Vibration Analysis of Rolling Piston-Type Compressors Driven by Single-Phase Induction Motors

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Abstract

Rolling piston-type compressors [1], [2] driven by single-phase induction motors are widely used in low power room air conditioners. Since a rolling piston-type compressor represents an eccentric load to the motor, vibration problems associated with the compressor and motor drive assembly always occur. Furthermore, for ease of starting, a single-phase induction motor is usually designed with unsymmetrical stator windings, which is far more difficult to be analyzed as compared to a typical symmetrical three-phase induction motor. This paper establishes the state-space model for a rolling piston-type compressor driven by a single-phase induction motor. An inverter is proposed for driving the motor-compressor assembly. By varying the line frequency and voltage magnitudes on both primary and secondary windings of the induction motor, this paper seeks to reduce the vibration accompanied with the motor-compressor assembly of a room air conditioner. The paper presents some useful design criteria for reducing vibrations based on computer simulation results.

I. INTRODUCTION

Rolling piston-type compressors driven by single-phase induction motors are widely used in room air conditioners. Since a rolling piston-type compressor represents an eccentric load to the motor, vibration problems associated with the compressor and motor drive assembly always occur. The major vibration sources in a rolling piston-type compressor include load torque and radial force variation due to gas compression, bending vibration due to unbalanced inertia of shafts, motion of internal elements such as discharge valves and vanes, and motor torque variation [1]. These vibration sources generate audible noises and cause maintenance problems such as damage to the mechanical assembly due to long term operation.

In a conventional room air conditioner, the compressor is usually driven by a single-phase induction motor due to its low cost and wide spread use in home appliances. Though recent air conditioners have used brushless dc servo motors to drive compressors, the application has not yet gained major market share. Single-phase induction motor drives are still the dominant drives in providing driving torques for compressors that are used in low power home appliances. Due to compressor characteristics as described in the previous paragraph, it is important to establish a mathematical model that describes the compressor-motor dynamics and then, using this model, to design a better controller for reducing vibrations and noises. To reach this goal, the state-space model for the compressor-motor assembly is established in Section II. Both the motor and the compressor are represented by nonlinear dynamic equations. In the case of the compressor, the required torque varies nonlinearly with the angular shaft position at each steady-state operating speed. The generated torque of the single-phase induction motor also fluctuates with time, as the motor has unsymmetrical primary and auxiliary windings. The resultant motor-compressor speed shows larger speed variation and hence vibration than those of a compressor driven by either a brushless dc motor or a three-phase symmetrical winding induction motor.

To reduce speed variation and assembly vibration, a single-phase full-bridge inverter is proposed to drive the motor-compressor assembly in Section III. The primary and auxiliary windings of the motor are connected to the two legs of the inverter. A microprocessor is used to generate PWM signals to the drivers of the inverter. Using constant V/f control, the voltage magnitudes and line frequencies applied to the two motor windings can be varied. To achieve best results, the phase difference between the two voltage waveforms are kept in quadrature to each other, i.e., 90 degrees. A prerequisite for using this approach is that the capacitor and centrifugal switch are eliminated from the motor. The consequence is that the performance and reliability of the motor can be increased. To evaluate the proposed drive

performance as compared to other approaches, computer simulation is conducted in Section IV. The simulation studies several control configurations and compare their performance in terms of speed, torque, and current fluctuations. The aim is to choose a control configuration that can reduce most motor-compressor vibrations. Simulation results show that the proposed constant V/f control is a promising candidate. Finally, some concluding remarks are given in Section V.

II. MOTOR-COMPRESSOR DYNAMIC EQUATIONS

The voltage and current state-space equations for a 2-pole, single phase, or, more accurately, 2-phase, unsymmetrical induction motor are formulated, in the stationary reference frame, [3], as follows.

