Abstract - Induction motors are treated as the workhorse of modern day industries. During operation, they are subjected to various operational stresses that degrade their performance with time. Condition monitoring of induction motors are thus of prime importance. Among several techniques, the stator current on-line monitoring technique is one of the popular techniques for health monitoring and fault diagnosis of induction motors. Stator currents’ Park’s pattern or Concordia pattern has been demonstrated to be indicative of the state of motor health and any incipient fault. These Concordia patterns, however, are also affected by operating conditions of the motor such as supply voltage and mechanical loading. The aim of this paper is to observe the effects of variations in external operating conditions on the stator currents’ Park’s pattern. External operating conditions include stator supply voltage variations in balanced and unbalanced manner and also mechanical load variations in balanced and unbalanced manner.

I. INTRODUCTION

Induction motors, mainly due to their low cost, ruggedness, controllability and low maintenance, have become one of the most critical components for today’s electric utilities and process industries. A motor failure, in such utilities, can result in the shutdown of a generating unit or production line. This requires monitoring their operation for detection of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of the system. In fact, in recent years monitoring of induction motors has become very important to reduce maintenance costs and prevent unscheduled downtimes. Therefore, there has been a substantial amount of research to provide new condition monitoring techniques for induction motors.

An induction motor can fail due to combination of a variety of fault mechanisms [1]. Stator winding failures, which can occur due to a combination of thermal, electrical, mechanical and environmental stresses that act on the stator [1], are found to be one of the major causes of motor failure. The subject of on-line detection of inter-turn short circuits in the stator windings of three-phase induction motors has been addressed by several researchers. One of the most widely used techniques to obtain information on the health state of induction motor is based on the processing of the stator line current [2]. Techniques such as those based on the spectral analysis of the motor current [3-5], frame vibration [6], axial leakage flux [6-7], and partial discharges testing [8] have been proposed.

Another potential fault detection method based on the analysis of the machine line currents is the Park’s vector approach [9-11]. The Park’s vector approach is based on the identification of a specified current pattern obtained from the transformation of the three-phase stator currents to an equivalent two-phase system. Researches concerning on-line monitoring of current, voltage, and flux Park’s Vectors, have shown that this approach can be used for diagnosing malfunctions, such as, single-phasing, stator-winding inter turn short-circuits and rotor faults, in three-phase induction motors. This on-line diagnosis method is based on identifying unique patterns in the figures obtained, corresponding to the Park’s Vector representation of current, voltage, and/or flux. In Park’s Vector representation, ellipticity of the figure increases with the severity of the fault and its major axis orientation is associated to the faulty phase.

The Park’s vector representation, however, is sensitive to motor operating conditions, in addition to motor internal faults. These operating conditions include motor supply voltage and output loading. It is thus, a matter of concern to isolate Park’s Vector patterns due to motor internal faults and external operating conditions. In order to provide a more detailed insight into the results obtained by the Park’s Vector, this paper reports results of a detailed study on how the Park’s Vector patterns are influenced by motor external operating conditions.

II. PARK’S VECTOR APPROACH – THEORETICAL PRINCIPLES

Through the use of Park’s Vector approach a two-dimensional (2-D) representation can be used to describe three-phase induction motor phenomena. A suitable 2-D representation is based on the current Concordia vector; sometimes called Park’s vector.

The 3-phase stator current equations are reducible to a set of two appropriate variables in a 2-phase reference frame (called the $\alpha\beta$-reference frame). One straightforward way of transferring variables to the $\alpha\beta$-reference frame is a simple vector addition of the 3-phase variables. This vector is obtained by applying the Clarke-Concordia, $\alpha\beta$ or 3→2
transformation in order to maintain invariant power. The current Concordia vector components \( (I_a, I_b) \) are a function of mains phase variables \( (I_R, I_Y, I_B) \) as

\[
I_a = \frac{\sqrt{2} I_R}{3} - \frac{1}{\sqrt{6}} I_Y - \frac{1}{\sqrt{6}} I_B
\]

\[
I_b = \frac{1}{\sqrt{2}} I_Y - \frac{1}{\sqrt{2}} I_B
\]

(1)

In ideal conditions, three-phase currents lead to a Concordia vector with the following components:

\[
I_a = \frac{6}{2} I_M \sin \omega_s t
\]

\[
I_b = \frac{6}{2} I_M \sin \left( \omega_s t - \frac{\pi}{2} \right)
\]

(2)

where \( I_M \) is the supply phase current maximum value and \( \omega_s \) is the supply frequency.

