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Detection and Diagnosis of Compound Faults in a Reciprocating Compressor based on Motor Current Signatures

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Abstract. Induction motors are the most common driver in the industry and consume tremendous energy every year. Monitoring the status of a motor and its downstream equipment and diagnosing faults in time not only avoids great damage to mechanical systems but also allows the motor to run at optimal efficiency. This paper studies the use of information from motor current signals to detect and diagnose faults of a reciprocating compressor (RC) and its upstream three-phase motor. The motor is applied by the RC with an oscillator torque which induces additional components in measured current signals. Moreover, the current signatures contain changes with the torque profiles due to different types of faults. Based on these analytical studies, experimental studies were carried out for different common RC faults, such as valve leakage, intercooler leakage, stator asymmetries and the compounds of them. The envelope analysis of current signals allows accurate demodulation of the torque profiles and thereby it can be combined with overall current levels for implementing model based detections and diagnosis. The results show these simulated faults can be separated under all operating pressures.

Keywords: Reciprocating compressor, induction motor, stator asymmetries faults, envelope analysis, motor current signatures analysis.

1 Introduction

Reciprocating compressors (RC) and their associated induction motor plays an important part in various industrial systems because of their powerful design, flexibility in use and high thermo-efficiency offering high value of reliability. Due to the RC working condition requirement, some of its components work under harsh conditions such as high pressure and high temperature [1]. Therefore, failures occurring in RC not only degrade performance, consume additional energy, but also possibly even result in system shut-down [2]. According to [3], damages to RC valves can lead to serious machine breakdown, which represents the biggest source of compressor failures and accounts for 31% of machine breakdowns. Additionally, failures in its associated motor such as broken rotor bar or stator asymmetry winding could also affect the compressor performance. Increases in stator resistance of a three phase induction motor can lead to voltage imbalances in the motor causing a reduction of motor efficiency, increase in motor temperature and oscillatory running conditions. Therefore, efficient and effective condition monitoring techniques are actively studied to detect and diagnose RC and its associated motor faults at an early stage in order to prevent any major failures on motors [4, 5].

In practice, faults in machines may develop simultaneously and the combined faults may create more damage or performance reductions to the machine. It has been found that the exposure of the motor to asymmetry supply and combined fault significantly increases the temperature and reduces the efficiency of the machine [6, 7]. However, the combined faults make the fault features more complicated to interpret and the fault detection even more challenging. Recently, research has been carried out in this area. Ballal et al.[8] improved a combined method with neural fuzzy inference system logic to detect stator inter-turn insulation and bearing wear faults in a single phase induction motor. In [9], Garcia-Perez successfully used high-resolution spectral analysis for identifying multiple combined faults in induction motors.

Motor current signature analysis (MCSA) has been proven as an effective and efficient technique for monitoring different motor faults, including air-gap eccentricity, broken rotor bar [10, 11] and turn to turn fault in the stator [12]. In [13], Haynes and Kryter showed that MCSA can also be employed for detecting abnormalities in the downstream machines such as compressors, pumps, rolling mills, air blowers and air conditioning systems. Particularly, Gu et al. [14] has investigated using motor current signals for diagnosing individual faults of RC machines. These all show the great benefit of MCSA in that it does not require any additional systems for measurements [10, 11].

This paper studies further the use of information from motor current signals to detect and diagnose faults of a RC and its associated three-phase motor. Three types of common single faults including intercooler leakage, valve leakage and stator asymmetries and one compound fault are introduced on the RC. The experimental results showed that all the simulated faults can be successfully separated through the analysis of the motor current signal.

2 Reciprocating Compressor Fault Features

2.1 Valve Leakage

Valve leakages are considered as the most common fault in RC and the most frequent root cause for unplanned compressors shutdowns [15]. In multi-stage compressors, especially at high pressure stages, both suction and discharge valves are exposed to a high number of impacts per second and also to high speed flow and high temperature. This harsh working environment often causes non-uniform wear of the sealing surfaces between the valve seat and its plates, which thereafter causes leakage in the valve system. Leakage within the valve allows high temperature gases to be pushed through the valve and accelerates valve system deterioration which eventually affects the compressor efficiency [16].

Under these conditions, when the compressor starts the compression process it requires more power whereas expansion needs less power, hence the motor speed will vary accordingly. When the RC runs under normal conditions, the fluctuation increases as the discharge pressure increases which means the motor current signals change with this fluctuation and the measured current signal will exhibit amplitude modulation. Thus, if the compressor produces a fault such as valve leakage, the load fluctuation will increase and hence cause a high degree of amplitude modulation [17].

