uninterruptable power supply application [23] and direct-current (dc) – dc converter [24] for good transient and steady-state performances. A simple and robust AD technique for the grid-side converter is proposed.

In that paper, the antiphase capacitor resonating voltages are subtracted from the voltage references in the synchronous reference frame. However, the phase shift of voltages due to the LC filter is not addressed. A genetic-algorithm-based AD technique for the grid-side converter was also proposed [19]. Active damping technique uses compensating voltages and damping factor to reduce resonance frequency oscillations.

Main features of proposed active damping technique:

- To corrects the delay in damping signals caused by the switching action of the VSI.
- Damp out the transient voltage oscillations and minimises the steady-state resonant frequency oscillations.
- It does not affect the main control loop of the field-oriental control.
- It emulates a virtual series resistance of LC-filter.

II. DESCRIPTION OF SIMULATED POWER CIRCUIT AND CONTROL SCHEME

A. Description of Simulated Power Circuit:

Figure 1(a) shows the block diagram of simulink power converter structure. In this circuit, an LC-filter inserted between voltage source inverter and ac motors. Here, VSI output voltages are controlled by adjustment of DC source and it has capability to maintain balanced constant voltages under any load conditions. And LC filter is used to filters the inverter output voltages and this output given to AC motors then machines are driven with those output voltages at higher efficiency.

Figure.1 (b) represents construction of power circuit for AC Drive (I.M or S.M) with VSI and LC-Filter. In this circuit an AC Machine (I.M/S.M) operated with output of LC- Filter and output of VSI to get machine per phase voltages and per phase currents. Where L_f and C_f are represents the filter inductance and the filter capacitance respectively. v_{sr} ,v_{sy} and v_{sb} are represents the capacitor voltages. i_{sr} , i_{sy} and i_{sb} are the machine currents. i_{fr} , i_{fy} and i_{fb} are represents the filter currents. Fig.2 (a) and fig.2 (b) shows simulated power circuit of Induction motor and synchronous motor respectively. The operation of simulink power converter circuit with Induction machine or Synchronous machine is same as power converter circuit is shown in below figure.

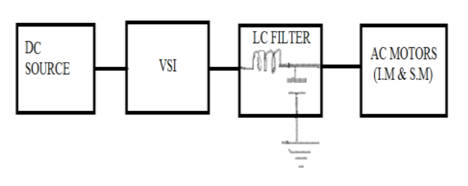

Figure 1(a): Block Diagram of simulink power circuit.

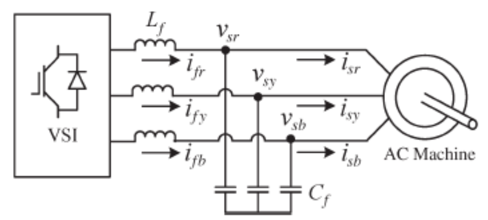

Figure 1(b): Construction of Power Circuit.

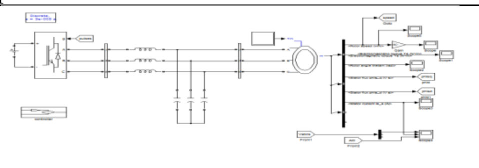

Fig. 2(a): Simulink Diagram of Power Converter circuit with Induction Motor

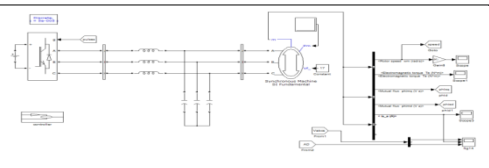

Fig 2(b): Simulink Diagram of Power Converter circuit with Synchronous Motor.

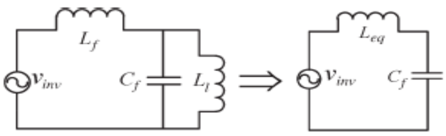

Fig.3 (a): Equivalent *LC* circuit. 3(b). Thevenin's Equivalent of *LC* circuit

Fig. 3(a) and (b) is the equivalent circuits of an AC motor. In above circuit, L_l is represents leakage inductance of the machine. For an induction machine, leakage induction (L_l) is the sum of the stator leakage inductance (L_{ls}) and rotor leakage inductance (L_{lr}). For a synchronous machine, L_l is equal to synchronous inductance (L_s). Where, filter capacitor C_f and the parallel combination of filter inductance (L_f) and leakage inductance (L_l) are equivalent resonating elements. For a synchronous machine, synchronous inductance $L_s$is large as compared with the filter inductance (L_f).Therefore, equivalent inductance (L_{eq}) of the synchronous machine is almost same magnitude as filter inductance (L_f).

For the induction machine,

$L_{eq} = [L_f \times (L_{ls} + L_{lr})]/[L_f + (L_{ls} + L_{lr})]$...(1)

For the synchronous machine,

$L_{eq} = (L_f L_s)/(L_f + L_s) \approx L_f$ ..... (2)

Equations (1) and (2) are derived by above thevinizing equivalent circuits are shown in Fig. 3(a) and (b). The resonant frequencyω_n of the system is decided by,

$\omega_n = \frac{1}{\sqrt{L_{eq} C_f}}$ ...... (3)

Resonance is a particular type of phenomenon inherently found in every kind of systems like Electrical, Mechanical, Optical, Acoustical and even automatic. Resonance is occurrence when the circuit should consists two types of energy storage elements have capability of inter changing energy between one to another. However it does not exists when only one type of energy storing element is present in the system. Around 10% voltage drop is allowed across the filter inductor. The inductor is made up of reduction of inductor current ripple amplitude and inductor size. The capacitor value can be chosen such that when the system resonant frequency ω_n is lesser than one third of the inverter switching frequency [3]. This is a trade-off between the filter size and attenuation of the resonant frequency by the control action. The filter details for an induction motor and synchronous motor are given in Table (I) and Table (II). The machine details are given in the Appendix.

