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Reliability Analysis using Fault Tree Criterion: A Case Study of Inlet Guide Valve of Centrifugal Air Compressor

Tushar J. Padave**, Alok P. Tibrewala
Mechanical Engineering, University of Pune, India

Abstract
Inlet guide valves (IGVs) are one of the most important components in centrifugal air compressors. Evaluating and analyzing the workings and potential failures of IGV ensures efficient working of centrifugal air compressor by eliminating the potential failure modes. Also, analyzing the risk of the component helps in ensuring reliability and safety, which can in turn ensure higher availability and utilization of the system as a whole. Reliability of IGV will directly affect the safety and operational availability of the centrifugal air compressor. This paper includes the basic concept behind inlet guide vane and fault tree analysis (FTA). Also included is the qualitative FTA of the IGV actuation mechanism.

Keywords: *fault tree analysis, centrifugal air compressor, inlet guide valve, reliability analysis*

****Author for Correspondence*** E-mail: tushar.padave9@gmail.com

INTRODUCTION

Inlet guide valve (IGV) is an umbrella term which comprises both inlet guide vanes and the mechanism to actuate them. A centrifugal compressor can be divided into four major parts *viz.*, the inlet guide vanes, the impeller, the diffuser and the volute. One of the main components of the compressor is inlet guide vane which is fitted at the suction end of the air compressor. Inlet guide vanes provide an efficient method of turndown for centrifugal compressors. Guide vanes not only provide the inlet pressure drop but also impart a whirl motion to the gas as it enters the compressor impeller. Since this whirl motion is in the rotational direction of the impeller, it reduces the amount of work the impeller is required to do on the gas. It is this whirl motion that results in energy savings at the design conditions [1].

Recent technological developments in systems worldwide have led to an increase in their complexity. This increased complexity makes the running of components difficult which in turn leads to failures. The failures within these systems can cause disruption to the operational functionality causing major revenue losses to industries. Fault location has thus gained paramount importance in corrective maintenance policies and procedures. Several techniques have been developed for identifying faults. One such method is Fault Tree Analysis (FTA) which uses graphical components to try to identify potential failures before their occurrence.

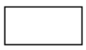
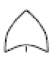
FTA can thus be defined as a type of systematic safety analysis method that was developed in the last 40 years to promote the safety of complex technical systems. The technique of FTA was first used by Bell Telephone Laboratories in 1962 to study the safety of the launch control system for Minuteman missiles [2]. Since the inception of the idea of FTA, there have been continuous efforts to refine the technique. One such latest development in the field is the use of Bayesian Networks (BN) in this process as discussed by Duan and Zhou in their paper [3]. Although there are many risk assessment methods to assess systems, FTA is the most appealing due to the ease of its use and understanding.

FAULT TREE ANALYSIS (FTA)

FTA can be defined as a systematic safety analysis tool that proceeds deductively from the occurrence of an undesired event (accident) to the identification of the root causes of that event. FTA starts with a 'top event or the main event' that is generally displayed with rectangular box and related events based on logical relations are drawn below, branching downward as a tree. In most cases, the top event is chosen based on its criticality i.e., higher the criticality of event more is its change of being chosen as the top event and vice versa. In addition, intermediate events based on the reasons for their occurrence are divided into the branches. The analysis continues at each level of the tree, until basic causes are reached. Basic events are shown with a circle. Undeveloped events are those events whose failure data is not available and are shown in diamond symbol. A triangle symbol is used to show transfer in FTA which indicates the tree is developed further at other trees. FTA uses two logical operators—OR and AND gates [1].

AND-gate indicates that all subevents are necessary to cause the main event, while for an OR-gate only one subevent is necessary [4]. Apart from these two usual gates there is another gate that is used rarely, the INHIBIT gate. INHIBIT-gate states that in addition to the cause stated in the subevent, the condition (in the oval) has to be true to trigger the main event [4]. The various fault tree symbols are shown in Table 1. A basic fault tree diagram is shown in Figure 1.

Table 1: *Symbols used in FTA [4].*

Event	
AND Gate	
OR Gate	
INHIBIT Gate	

The basic steps that can be used to develop a fault free diagram are [2]:

1. System configuration understanding.
2. Logic model generation.
3. Qualitative evaluation of the logic model.
4. Equipment failure analysis and obtain basic data.
5. Quantitative evaluation of the logic model.
6. Recommended appropriate corrective actions.

Probability of Occurrence of Logic Gates

The probability of occurrence of the top events depends on the probability of occurrence of the subevents. Thus, it becomes sometimes necessary to determine the probability of occurrence of subevents to find the risk of possibility of occurrence of the top event.

Generally, the two gates that are used in FTA are OR and AND gate.

OR Gate

Equation to estimate the probability of occurrence of OR gate is as shown below [2]:

$$\mathbf{P(X_0) = 1 - \prod_{j=1}^{m}(1 - P(X_j))} \qquad (1)$$

Where, m is the number of input fault events,
P (X_0) is the probability of occurrence of OR gate's output fault event X_o,
P (X_j) is the probability of occurrence of input fault event X_j, for j = 1, 2, 3, . . ., m.