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ 0 \\ 0 \end{bmatrix} = \frac{p}{\omega_b} \begin{bmatrix} X_{ss} & 0 & X_{ms} & 0 \\ 0 & X_{ss} & 0 & X_{ms} \\ X_{ms} & 0 & X_{rr} & 0 \\ 0 & X_{ms} & 0 & X_{rr} \end{bmatrix} \begin{bmatrix} i_{qs}^s \\ i_{ds}^s \\ i_{qr}^s \\ i_{dr}^s \end{bmatrix} + \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & -\frac{N_s}{N_r} \frac{\omega_r}{\omega_b} X_{ms} & R_r' & -\frac{N_s}{N_r} \frac{\omega_r}{\omega_b} X_{rr}' \\ \frac{N_s}{N_r} \frac{\omega_r}{\omega_b} X_{ms} & 0 & \frac{N_s}{N_r} \frac{\omega_r}{\omega_b} X_{rr}' & R_r \end{bmatrix} \begin{bmatrix} i_{qs}^s \\ i_{ds}^s \\ i_{qr}^s \\ i_{dr}^s \end{bmatrix} \quad (1)$$

where the subscripts, s , S , r , and R , denotes unsymmetrical stator and rotor windings. The two-axis stator voltages and currents are denoted as V_{qs}^s , V_{ds}^s , i_{qs}^s , and i_{ds}^s , respectively; the rotor currents are denoted as i_{qr}^s and i_{dr}^s . The stator and rotor self and mutual reactances are given by X_{ss} , X_{ss}' , X_{rr}' , X_{rr} , X_{ms} , and X_{ms} , respectively. The stator and rotor resistances are given respectively as R_s , R_s' , R_r' , and R_r . N_s/N_r denotes the turn ratio of unsymmetrical windings, ω_r is the rotor speed, and ω_b is the base speed.

To facilitate motor starting, a capacitor is usually connected in series with the auxiliary winding of the motor. The term $\frac{p}{\omega_b} X_{ss}$ given in (1) is replaced by $\frac{p}{\omega_b} X_{ss} + \frac{\omega_b}{p} X_C$. Let $z = \frac{is}{p}$, which can be augmented with (1) to form a complete set equations for describing the motor dynamics with a starting capacitor. The generated motor torque is

$$T_e = \frac{P N_s}{2 N_r} \frac{X_{ms}}{\omega_b} (i_{qs}^s i_{dr}^s - i_{ds}^s i_{qr}^s) \quad (2)$$

and the electro-mechanical equation is

$$J \frac{2}{p} p \omega_r + B \omega_r + T_L = T_e. \quad (3)$$

The dynamic equations of a single-phase motor is more complicated than those of a three-phase symmetrical winding induction motor. The unsymmetrical winding arrangement in a single-phase induction motor causes greater torque and speed fluctuations than those of a three-phase induction motor. This is a major factor affecting the performance of a motor-compressor assembly.

The basic equation representing the rotational fluctuations of a rolling piston-type compressor is defined in the following:

$$J \ddot{\theta} + T_L(\theta) = T_e(\dot{\theta}) \quad (4)$$

where J = moment inertia of crankshaft,
 $T_L(\theta)$ = load torque of compressor,
 $T_e(\dot{\theta})$ = motor output torque,
 θ = crank angle.

In (4) the required load torque is given by

$$T_L(\theta) = T_g(\theta) + T_v(\theta) + T_f(\theta) \quad (5)$$

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where $T_g(\theta)$ = gas compression torque,
 $T_r(\theta)$ = reaction torque,
 $T_f(\theta)$ = friction torque.

The equations of gas compression torque are:

$$T_g(\theta) = W_g e \sin\{(\alpha + \theta)/2\} \quad (6)$$

$$W_g = (P_c - P_s)(2r_p) \sin\{(\alpha + \theta)/2\} H \quad (7)$$

where W_g = bearing load for compression,
 e = eccentricity of crank,
 α = offset angle of rolling piston center,
 P_c = pressure in compressor chamber,
 P_s = pressure in suction chamber,
 r_p = rolling piston radius,
 H = rolling piston height.