TABLE (I) Filter details for Induction machine at switching frequency 2.4 kHz and 4.9 kHz

Filter Inductance	L_f	2mH	0.05 p.u.
Machine total leakage inductance	$L_{ls} + L_{lt}$	3.24 mH	0.09 p.u.
Filter Capacitance	C_f	30µF	0.2 p.u.
Resonant Frequency	ω_n	828 Hz	16.6 p.u.

TABLE (II) Filter details for Synchronous Machine

Filter Inductance	L_f	5mH	0.12 p.u.
Synchronous inductance	L_s	50.2mH	1.25 p.u.
Filter Capacitance	C_f	20µF	0.08 p.u.
Resonant Frequency	ω_n	503 Hz	10.06 p.u.

B. Philosophy of the Control Technique:

Combination of LC-Filter inserted between VSI and AC drives is the best methodology in industry to developed pure sinusoidal voltages for AC Drives. Whenever these ac machines are operated with pure sinusoidal voltages then machine efficiency is improved and to get accurate output values also depending upon load requirement. Active Damping technique is the best protective method to protect the machines from the effect of changing in loads or speeds at any unbalanced load conditions and this technique to eliminate the resonance frequency oscillations in motor terminal voltages and in machine currents. Generally designing purpose of view an AC machines performance level is good by default condition at any load changes in steady state or transient state but this ac machines does not give required accurate output values comparatively whenever these same ac machines are operated without adding any protective devices. However, to get accurate output values have to use any protective methods to avoid afore mentioned problem and any changes of loads also may not damages the machines due to resonance frequency oscillations with the help of these protective devices. For this project point of view Active damping technique is used to control above mentioned problem. This proposed technique is one of best method to damp out the resonance frequency oscillations by using damping factor. LC-Filter is containing virtual resistance. This virtual resistance may leads to resistance drop in circuit but this resistance drop is eliminated by controlling the motor terminal voltage.

In this proposed technique VSI is operated at more than 2 kHz inverter switching frequency because at this switching frequency the capacitor voltage does not contain the significant switching frequency components and this Capacitor voltage consist higher magnitude resonant components than the fundamental components at this inverter switching frequency. Hence extraction of resonance components from fundamental components in capacitor voltage is simple to eliminating the resonance frequency oscillations in that capacitor voltages by using active damping technique and this Capacitor voltage signal is shown in figure(4).

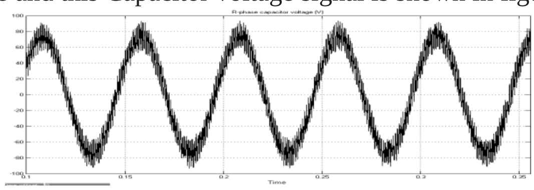

Fig 4. R-Phase capacitor voltage at 20Hz and 2.4 kHz inverter switching frequency

Capacitor current also contains fundamental components and resonant frequency components. But this capacitor current contain considerable amount of switching frequency components at more than 2 kHz inverter switching frequency and this switching frequency (2 kHz) is very closed to resonance frequency (828Hz) with higher magnitude. Hence it creates difficult to extracting the resonant components from sensed capacitor current and this capacitor current will noise. This noisy of capacitor current is eliminated by controlling the capacitor voltages whenever inverter switching frequency is used more than 2 kHz and this capacitor current is shown in figure(5).

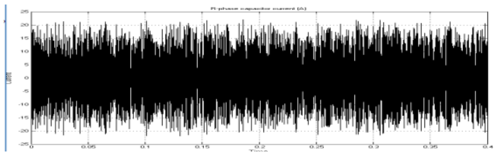

Fig 5. R-Phase capacitor current at 20Hz and 2.4 kHz inverter switching frequency

If the inverter switching frequency is very low around 500Hz for this proposed technique then the capacitor voltages are having higher magnitude switching frequency components than resonant components hence those capacitor voltages are having higher switching frequency oscillations instead of resonance frequency oscillations. At that condition suitable PWM techniques have to adopt to reduce these higher switching frequency oscillations in capacitor voltages [28]. But this proposed active damping technique is not suitable for eliminating these higher switching frequency oscillations in the capacitor voltages or currents because this Active damping technique have the capability to reduce the resonance frequency oscillations in that capacitor currents or voltages hence VSI are operated at more than 2 kHz switching frequency oscillations for this proposed technique.

III. ELIMINATION OF RESONANCE FREQUENY OSCILLATIONS

For this proposed technique elimination process of resonance frequency oscillations in the capacitor voltages is done by two steps using active damping technique and these capacitor output voltages are compared with Induction motor and Synchronous motor after eliminated resonance frequency oscillations.

Step (I). Resonant-Frequency Signal Extraction Block

Fig. (6) Describes the resonant frequency signal extraction block. In this signal extraction block, low pass LC filter is used to eliminate higher order frequencies and gives the lower order resonance frequencies in the capacitor signals for each phase.

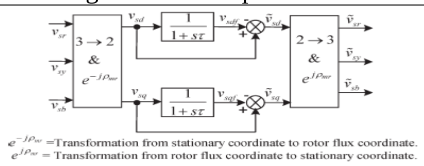	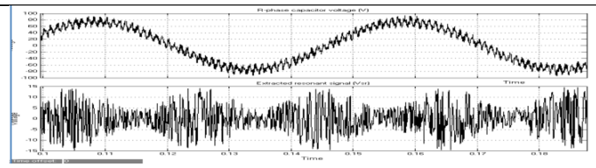
Fig 6. Signal Extraction Block	**Fig 7**. R-Phase capacitor voltage v_{sr} and Extracted resonant signal $\tilde{v}_{sr}$ at 20 Hz and 2.4 kHz inverter switching frequency.