In the motor current spectrum, the modulation will exhibit a series of sidebands f_{sb} at the supply frequency, which can be measured as [17]:

$$f_{sb} = f_c \pm m f_x \tag{1}$$

where f_c denotes the frequency of supply, f_x is the working frequency of the compressor and $m = 1,2,3,...$

2.2 Stator Asymmetries Faults

A small amount of resistance imbalance will cause an increase in the stator winding temperature by a large amount. As a general rule the temperature rises by 25% (in ºC) for every 3.5% voltage imbalance [18]. For every 1% voltage imbalance, there is a 7% current imbalance expected, which is equivalent to the negative sequence voltage that causes negative braking torque. Rotating flux opposes the main flux asymmetry-voltage operation that will also create a pulsating torque which produces speed pulsation, mechanical vibration and consequently acoustic noise [19]. The voltage imbalance can be defined as[20]:

$$\text{Voltage imbalance} = \left(1 - \frac{3v_{\min}}{\sum \mathrm{v}}\right) \times 100 \tag{2}$$

where, v_{min} is the lowest phase voltage (V), and V is the voltage cross each phase (V). This asymmetric voltage would also lead to changes in motor speed-torque behaviour in the form of current signature changes.

3 Experimental Setup

A two-stage, single action V-shape Broom Wade TS9 reciprocating compressor is employed for testing. It can deliver compressed air up to 0.8MPa (120 psi) to a horizontal air tank. The compressor is derived by a three phase KX-C184, 2.5kw induction motor. In the test, five working conditions were performed one by one: healthy condition (BL), discharge valve leakage on the second stage (DVL), leakage on the intercooler (ICL), asymmetry stator winding (Stator) and a combined fault with both DVL and Stator (DVL and Stator).

From the first and second cylinder pressure comparison in Fig. 1, it can be seen the simulated faults have caused observable changes on the compressor performance.

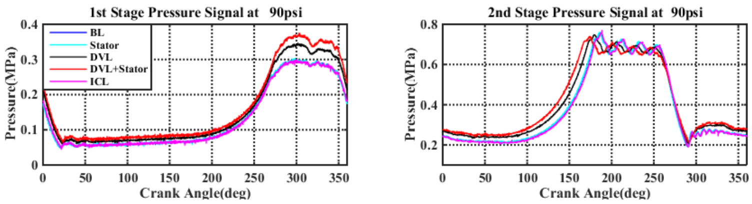

Fig. 1. Measured cylinder pressures for 1st and 2nd stage

4 Results and Discussion

4.1 Motor Current Signal Analysis

The motor current signals for all test cases under pressure of 80psi are presented in Fig. 2 in both time domain and frequency domain. A clear amplitude modulation (AM) effect can be clearly observed from the waveform and the current amplitude under faulty conditions (DVL and DVL+Stator) is slightly higher than that of healthy conditions (BL). From the spectra in Fig. 2 (b), a clear AM effect can also be seen. A series of sidebands appear around the 50 Hz carrier component with a fundamental frequency at 7.5Hz (working frequency of the compressor). These sidebands are caused by an asymmetry between three phases, power supply imbalance and machine operation load fluctuation, with sufficient information for fault diagnosis. Note that the sideband amplitude of the motor current for the leaking valve and combined fault seems slightly higher than that the healthy conditions.

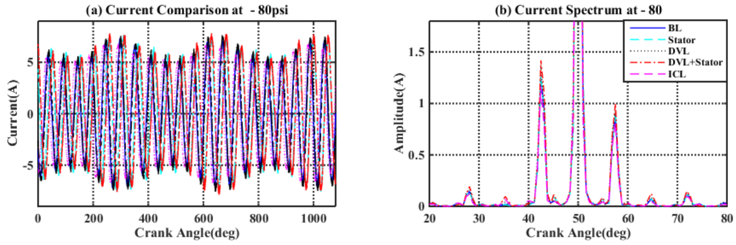

Fig. 2. Current signals for all test cases: (a) time domain and (b) frequency domain

By calculating the average amplitude of the first lower and upper sidebands, i. e. 50±7.5Hz, as symbol sideband amplitude for the corresponding pressure condition, a trend for the symbol sideband changing under pressure is presented in Fig. 3.

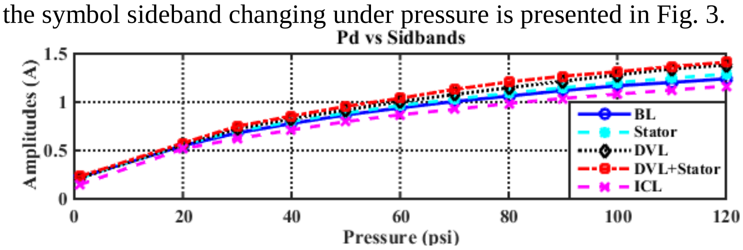

Fig. 3. Amplitudes of sidebands average for all cases.