The equations of reaction torque are:

$$J_p \dot{\omega}_p = M_c - r_p \mu_v F_v - M_b \quad (8)$$

$$T_v(\theta) = -F_v e \sin(\alpha + \theta) \quad (9)$$

where J_p = inertia moment of piston,
 ω_p = angular velocity of piston,
 M_c = fraction moment of piston inside,
 M_b = fraction moment of piston edges,
 μ_v = friction coefficient of vane tip,
 F_v = friction force at vane tip.

Finally, the equation of friction torque is:

$$T_f = r(F_{fl} + F_{fu}) + T_{th} \quad (10)$$

where F_{fl} = friction force at lower bearing,
 F_{fu} = friction force at upper bearing,
 r = crankshaft radius,
 T_{th} = friction torque of thrust bearing.

The compressor load torque serves as a torque disturbance to the driving motor shaft. However, it is difficult to use the complete motor-compressor dynamics for design and simulation, since the dynamic equations describing the compressor load torque are highly nonlinear and contain several design parameters that are only available to the compressor manufacturers. For ease of design, the torque pattern in one cycle operation for a certain compressor shown in Fig. 1 is saved in a lookup table and is used in subsequent simulation study. In each revolution, the torque is a nonlinear function of the motor shaft angular position. During simulation, the motor shaft angular position in each integration step must be known so that the corresponding compressor load torque value is obtained. Also, the parameters of the single-phase induction motor used in the simulation are listed as follows:

110V, 60Hz, 2p, 1 Hp
 $R_s = 2.02\Omega$ $X_{ls} = 2.79\Omega$
 $R_r = 7.14\Omega$ $X_{lr} = 3.22\Omega$
 $X_{ms} = 66.8\Omega$ $X_{mr} = 92.9\Omega$
 $R'_r = 4.12\Omega$ $X'_{lr} = 2.12\Omega$
 $R_r = 5.74\Omega$ $X_{lr} = 2.95\Omega$
 $X_{cs} = 14.5\Omega$ $X_{cr} = 172\Omega$
 $R_{cs} = 3\Omega$ $X_{cr} = 9\Omega$
 $J = 0.0146 \text{ Kg} \cdot \text{m}^2$
 $\frac{N_s}{N_r} = 1.18$.

Fig. 2 shows the steady-state shaft speed response in rad/sec of a split-phase induction motor. The motor is connected to the 60 Hz 110V single-phase supply. The corresponding motor torque and load torque responses are shown in Fig. 3. Comparing Fig. 2 and Fig. 3, when the load torque is larger than the generated motor torque, the motor decelerates; conversely, the motor accelerates. Notice the fluctuating feature of the generated motor torque. Combining this with the nonlinear loading effect produces large speed variation during steady-state operating condition. The resultant vibration effects on motor-compressor assembly are clearly shown.

III. INVERTER CONTROL OF INDUCTION MOTOR

For a rolling piston-type compressor driven by a single-phase induction motor, large rotor shaft speed fluctuations are inevitable, which has been

verified by computer simulation shown in the last section. By reducing speed fluctuation through certain control means, the resultant vibration of the motor-compressor assembly should also be reduced. The speed and torque variations are due to the unsymmetrical windings arrangement of the induction motor. The question naturally arises as how to choose a control method to reduce these variations. One obvious solution is to replace the single-phase induction motor by a symmetrical-winding balanced three-phase induction motor or a dc brushless motor, since these motors have better smooth speed and torque responses. However, a more difficult approach is to retain the single-phase induction motor, while seeking a control strategy to improve its running performance.