These 3-phase inverter voltages (v_{sr} , v_{sy} and v_{sb}) are transferred in to 2-phase voltages by using d-q transformation. This transformed d-q voltages (v_{sd} and v_{sq}) are having both fundamental components (v_{sdf} andv_{sqf}) and resonance components ($\tilde{v}_{sd}$And$\tilde{v}_{sq}$). Where v_{sdf} And v_{sqf} are DC quantities and $\tilde{v}_{sd}$ and $\tilde{v}_{sq}$ are AC quantities.

The capacitor voltages are given below by d-q transformation,

$$v_{sd} = v_{sdf} + \tilde{v}_{sd} \dots\dots (4)$$

$$v_{sq} = v_{sqf} + \tilde{v}_{sq} \dots\dots\dots (5)$$

v_{sd} And v_{sq} voltages are filtered with the help of low-pass filters with cut off frequencies at around 10 Hz. The outputs of the low-pass filters are v_{sdf} and v_{sqf} are subtracted from v_{sd} and v_{sq} to avoid those DC quantities (v_{sdf} and v_{sqf}) then get extracting resonant capacitor voltages $\tilde{v}_{sd}$ and $\tilde{v}_{sq}$ in d-q transformation by the process of signal extraction block. This extracted resonant frequency components ($\tilde{v}_{sd}$and$\tilde{v}_{sq}$) have frequencies are ω_n and ω_f due to the *d–q* transformation. Hence these frequencies ($\tilde{v}_{sd}$and$\tilde{v}_{sq}$) are varies with the variation of ω_f. To get rid of this variation of ω_f in $\tilde{v}_{sd}$ and $\tilde{v}_{sq}$, those extracted resonant capacitor voltages are transformed back to the three-phase domain. Then get the outputs of the reverse transform are $\tilde{v}_{sr}$, $\tilde{v}_{sy}$ and $\tilde{v}_{sb}$. Due to the reverse transformation the extracted per phase resonant frequency capacitor voltages ($\tilde{v}_{sr}$,$\tilde{v}_{sy}$ and $\tilde{v}_{sb}$) are exactly at ω_n but not varied with fundamental component (ω_f). The extracted resonant capacitor voltage ($\tilde{v}_{sr}$)

waveform is shown in Figure (7). Most of the Active Damping techniques available in the literature do not compensate in the three-phase domain but in the *d–q* domain [17], [18]. Hence, the frequency of the extracted components lies at ($\omega_n - \omega_f$). Therefore, a little frequency mismatch exists in these techniques.

Step (II). LC Filter Control Block with Active damping technique

A. LC Filter representation

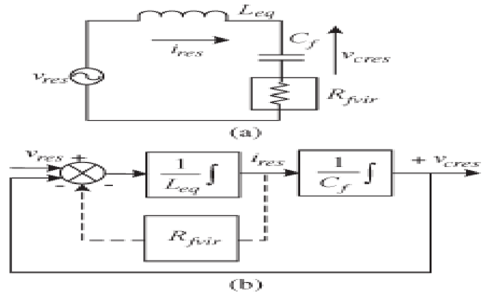

Fig. 8(a). Circuit representation And Fig. 8(b). Control block diagram.

Figure.8 (a) represents LC filter control block. In this circuit, filter virtual resistance (R_{fvir}) is due to the energy storage elements are inductor (L) and capacitor (C). It makes small resistance drop. This drop may damp the current magnitudes hence the power loss in the circuit. This small resistance drop eliminated by controlling the terminal voltage in the circuit and also multiplying the compensating voltages to damping factor using active damping technique. Where inductor is limiting the currents and capacitor is reduces the ripples in the voltages. At resonance frequency condition both inductor and capacitor voltages are equal. If the combination of inductor and capacitor voltages is greater than the source voltage (v_{res}) in the circuit then this phenomena is called “Voltage magnification” And this voltage magnification is eliminated by maintain wide different impedance variation between inductor and capacitor.

Figure.8 (b) represents the control block diagram of LC circuit. When LC circuit is excited by source voltage (v_{res}) then inductor integrate the extracted resonant voltages and get the resonance inductor currents (i_{res}). This resonance inductor currents are again integrated by filter capacitor then it gives resonance capacitor voltages (v_{cres}). Filter virtual resistance create some small resistance drop in the circuit. When capacitor current (i_{res}) at resonance frequency is multiplied by the filter virtual resistance (R_{fvir}) and subtracted from source voltage (v_{res}) then this resistance drop is eliminated.

B. Active damping controller with LC filter for both induction motor & synchronous motor

Active damping technique means that “it compares both active component output and passive component output with resonance frequency oscillations and those unwanted resonance oscillations eliminates by use of compensating voltages and damping factor for any electrical drive system ”.

In the proposed method of AD, a series resistance in the *LC* circuit is emulated in the control. A resistance connected in parallel with the capacitor can be also adopted [22], [26 Sec 11.5]. However, this technique causes additional delay in the system as the corrective signals have to pass through the current control loops. Figure (9) represents complete simulink circuit for both Induction machine and Synchronous machine with active damping technique to eliminate resonance frequency oscillations in machine per phase voltages and machine per phase currents in both induction motor and synchronous motor with the help of damping factor and compensating signals of control system. In this, per phase inverter voltages are extracted by the resonant frequency signal extraction block (Fig 6). However, the purpose of resonant frequency signal extraction block is that “it separates the fundamental frequency components from resonant frequency components in the capacitor voltages per each phase and it eliminates higher order resonant frequencies of those particular capacitor voltages and given the lower order resonant capacitor voltages only”. This 3- phase extracted capacitor voltages ($\tilde{v}_{sr}$,$\tilde{v}_{sy}$ and$\tilde{v}_{sb}$) are converted into 2-phase voltages by d-q transformation for simple mathematical calculation. These extracted resonant capacitor voltages are having both AC and DC fundamental frequency components in d-q transformation and they lag by 90 degrees from resonance capacitor currents is shown in Figure (11). But this DC fundamental component creates DC drift problems in capacitor voltages. In order to avoid this DC drift problems used low pass filter instead of pure integrator to generate the integrating capacitor voltages per each phase($\tilde{v}_{sr\_int}$,$\tilde{v}_{sy\_int}$, and $\tilde{v}_{sb\_int}$).