The current Concordia vector (plot between \( I_a \) and \( I_b \)) is a circular pattern centered on the origin of the coordinates as shown in Fig. 1. This acts as a reference figure that allows the detection of abnormal conditions by monitoring the deviations of acquired patterns.

Under balanced supply voltage condition and a healthy motor with balanced load, the corresponding \( \alpha \beta \) stator current components trajectories create a uniform circle in the state space [2, 9-10]. In the case of a fault in the stator winding, the \( \alpha \beta \) trajectory no longer remains circular, but becomes elliptic whose major axis orientation is associated to the faulty phase. Such a situation is reproduced from [10] and is shown in Fig. 2.

The current Concordia patterns are also sensitive to rotor faults, including broken bar [12] and air gap eccentricity [13-14]. Such a situation with rotor broken bar fault is shown in Fig. 3, reproduced from [12]. Concordia patterns, as will be demonstrated in the later sections of the paper, are strongly dependent on the external operating conditions as well. It is thus eminent, that for correlating Concordia patterns with the type and severity of internal faults, it is essential to differentiate between external operating conditions and internal faults. With this in view, the present contribution reports the dependencies of stator current Concordia patterns on external operating conditions including supply voltage and mechanical load.

III. EXPERIMENTAL SET UP

Experiments were performed on a three phase 1 HP, 415 V, 4 pole induction motor drive system. Stator current measurements were performed with YOKOGAWA MODEL 96001 current probe with resolution of 10mV/A. The data was sent to a PC through an acquisition board connected to APLAB Model 36100DC Digital Storage Oscilloscope (DSO). The stator current patterns as observed have fundamental component along with other higher frequencies. These higher harmonic components can be attributed to supply side injections and mechanical imbalance, as the case may be. The schematic diagram of the experimental set up with driver, motor, belt-pulley load, and data acquisition system is shown in Fig. 4.

A. Study Points

The motor was operated under both normal balanced conditions and, abnormal and unbalanced conditions. Balanced operating conditions were obtained with

- Variable balanced supply voltage with constant mechanical load
- Balanced supply voltage with variable balanced mechanical load

Apart from running the motor at these balanced conditions, the following abnormal running conditions were forcefully imposed on the motor:
• Unbalanced supply voltage
• One phase snapped
• Unbalanced mechanical load

Under balanced condition, supply voltage variations were obtained with the help of an auto transformer from 60 to 100% of the rated voltage with mechanical load remaining constant. Then, at constant balanced supply voltage, the mechanical load was varied from 40% to 100%.

Mechanical load unbalances were created by adding steel bolts and nuts on a balanced Aluminum disk mounted on the motor shaft. The nut and bolt were placed in holes drilled at different radial distances from the shaft. The disk has eight holes, drilled in a way to keep the disk balanced, at radial distances of 7, 9, 11 and 13 cm on both sides from the motor shaft. Profile of the disc is schematically shown in Fig. 5 and Fig. 6 shows actual mounting on motor shaft.

S12 is with 140 grams each of two nut-bolt sets in holes 7 and 9 cm away on one side of the disc. S13 is with 140 grams of nut-bolt sets on all the four holes on one side of the disc. Mechanical unbalance of Level1 (S12) can be quantified with 58.57% change in moment of inertia and 39% shift in centre of inertia w.r.t the disc radius, as compared to balanced condition (no nuts or bolts). Mechanical unbalance of Level2 (S13) is quantified with 180% change in moment of inertia and 59.5% shift in centre of inertia w.r.t the disc radius, as compared to balanced condition (no nuts or bolts).