For a typical unsymmetrical 2-phase induction motor operated from a fixed frequency single-phase source, the motor is always subjected to unbalanced applied stator voltages. In order to provide more balanced stator voltages to the primary and auxiliary windings, a single-phase full-bridge inverter is used to drive the motor. The connection diagram is shown in Fig. 4. The converter-inverter consists of three-leg IGBTs, in which one leg is used for rectifying the input single-phase voltage and providing dc voltage source to the full-bridge inverter. Two equal capacitors are connected in series across the dc input and their junction is at a midpoint. The other two legs of IGBT form the single-phase full-bridge inverter, in which the upper primary and auxiliary windings are connected to the centerpoint of each leg and the both lower windings are wired together to the capacitor center junction. This circuit arrangement has the advantage of saving a diode bridge for ac-to-dc conversion. Furthermore, using transistors for rectifying purpose, bi-directional energy flow can be achieved and, thus, unity power factor operation can be realized. However, the unity power factor issue will not be addressed here. Instead, this paper will concentrate on the inverter operation and its effects in reducing motor torque and speed fluctuations.

The proposition of a motor-compressor assembly driven by an inverter has the following advantages. Firstly, the centrifugal switches and external capacitors for starting and running that are found on many single-phase induction motor types are eliminated, since the starting and running of a single-phase motor is controlled solely by varying inverter output voltage magnitudes and line frequencies. In fact these external capacitors are designed to be operated under the nominal 60 Hz condition and can be seriously damaged when operated under high switching frequencies. Thus, the cost of motor is down and the reliability of motor is improved. Secondly, in room temperature control environment, using a drive which can adapt the motor speed to the actual cooling demands will result in higher overall system efficiency than a conventional inefficient thermostatic on-off control. Thirdly, an inverter driven single-phase induction motor drive will provide wide speed control range for various load torque characteristics.

Many methods have been proposed in the past for designing variable speed single-phase induction motor drives. For example, in [4] and [5], a 2-phase inverter-fed induction motor drive is considered. The motor speed is adjusted by controlling the phase difference between the two phase voltages [5] and the speed control range is fairly limited. [6] presents the design of an inverter with eight transistors for adjusting the speed of a fractional horsepower two-phase symmetrical motor. The circuit configuration is more complicated than the one proposed in this paper. [7] considers an adjustable speed single-phase induction motor drive with direct angle control of the auxiliary winding supply. The primary winding is connected directly to the utility supply and the auxiliary winding is connected to a fixed frequency voltage source of variable magnitude and phase angle. The speed control range is still limited. An adjustable voltage adjustable frequency inverter-driven single-phase induction motor drive is considered in [8]. Some valuable design information is provided. However, the analysis results given in [8] are based on sinusoidal steady-state conditions and the input voltage source for the motor used in the experiments are conducted using a variable-speed synchronous generator instead of an inverter.

As shown in Fig. 4, a microprocessor is used for sending PWM signals to the three legs of the inverter. The PWM strategy chosen for study is the conventional sine PWM, which is the most widely used one. To save computation time, the firing angles corresponding to the intersection points of sine and triangular carrier waves are pre-computed and stored in a lookup table. Using the constant V/f control, the microprocessor computes the two phase stator voltage magnitudes based on the input frequency command which is generated from the room temperature regulator. In order to further reduce torque and speed fluctuations, the ratio between the primary and auxiliary voltage magnitudes is set equal to $N_s/N_r = 1.18$. That is, the auxiliary windings must sustain higher voltage stress than the primary windings. The phases between the primary and auxiliary voltages are shifted by 90 degree electrical angle. This is the optimum angle for obtaining good starting and running torques and minimizing torque ripples. The computed two phase PWM voltage waveforms and fundamental waveforms are shown in Fig. 5

TABLE I. AVERAGE ROTOR SHAFT SPEEDS IN RAD/SEC

	35Hz	40Hz	45Hz	50Hz	55Hz	60Hz
Case 1	199.5	230.0	259.1	288.2	316.3	344.2
Case 2	186.5	222.1	255.8	289.2	321.7	354.0
Case 3	197.2	229.2	261.4	292.7	324.5	356.1
Case 4	190.2	222.3	254.1	286.3	317.8	349.6
Case 5	197.2	229.1	261.1	292.5	324.1	355.5
Case 6	197.2	229.2	261.3	292.7	324.5	355.8

TABLE II. COMPUTED SLIPS IN PER CENT

	35Hz	40Hz	45Hz	50Hz	55Hz	60Hz
Case 1	9.3	8.5	8.4	8.3	8.6	8.8
Case 2	15.2	11.7	9.6	8.0	6.9	6.1
Case 3	10.3	8.8	7.7	6.8	6.1	5.6
Case 4	13.5	11.5	10.1	8.9	8.1	7.3
Case 5	10.3	8.8	7.7	6.9	6.3	5.6
Case 6	10.3	8.8	7.7	6.8	6.1	5.6

for carrier frequencies 720 Hz and 7.2 KHz, respectively.