These integrating voltages are lag by 180 degrees out of phase from the resonant capacitor currents and lag by 90 degrees to extracted resonant capacitor voltages is observed in phasor diagram shown in Fig (11).

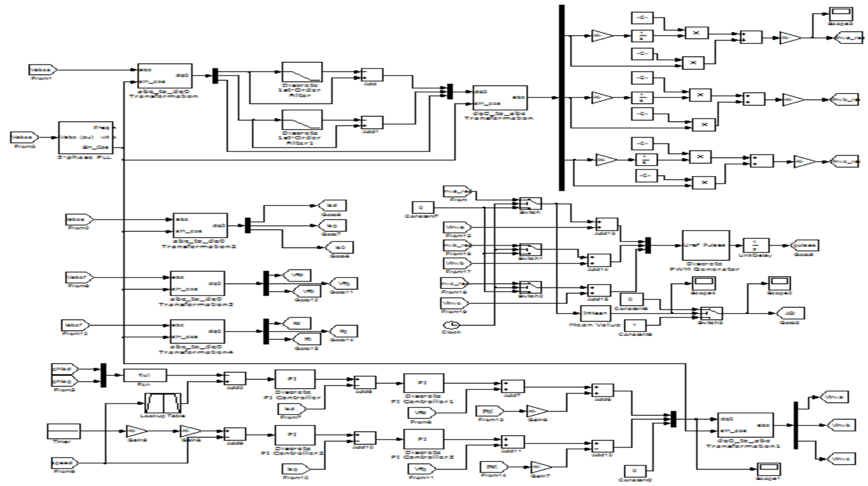

Fig 9. Complete Simulink diagram for both Induction and Synchronous motors with Active damping technique.

After avoiding DC quantities in integrating capacitor voltages, these 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 delay of$\omega_n T_s/2$ introduced by the inverter. The inverter switching frequency is$f_s$and the inverter time constant is $T_s/2$. The relation between time constant and switching frequency is $T_s = 1/f_s$. The r-phase compensating signal (v_{r-comp}) is obtained from integrated capacitor signal ($\tilde{v}_{sr\_int}$) and extracted resonant capacitor signal ($\tilde{v}_{sr}$) with phase advancement of $\omega_n T_s/2$ and this compensating signal for r-phase is given in below equation,

$$v_{r\_comp} = \tilde{v}_{sr\_int} \cos(\omega_n T_s/2) + \tilde{v}_{sr} \sin(\omega_n T_s/2) \qquad \text{........ (6)}$$

Similarly the compensating signals for other two phases (y-phase and b-phase) are also getting in same manner of constructing r-phase compensating signal. Where $\cos(\omega_n T_s/2)$ and $\sin(\omega_n T_s/2)$ are fixed numbers for compensate the inverter delay can be easily and accurately introduced. Here these compensating signals are having small resistance drop. This resistance drop is eliminated by multiplying damping scaling factor (K_d) to that compensating voltages in this proposed Active damping hence eliminate this resistance drop also then getting inverted resonance frequency output voltage ($v_{invr-res}$) without resonance oscillations in r-phase and it is given below,

$v_{invr\_res} = K_d * v_{r\_comp}$ ...... (7)

Similarly other two phases inverter resonant frequency voltage signals ($v_{invy-res}$ And$v_{invb-res}$) are getting same as the r-phase inverter resonant frequency voltage ($v_{invr-res}$) without resonance oscillations for both induction machine and synchronous machine. These$v_{invr-res}$, $v_{invy-res}$ and $v_{invb-res}$ signals are directly added to the inverter voltage references (v^*_{invr} , v^*_{invy} andv^*_{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. The above complete process is done for elimination of resonance frequency oscillations by using active damping technique for both induction motor and synchronous motor is implemented by Simulink / Matlab software is shown in Fig(9). From equation (7), K_d Can be expressed in terms of the Damping factor (δ) and it can be written as,

$K_d = R_{fv} \left| i_{res}(t)/v_{r\_comp} \right| = 2\delta$ ..... (8)

In the above equation 'δ' is damping factor and it is given by,

$\delta = (R_{fv}/2)\sqrt{C_f/L_{eq}}$ ...... (9)

From Simulation results it is observed that, the system most effectively works for varying damping factor (δ) from 0.2 to 0.4. For the lower variation of damping factor, the damping effect is not prominent and for the higher variation of damping factor, the compensating signals cause distortion to the actual voltage signals. Figure (10) shows waveform for r-phase extracted capacitor voltage ($\tilde{v}_{sr}$), integrated voltage ($\tilde{v}_{sr\_int}$) and compensating signal (v_{r-comp}) at 20 Hz changing frequency and at 4.9 kHz inverter switching frequency. And Figure (11) shows the phasor relationship of capacitor signals at resonant frequency. In this phasor representation, the inverter source voltage v_{res} and the resonant capacitor current i_{res} are in the same phase. The extracted capacitor voltage $\tilde{v}_{sr}$ lags by 90◦ to resonance voltage (v_{res}). Integrated voltages $\tilde{v}_{sr-int}$, $\tilde{v}_{sy\_int}$ and $\tilde{v}_{sb\_int}$ are at the opposite phase withi_{res} and these$\tilde{v}_{sr_int}$,$\tilde{v}_{sy\_int}$ and$\tilde{v}_{sb_int}$ signals are phase advanced by $\omega_n T_s/2$ to 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. Table (III) elaborates the phase delay ($\omega_n T_s/2$)

generated by the inverter for this proposed technique. The phase delay is predicted from the system resonance and switching frequencies of the inverter.