### Table I

<table>
<thead>
<tr>
<th>Study Point</th>
<th>Vr (%)</th>
<th>Vy (%)</th>
<th>Vb (%)</th>
<th>Speed (RPM)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1470</td>
<td>No-Load</td>
</tr>
<tr>
<td>S2</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>1460</td>
<td>No-Load</td>
</tr>
<tr>
<td>S3</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>1452</td>
<td>No-Load</td>
</tr>
<tr>
<td>S4</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1444</td>
<td>100 % load</td>
</tr>
<tr>
<td>S5</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1455</td>
<td>80% load</td>
</tr>
<tr>
<td>S6</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1460</td>
<td>60% load</td>
</tr>
<tr>
<td>S7</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1465</td>
<td>40% load</td>
</tr>
<tr>
<td>S8</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>1429</td>
<td>No-Load, R phase open</td>
</tr>
<tr>
<td>S9</td>
<td>100</td>
<td>80</td>
<td>60</td>
<td>1456</td>
<td>Unbalanced voltage</td>
</tr>
<tr>
<td>S10</td>
<td>60</td>
<td>100</td>
<td>100</td>
<td>1461</td>
<td>Unbalanced voltage</td>
</tr>
<tr>
<td>S11</td>
<td>100</td>
<td>60</td>
<td>100</td>
<td>1458</td>
<td>Unbalanced voltage</td>
</tr>
<tr>
<td>S12</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1462</td>
<td>Mechanical unbalance, Level 1</td>
</tr>
<tr>
<td>S13</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1456</td>
<td>Mechanical unbalance, Level 2</td>
</tr>
</tbody>
</table>

The degree of mechanical unbalance was varied by adding more weight to the unbalancing disc at different holes. Study point S13, as mentioned in Table I, has the highest degree of unbalance followed by study point S12 with lesser degree of mechanical unbalance. In all the cases, the stator current signals were obtained through current probe and subsequently transferred to the PC. From the 3-phase line currents, current Concordia vectors in αβ domain were obtained through a MATLAB routine.

### IV. RESULTS AND DISCUSSIONS

#### A. Balanced full voltage at no-load

Current Concordia pattern obtained with the motor in unloaded and healthy condition with balanced full voltage supply corresponding to study point S1 is shown in Fig.7. With balanced supply voltage and motor to be assumed un-faulty, the Current Concordia pattern in Fig.7 should have been a perfect circle. However, as it can be seen in Fig.7, the obtained data does not create a perfect circle. This is due to a small unbalance present in the supply voltage which forces a
small unbalanced current in the three phases. Deviations are also there in the input supply waveform, which has not been a pure sinusoid. Also small deviations were found in the measured resistance and reactance values of the three stator windings.

B. Balanced reduced voltages at no-load

Study points S2 and S3 represents, once again, healthy motor under no-load condition, but now with reduced supply voltages, though balanced. The stator current Concordia patterns for S2 and S3 are combined and plotted in Fig.8. As expected, the two plots in Fig.8 are of similar shape, but the circle pattern with 60% of rated voltage has smaller diameter as compared to that with 80% of rated voltage.

C. Balanced full voltage with balanced full mechanical load

In study point S4, the motor was supplied with 100% rated voltage, but a mechanical load was applied to its shaft. The corresponding stator current Concordia pattern is shown in Fig.9. Fig.9 also contains the plot corresponding to study point S1, for comparison.

D. Balanced full voltage with balanced reduced mechanical loads

In study points S5, S6 and S7, the motor was supplied from a balanced 3-phase voltage source with full rated supply voltage. However, the mechanical load was varied in steps as detailed in Table I. Fig.10 contains combined stator current Concordia patterns for study points S5, S6 and S7.

It is observed that, as expected, the stator current Concordia patterns corresponding to no-load and loaded condition with balanced supply voltage are similar in nature but varying in diameter. Current Concordia pattern for S4 condition with mechanical load has higher diameter as compared to the circular pattern corresponding to study point S1 which is at no-load.

It is observed from Fig.10 that as the loading decreases, the stator current Concordia pattern circles reduce in diameter. In addition to the deviations in diameter, the shapes also vary in shape. This may be due to the fact that at different loading conditions, the currents in the three phases may tend to become unbalanced due to the differences in impedances of the three phases.
E. One supply voltage phase open

One abnormal situation was simulated in Study point S8, where one of the motor supply lines (R phase) was snapped intentionally while the motor was still under running condition. The current Concordia pattern is shown in Fig. 11. Fig 11 also contains the current Concordia pattern for healthy condition (S1 study point) for comparison.

The elliptical current Concordia pattern corresponding to one open phase (R phase open - S8) is clearly distinguishable from the healthy motor circular pattern (S1). The major axis of the elliptic pattern is found to be collinear with the faulty phase (R phase) axis. In an attempt to correlate the co-linearity of the current Concordia ellipse major axis with the faulty phase axis, a similar open circuit condition was imposed on phase B of the supply. The corresponding plot is shown in Fig. 12.

![Fig.11. Current Concordia pattern for supply R phase open; study point S8](image1)

![Fig.12. Current Concordia pattern for supply B phase open](image2)

Similar nature of Concordia pattern variations with open phase was demonstrated in [9].