IV. COMPUTER SIMULATION

To gain more insight in evaluating the performance of an inverter driven motor-compressor assembly, several cases are formulated and their performance is compared using computer simulation. These cases are:

- Case 1: The motor is a split-phase type and is driven by a variable-frequency fixed magnitude sinusoidal voltage source. The capacitance is 183 μF .
- Case 2: The motor is a capacitor start, capacitor run type and is also driven by a variable-frequency fixed-amplitude sinusoidal voltage source. The start capacitance is 183 μF and the run capacitance is 15.4 μF .
- Case 3: The motor is wired as two-phase unsymmetrical and is driven by an ideal two-phase variable-frequency fixed-amplitude sinusoidal voltage source. No start or run capacitor is used. The phase between the two phase voltages is shifted by 90 degree electrical angle. This is the ideal operating case and serves as a reference for comparing with all other cases.
- Case 4: The motor is two-phase unsymmetrical and is driven by a two-phase variable-voltage variable-frequency square wave inverter. No start or run capacitor is required.
- Case 5: The motor is two-phase unsymmetrical and is driven by a two-phase variable-voltage variable-frequency PWM inverter with the carrier frequency set at 720 Hz. No start or run capacitor is required.
- Case 6: The motor is two-phase unsymmetrical and is driven by a two-phase variable-voltage variable-frequency PWM inverter with the carrier frequency set at 7.2 KHz. No start or run capacitor is required.

For cases 3 to 6, the ratio of primary to auxiliary voltage magnitude is set equal to N_s/N_r . The speed, torque, and current responses are simulated using the motor-compressor dynamic equations presented in Section II. The input frequency is varied from 35 Hz to 60 Hz with an increment of 5 Hz. For $f = 60 Hz$, the speed responses for cases 1, 3, and 6 are shown in Fig. 6. The average speed ω_{ave} , which is the mean of peak and bottom speeds, in each case can be calculated and, for all the cases, is tabulated in Table I. Define the synchronous speed $\omega_e = 2\pi f$ and the slip ω_{sl} as

$$\omega_{sl} = \frac{\omega_e - \omega_{ave}}{\omega_e} \quad (11)$$

The resultant slips for all the simulated cases are tabulated in Table II. Also, let $\Delta\omega_r$ be the difference between peak and bottom speeds in each of the case shown in Fig. 6. The speed variations for all the cases are given in Table III. In all cases, the proposed approach (i.e., case 6) shows better performance, smaller slips and smaller speed variations, in the frequency range from 45 Hz to 60 Hz. As the frequency is reduced from 35 Hz to 40 Hz, the slip in case 6 increases in order to maintain rated torque. The corresponding primary line current will also increase due to increase slip, which is shown in Table IV. These results are identical to the ones presented in [8].

Next, the steady-state motor generated torque and load torque responses for cases 1, 3, and 6, are shown in Fig. 7. The proposed approach, case 6, shown in Fig. 7 (c) reduces the generated torque variation quite effectively

TABLE III. STEADY-STATE SPEED VARIATIONS IN RAD/SEC

	35Hz	40Hz	45Hz	50Hz	55Hz	60Hz
Case 1	6.61	6.63	6.65	6.42	6.29	6.18
Case 2	5.81	5.01	4.46	4.05	3.34	3.21
Case 3	5.32	4.43	3.91	3.31	3.22	2.89
Case 4	5.42	4.76	4.42	4.41	3.52	3.30
Case 5	5.52	4.51	4.03	3.72	3.48	3.19
Case 6	5.33	4.45	3.94	3.32	3.23	2.90