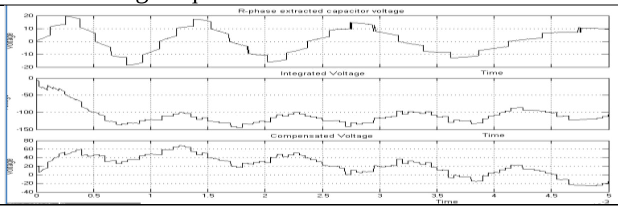

Fig10. R-Phase extracted capacitor voltage $\tilde{v}_{sr}$, integrated voltage v_{sr-int} and compensated signal (v_{r-comp}) at 20Hz and f_{sw} = 4.9 kHz.

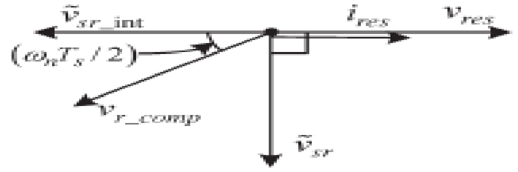

Fig (11). Phasor description for sustained oscillation at the resonant frequency

A. Mathematical Analysis

From simulated Active damping control diagram (Fig. 9) Compensating signal voltages for r, y and b-Phases are:

$$V_{r\_comp} = \tilde{V}_{sr\_int} \cos \omega_n T_s/2 + \tilde{V}_{sr} \sin \omega_n T_s/2$$
$$V_{y\_comp} = \tilde{V}_{sy\_int} \cos \omega_n T_s/2 + \tilde{V}_{sy} \sin \omega_n T_s/2$$
$$V_{b\_comp} = \tilde{V}_{sb\_int} \cos \omega_n T_s/2 + \tilde{V}_{sb} \sin \omega_n T_s/2$$

Inverter resonating voltages for r, y and b –phase are

$V_{invr\_res} = K_d * V_{r\_comp}$ .... (10)

$V_{invy\_res} = K_d * V_{y\_comp}$ .... (11)

$V_{invb\_res} = K_d * V_{b\_comp}$ .... (12)

From equation (10),

$$K_d = \left|\frac{V_{invr\_res}}{V_{r\_comp}}\right|$$
$$K_d = \left|\frac{i_{res}(t) * R_{fvir}}{i_{res}(t) * X_L}\right|$$
$$K_d = \left|\frac{R_{fvir}}{X_L}\right|$$

$K_d = \left|\frac{R_{fvir}}{\omega_n * L}\right|$ ...... (13)

From Series RLC Circuit

$2\delta = \frac{R}{\omega_n L}$ .... (14)

From equation (13) and (14)

$K_d = 2\delta$ …… (15)

Where,

Resistor, R= R_{fvir}

K_d= Damping Scaling factor

$\delta = \frac{R}{2}\sqrt{\frac{C_f}{L_{eq}}}$= Damping factor

From the equation (15) mathematically proved that the resistance drop in capacitor voltages per each phase is eliminated by multiplying damping factor to compensating signal.

B.System Robustness

The values of the stator and rotor leakage inductances may vary with time hence there may be error in the machine per phase voltages or currents. In this proposed technique, ±20% variation of the total stator and rotor leakage inductances is considered and to account above mentioned variations with changing in resonant frequency (f_n) and the damping factor (δ) values are given in Table (IV). Due to the variation in the resonant frequency (f_n) and the damping factor (δ) values of the system with the variation in stator and rotor leakage inductance values of ac drives will causes to the following changes in the system.

Those changes are:

1) The resonant frequency will change.

2) Damping factor (δ) will change.

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 damping factor (δ) will change the value of the damping resistance to be added in the system. However, this small variation also mentioned in Table (IV) and this small change in damping factor (δ) will not cause much variation in the proposed damping and it is clearly observed from simulation results for both Induction motor and Synchronous motor as show in Figure (18) and Figure (19). This variation of damping factor (δ) demonstrate the robustness of the proposed damping technique with respect to Induction Motor and Synchronous Motor.

IV. SIMULATION RESULTS

Simulated results for AC Drives (I.M and S.M) are compared to each other with the elimination of resonance frequency oscillations using Active damping technique in three cases under steady state, transient state and robustness condition respectively and implemented by Simulink/ Matlab platform.

CASE (1): Simulation results for Induction motor and synchronous motor in Steady state.

For simulation of Induction motor, the inverter switching frequency is kept at 2.4 and 4.9 kHz. The system resonant frequency is fixed at 828Hz. Figure 12(a) and 13(a) is simulated waveforms at 0.3 damping factor (δ) and 4.9 kHz switching frequency. The damping factor decides the magnitude of the resistance to be included in the circuit. It is clearly observed from the waveform that is after action of AD loop in the control the capacitor voltage waveforms become oscillation free. Fig. 14(a) and Fig.15 (a) are Simulated results for that same induction machine and same LC-Filter but inverter switching frequency is 2.4 kHz and damping factor (δ) is 0.4. Phase advancement given to compensate the inverter delay at 61.1 degrees as shown in table (III).

For Synchronous motor inverter switching frequency is kept at 2.4 kHz and 4.9 kHz. The system resonant frequency is fixed at 503Hz. Fig 12(b) and 13(b) are simulated results at 4.9 kHz switching frequency and at damping factor δ =0.3 for synchronous machine. Figure 14(b) and 15(b) are also simulated results for that same Synchronous motor at 2.4 kHz inverter switching frequency and at δ=0.4. The machine and filter details are shown in the appendix and in table (II). The Phase advancement for synchronous machine is given to compensate the inverter delay is 18.6 degrees as shown in table (III). These results demonstrate the effectiveness of the proposed technique in order to reduce the resonant frequency components in the Synchronous machine terminal voltages. Fig (12) and (13) simulated results are compared at 4.9 kHz switching frequency and 'δ' is 0.3 with the changing frequency at 5Hz and 43Hz for an Induction motor and Synchronous motor are shown below.