F. Unbalanced supply voltage with no-load

During operation of a motor under field conditions, it is not rare that there is voltage unbalance in the supply lines. To investigate such unbalanced supply voltage effects on the stator current Concordia patterns, study points S9-S11 have been considered. During this study, supply voltages at the three lines were varied to create unbalance as detailed in Table I. Fig.13 shows the current Concordia patterns for all these study cases along with the reference study case S1.

It was pointed out in [9-10] that the current Concordia pattern takes an elliptical shape, with major axis of the ellipse being indicative of the unbalanced phase. This statement can be verified in the Fig.13. The plot in Fig.13 is very similar to that reported by the authors in [9].

G. Balanced full supply voltage with unbalanced mechanical loads

The degree of mechanical load unbalance was varied by adding more nuts and bolts to different holes drilled on the additional metal disc fitted on the motor shaft. Level 1 unbalance (S12) was done with adding one nut and bolt to the hole nearest to the centre of the disc on one side. Level 2 unbalance (S13) was done with adding two sets of nuts and bolts added to the second hole from the centre of the disk on one side. Fig.14 is the plot of stator current Concordia patterns for study points S12 and S13.

![Fig.13. Current Concordia pattern for supply voltage unbalance; study points S9, S10 and S11](image3)

![Fig.14. Current Concordia pattern for mechanical unbalance; study points S12 and S13](image4)

As observed in Fig.14, the current Concordia patterns for mechanical imbalance (S12 and S13) have much higher
diameters as compared to the healthy motor (S1) circle. The major axis of S12 is almost in the same direction as compared to that of S1. This may be due to the fact that S12 is with level 1 unbalance, which does not make substantial difference in the Concordia pattern except for increase in size of the circle. The major axis for the Concordia pattern of S13 is, however, much shifted from its original position as in S1. This is due to large unbalance caused at level 2 (S13).

A statistical common method for data analysis is the Principal Component Analysis (PCA). By defining the eigenvectors, this technique is able to obtain the major axis of the data sample on the space-vector [15]. The first step is to obtain a data sample matrix S. The number of significant samples n corresponds to the number of rows of matrix S. The induction machine stator currents $I_{sa}$ and $I_{sb}$ form the columns of matrix S. The first sample will be $[I_{sa}(t_0), I_{sb}(t_0)]$, where $t_0$ denotes the initial time instant and subsequently $\Delta t$ denotes the sample interval.

After establishing the correlation matrix of S , denoted by $E$ on (3), their eigenvectors(v) , and the respective eigenvalues ($\lambda$), can be computed

$$E = S^T S$$

(3)

The eigenvectors and the eigenvalues of the correlation matrix are such that (4) holds true

$$E v = \lambda v$$

(4)

PCA can transform a set of correlated variables to a new set of uncorrelated variables. This new set of uncorrelated variables can be represented as a linear combination of the old ones, in a new space defined by the eigenvectors. The linear combination coefficients are the eigenvectors components. The principal component is the one where the data has more energy and the second principal direction is the one with the less energy. One should note that there can be as many principal directions as one chooses. Obviously, only the first ones are of interest, because they carry the most of the data energy. Angular shift of the major axis of current Concordia with respect to study point S1 is presented in Table II.

<table>
<thead>
<tr>
<th>Major Axis Shift in Degrees</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>-65</td>
<td>20</td>
<td>-45</td>
<td>-40</td>
<td>-25</td>
<td>0</td>
<td>-70</td>
<td></td>
</tr>
<tr>
<td>S10</td>
<td>S11</td>
<td>S12</td>
<td>S13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td>-60</td>
<td>55</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

Stator currents’ Park’s pattern or Concordia pattern has been used by researchers for induction motor condition monitoring. It is apparent that these patterns are affected equally by motor external operating conditions, as by internal faults. This paper thus, reports observations on experiments performed on an induction motor with variable supply voltage and mechanical loadings, both under normal and abnormal conditions. Current Concordia patterns thus obtained are found to be largely dependent on such external operating conditions. Knowledge on effects of such external variations will enable proper evaluation of current Concordia patterns while assessing motor internal faults.

VI. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of A. Mukhopadhyay, A. Chowdhury, D. Mitra, M. S. Mondal, R. Gourav and K. Awinash, students of Electrical Engineering Department, Haldia Institute of Technology for their support in performing experiments and simulations for data collection related to this work.

VII. REFERENCES