It can be seen very clearly that the sideband amplitude increases as the pressure increases. Furthermore, the trends for these five test cases can be roughly seperated, with the combined fault being the highest one, followed by valve leakage fault then stator asymmetry fault; the healthy condition and the intercooler leakage being the lowest one.

4.2 Envelope Signal Features

Envelope analysis is suitable for diagnostics of machinery where faults have an amplitude-modulating effect on the characteristic frequencies of the machinery [21]. Therefore, the envelope of the motor current signal is calculated using Hilbert transform [22] and the envelope signal for pressure at 40 psi and 100 psi are given in Fig. 4. It can be observed that the modulation effect becomes more obvious as the pressure increases. It is difficult to assess any change in the pattern, the shape and amplitude between healthy and faulty cases.

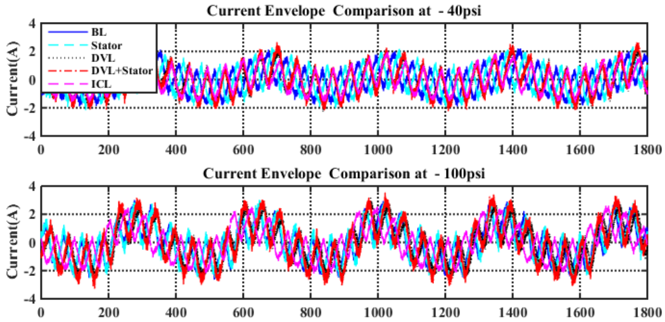

Fig. 4. Envelope signal for normal and faulty operation and envelope values for different discharge pressure

4.3 Diagnosis based on Combined Features

Take the current RMS value as a function of discharge pressure and envelope amplitude as shown in Fig. 5 (a) and (b), it clearly shows that both the healthy and faulty conditions have an increasing trend. The relationship between the motor current RMS values and discharge pressure is shown in Fig. 5 (a) clearly shows a difference between healthy and various fault cases. However it is unable to separate discharge valve leakage, stator asymmetric and combined fault. The envelope analysis in Fig. 5 (b) shows a substantial difference between healthy and faulty cases, especially between discharge valve leakage and combined fault but not for intercooler leakage. Stator asymmetry can be clearly viewed in the RMS values.

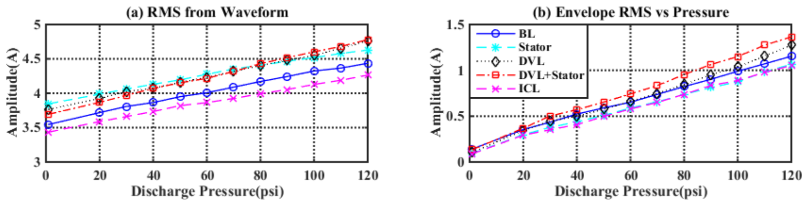

Fig. 5. (a) Current RMS values and (b) envelope amplitude values of different discharge pressure

The envelope analysis combined with overall current levels for implementing a model based approach. Fig. 6 (a) illustrates the combined envelope and current RMS. One can see that simulated faults can be separated under all operating pressures, furthermore, the differences spread over compressor discharge pressure range from 1 psi to 120 psi. It can be concluded that either too low or too high feature values will indicate a faulty or abnormal compressor operation.

On this basis, compressor fault diagnosis can be carried out at its operation pressure range (1psi to 120psi). The upper feature values can be used to differentiate the inter-cooler leakage from other faulty cases. In addition, all compressor faults can be classified though model based detections, shown as Eq. (3) and (4). The diagnosis results are presented in Fig. 6 (b)

$$\text{Model: } \hat{A}_e = 1.1073A - 3.7806 \quad (3)$$

$$\text{Residual: } R = A_e - \hat{A}_e \quad (4)$$

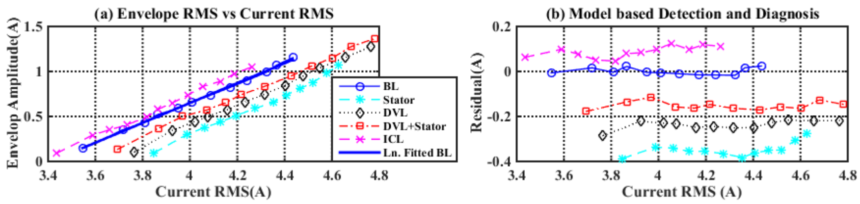

Fig. 6. (a). Envelop RMS vs Current RMS and (b) model based approach

5 Conclusion

This paper studies the usage of motor current signal for the diagnosis of faults on the induction motor, faults on its downstream reciprocating compressor and also the compound faults. The experimental results have shown the motor current signal contains sufficient information (average torque and dynamic torques) for diagnosing the simulated fault cases. A model based fault detection based on the relationship between current RMS and envelope RMS value are proposed. The proposed model is effective for a wide pressure range.

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