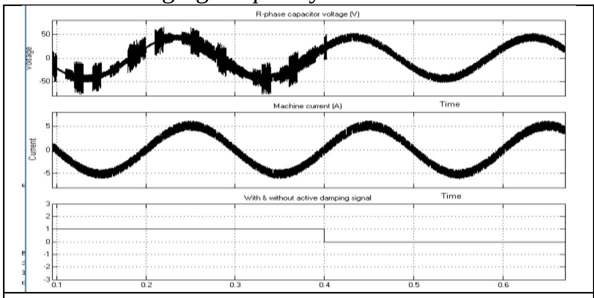

Fig 12(a). R-Phase capacitor voltage and machine current at 5Hz (δ =0.3) with and without AD for Induction motor.

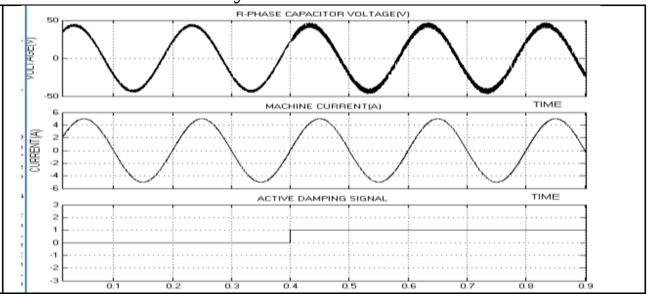

Fig 12(b). R-Phase capacitor voltage and machine current at 5Hz (δ=0.3) with and without AD for Synchronous motor.

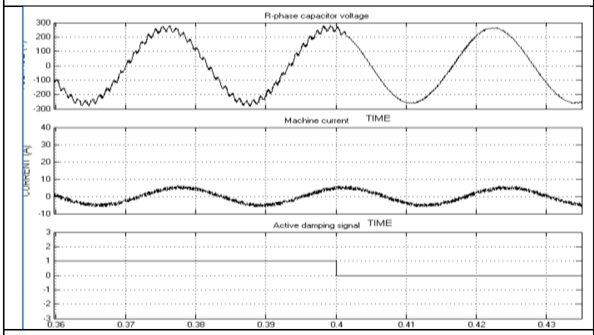

Fig 13(a).R-Phase capacitor voltage and machine current at 43Hz (δ=0.3) with and without AD for Induction motor.

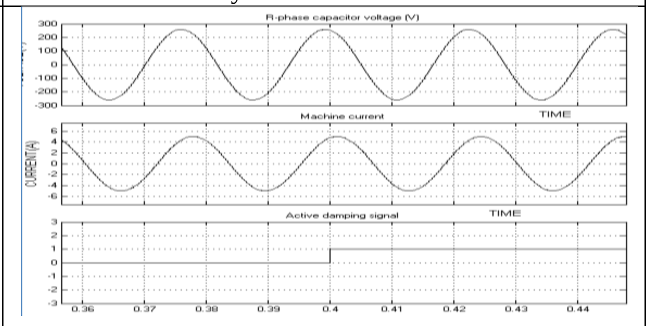

Fig 13(b). R-Phase capacitor voltage and machine current at 43Hz (δ=0.3) with and without AD for Synchronous motor.

Figure (14) and Figure (15) are simulated results compared at 2.4 kHz switching frequency and at damping factor δ =0.4 with the changing frequency
At 5Hz and 43 Hz are observed in below figures for an Induction motor and Synchronous motor respectively.

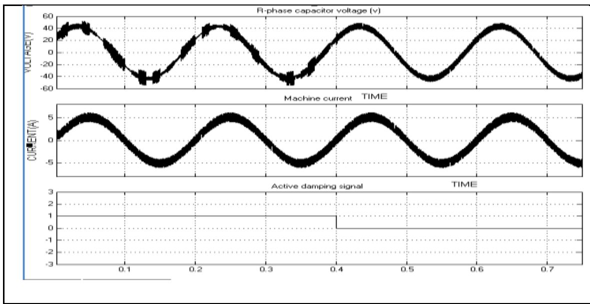

Fig 14(a). R-Phase capacitor voltage and machine current at 5Hz (δ=0.4) with and without AD for Induction motor.

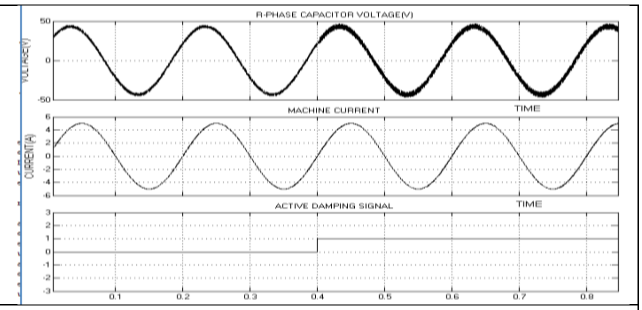

Fig 14 (b). R-Phase capacitor voltage and machine current at 5Hz (δ=0.4) with and without AD for Synchronous motor.

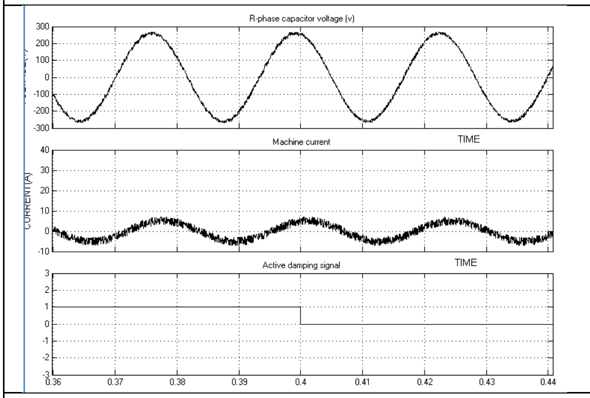

Fig 15(a). R-Phase capacitor voltage and machine current at 43Hz (δ=0.4) with and without AD for Induction motor.