TABLE IV. RMS VALUES OF THE PRIMARY STATE CURRENTS IN AMP

	35Hz	40Hz	45Hz	50Hz	55Hz	60Hz
Case 1	2.02	2.77	3.94	5.39	6.96	7.93
Case 2	4.31	3.94	3.73	3.53	3.18	3.08
Case 3	2.48	2.50	2.51	2.50	2.41	2.40
Case 4	1.95	1.93	1.93	1.92	1.92	1.95
Case 5	2.12	2.05	2.05	2.01	2.01	2.12
Case 6	2.45	2.49	2.50	2.49	2.36	2.32

as compared to the conventional approach, case 1, shown in Fig. 7 (a). In fact, the responses of case 6 and case 3, the ideal one, are almost identical. The torque variation, which is defined as the difference between the highest torque value and the lowest torque value in a steady-state torque response, is computed for each case and input line frequency and is tabulated in Table V. Again, torque variations in case 6 are the smallest and are identical to the ones in case 3, the ideal case.

An investigation of the steady-state two-phase stator flux loci can further explain the performance shown in the simulation cases. The stator flux loci are plotted in Fig. 8 for all six cases at a operating frequency of 60 Hz. The skewed elliptical flux locus for case 1 shown in Fig. 8 (a) indicates that the magnitudes of primary and auxiliary stator flux are unequal and their phase difference is not equal to 90 degrees. The elliptical flux loci shown in Figs. 8 (b),(c), and (f) indicate that, for cases 2, 3, and 6, the phase differences are all equal to 90 degrees but the two axis flux magnitudes are not equal. Should they be equal, then circular flux loci will be obtained resulting in more smooth torque responses that are similar to the symmetrical three-phase induction or dc brushless motor drives. The square wave inverter results in parallelogram shape flux loci, while the inverter with 720 Hz carrier frequency yields polygonal shape flux loci; both are not good candidates for achieving high performance single-phase induction motor control.

V. CONCLUSIONS

In this paper the mathematical equations describing the dynamics of a rolling piston type compressor driven by a single-phase induction motor provides a starting point for studying motor-compressor vibration and for developing a control strategy to reduce torque and speed fluctuations and hence vibration. A variable-voltage, variable-frequency two-phase inverter is proposed for achieving this design objective. Simulation results show that the proposed inverter outperforms all the other conventional single-phase motor such as split phase, capacitor start capacitor run. Experimental work is now being conducted to verify the validity of the proposed inverter control method.

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TABLE V. STEADY-STATE TORQUE VARIATIONS IN N·M.

	35Hz	40Hz	45Hz	50Hz	55Hz	60Hz
Case 1	5.42	8.62	10.82	13.38	16.58	18.11
Case 2	3.12	3.07	2.95	2.55	2.38	1.98
Case 3	1.10	1.22	1.17	1.13	1.08	1.08
Case 4	2.41	2.51	2.70	2.71	2.71	2.93
Case 5	4.35	4.35	4.35	4.35	4.47	5.36
Case 6	1.10	1.22	1.17	1.13	1.08	1.08

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Fig. 1. Compressor torque pattern.

Fig. 2. Steady-state motor speed response.

Fig. 3. Motor torque and load torque responses.

Fig. 4. Schematic diagram of an inverter driven single-phase induction motor.

(a)

(b)

Fig. 5. Two phase PWM and fundamental voltage waveforms. Carrier frequency is (a) 720 Hz and (b) 7.2 KHz.

(a)

(b)

(c)

Fig. 6. Steady-state speed responses at $f=60Hz$. (a) Case 1. (b) Case 3. (c) Case 6.

Fig. 7. Steady-state torque responses at $f=60\text{Hz}$. (a) Case 1. (b) Case 3. (c) Case 6.

Fig. 8. Steady-state two axis flux loci at $f=60\text{Hz}$. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4. (e) Case 5. (f) Case 6.