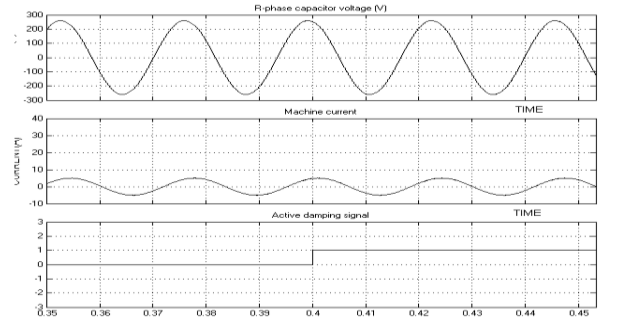

Fig 15(b). R-Phase capacitor voltage and machine current at 43Hz (δ=0.4) with and without AD for Synchronous motor.

Case (II): Simulation results for induction motor and Synchronous motor in Transient state condition.

Fig 16(a) demonstrate the simulated waveform for a sudden speed change of Induction machine from 2.5 to 43Hz with Active damping and it is compared with Simulated waveform of Synchronous motor operated at 2.4 kHz switching frequency and damping factor δ =0.3 is shown in Fig16 (b). Where Figure 17(a) demonstrates that Induction motor waveform for a sudden load change at 43 Hz and compared with Synchronous motor results is show in Fig 17(b). In this case clear observed that the Active damping loop does not affect the dynamic operation of the normal vector control. This technique only removes the resonant frequency oscillation from the capacitor and current waveforms. The Simulated waveforms for sudden change in speed and sudden change in load of Induction motor and Synchronous Motor are shown in below Fig 16 and Fig 17respectively.

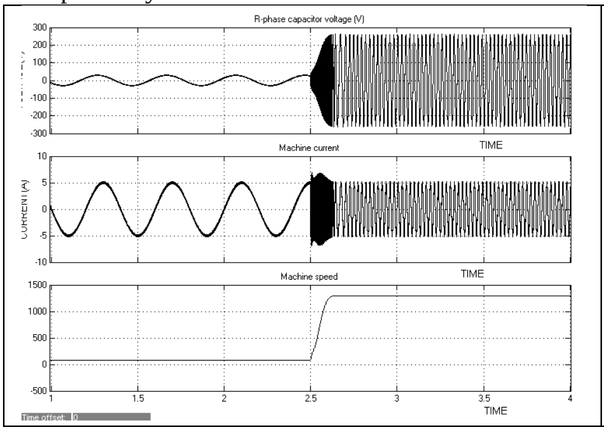

Fig 16(a). R-Phase capacitor voltage and machine current during the sudden speed change from 2.5 Hz to 43 Hz (δ=0.3) with Active Damping and machine speed for Induction motor.

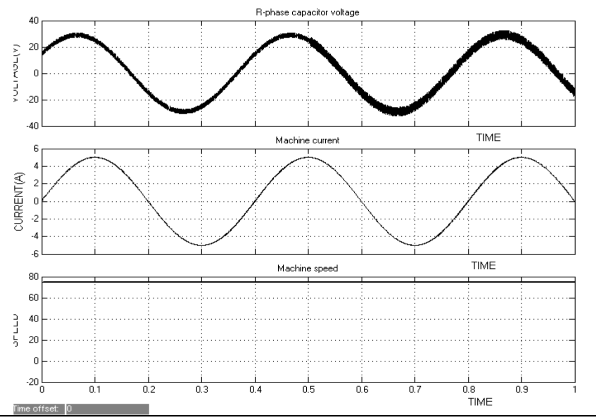

Fig 16(b). R-Phase capacitor voltage and machine current during the sudden speed change from 2.5 Hz to 43 Hz (δ=0.3) with Active Damping and machine speedfor Synchronous motor.

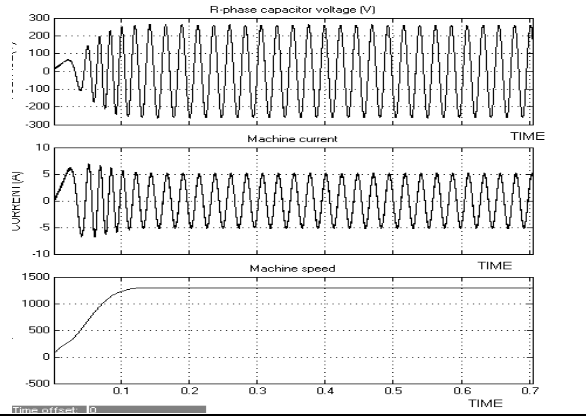

Fig 17(a). R-Phase capacitor voltage and machine current and machine speed during sudden application of 1-kW load at 43Hz (δ=0.3) with AD for Induction motor.

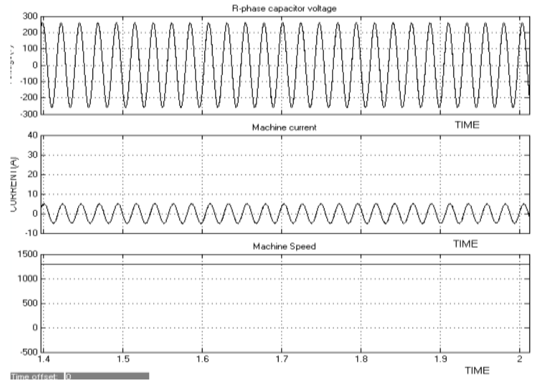

Fig 17(b). R-Phase capacitor voltage and machine current and machine speed during sudden application of 1-kW load at 43Hz (δ=0.3) with AD for Synchronous motor.

CASE (III): Simulation results for Induction motor and Synchronous motor in robustness condition.

Fig 18(a) & 19(a) and Fig 18(b) &19(b) are the capacitor voltage waveforms at 0.25 and 0.35 damping factor (δ) for both Induction motor and Synchronous motor respectively. From the simulated results it can be observed that the variation of leakage inductance do not disturb the system operation due to the small variations of damping factor. Induction motor and Synchronous motor simulated results are compared in below figure (18) and figure (19).

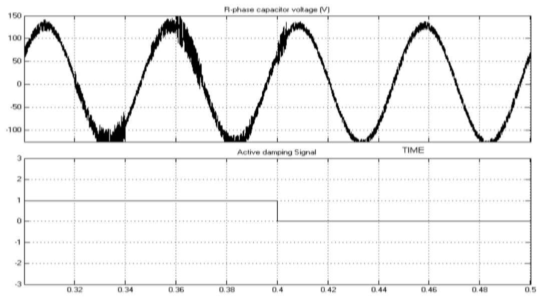

Fig 18(a). R-Phase capacitor voltage at 20Hz (δ=0.25) with and without active damping for Induction motor.

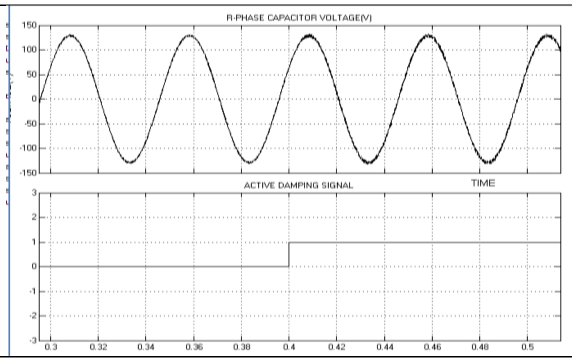

Fig 18(b). R-Phase capacitor voltage at 20Hz (δ=0.25) with and without active damping for Synchronous motor.

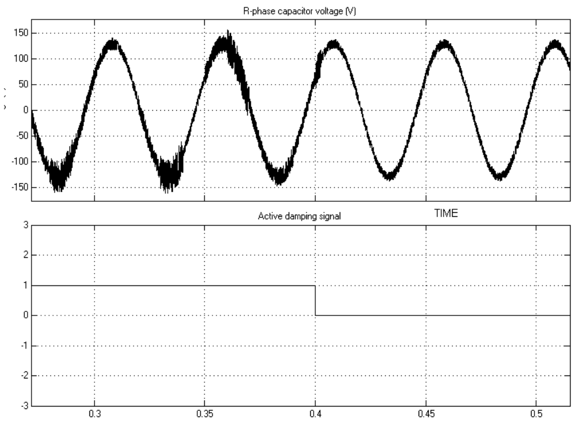

Fig 19(a). R-Phase capacitor voltage at 20Hz (δ =0.35) with and without Active damping for Induction motor.

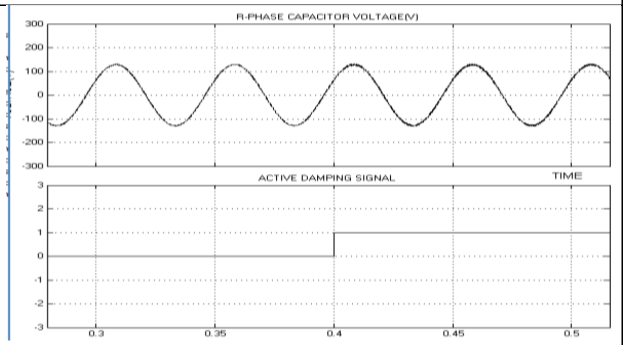

Fig 19(b). R-Phase capacitor voltage at 20Hz (δ=0.35) with and without Active damping for Synchronous motor.

V. CONCLUSION

The comparison between Induction motor and Synchronous motor with resonance frequency oscillations is done by Active damping technique and it is implemented in MATLAB/SIMULINK platform. This Active Damping technique has been proposed for reducing resonant frequency oscillations in motor terminal voltages. The Synchronous motor has very less resonant frequency oscillations compared to Induction machine because the external DC excitation of synchronous machine to controls the motor terminal voltages itself under any balanced or unbalanced load conditions. But, Induction machine does not have any external control itself to controlling the motor terminal voltages under any load changing conditions, that's why induction motor has higher resonant frequency oscillations in motor terminal voltages. So, in order to eliminate these higher resonant frequency oscillations, have to use Active damping technique. From the simulated results it is clearly conclude that the proposed Active damping technique is not required for Synchronous machine but it is compulsory for Induction machine.

APPENDIX

Induction Machine Details:

[1.1] Machine Details: 1.5-KW, 220 V, 11A, 1440 r/min four-pole Y-connected 50 Hz induction motor.

[1.2] Machine parameters: R_s = 0.66Ω, R_r = 0.21Ω, L_{lr} = 1.62mH, L_{ls} = 1.62mH, and L_m = 38.8mH.

[1.3] Filter parameters: L_f = 2mH, C_f = 30μF, and f_n = 828 Hz.

Synchronous Machine Details:

[2.1]Machine details: 15.8 HP three phase 400 V, 18.3 A, 1000 r/min, 50 Hz salient pole wound field synchronous machine.

[2.2]Field Circuit: 17 V, 13.8 A, R_{sf} = 1.2Ω and L_{sf} = 750mH.

[2.3]Armature Circuit: R_a=0.45Ω,
L_{md} = 42.54mH, L_{mq} = 26.35mH, and L_{ls} = 7.7mH.

[2.4]Filter parameters: L_f = 5mH, C_f = 20μF, f_n = 503Hz.

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