AND Gate

Equation to estimate the probability of occurrence of AND gate is as shown below [2]:

$$\mathbf{P\ (X_a) = \prod_{j=1}^{m}(P(X_j))} \qquad (2)$$

Where, P (X_a) is the probability of occurrence of AND gate's output fault event X_a.

Use of Bayesian Networks along with FTA

A new development in this field is the use of Bayesian Network (BN) proposed by Duan and Zhou in their paper [3]. The authors have used BN for System Diagnosis Optimization. The concepts of Diagnostic Importance Factor (DIF) and Minimal Cut Set were used in the research paper. DIF is defined conceptually as the probability that an event has occurred given the top event has also occurred [3].

$$\mathbf{DIF_{MCS} = P\ (MCS_n \mid S),\ DIF_C = P\ (C \mid S)} \qquad (3)$$

Where, MCS_n: n^{th} minimal cut sets,
C: a component in system S.

Types of FTA

FTA is generally divided into two types:

i. Qualitative analysis

The task of qualitative analysis is to identify the possible causes of system top event fault, or to find out the minimal cut sets of the fault tree. The method of finding minimum cut set is mainly upstream and downstream [5].

ii. Quantitative analysis

Quantitative analysis can also be carried out after obtaining all the minimal cut sets, if there is enough data which can support deducing probability of each basic event. The main aim of carrying out quantitative analysis is to find the characteristic quantities of the top event and the importance of the basic event, which in turn can determine the weakness of the system [5].

MECHANISM

Inlet Guide Valve

IGV is an umbrella term which includes both inlet guide vanes and the mechanism to actuate it. It provides an efficient method of turndown for centrifugal compressors. Higher energy savings can be realized using inlet guide vanes. Guide vanes not only provide the inlet pressure drop but also impart a whirl motion to the gas as it enters the compressor impeller. Since this whirl motion is in the rotational direction of the impeller, it reduces the amount of work the impeller is required to do on the gas. It is this whirl motion that results in energy savings at the design conditions [1].

Design Parameters

Following are the design parameters, for which the IGV was designed [1]:

1. Minimum opening diameter in fully closed position – 25 mm
2. Bore diameter – 200 mm
3. Inlet pressure – 1.033 bar
4. Pressure after air passes through the vanes – 1.033 bar
5. Bearing type to be used – PTFE
6. Bush type to be used – PTFE
7. Number of vanes – 11
8. Oil-free working of the design

Designed Parameters

To actuate inlet guide vane, a new efficient mechanism was designed—Linear Motion Mechanism. The mechanism as shown in Figures 1 and 2, will slide in reciprocating fashion on the movement guides provided on the housing of the structure. This will in turn ensure that the angles of inlet guide vanes are changed according to the position of the mechanism since the vanes will be coupled to the movement of the mechanism. Figure 1 shows the mechanism in fully open condition, while Figure 2 shows the mechanism in fully closed condition.

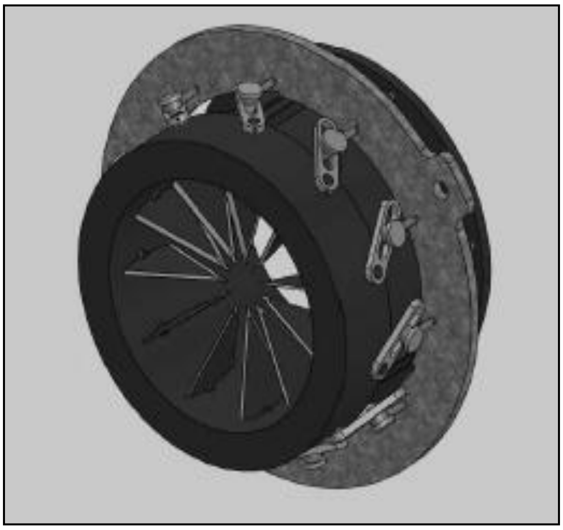


Fig. 1: *Mechanism in Fully Open Position [1].*

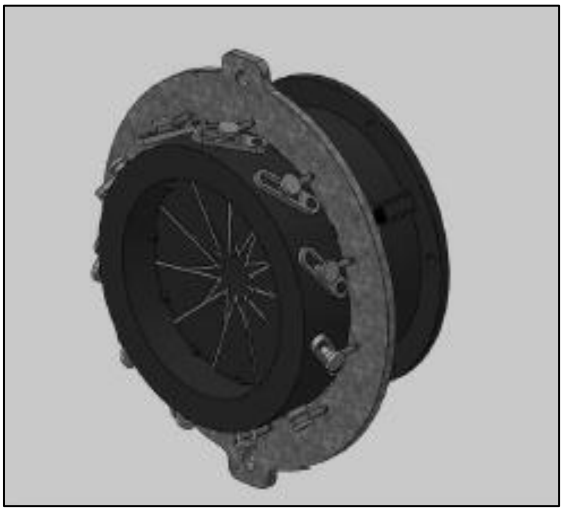


Fig. 2: *Mechanism in Fully Closed Position [1].*

The linear motion mechanism will consists of linear actuator for actuation. The linear actuator will be coupled to the ring that will move on the housing. PTFE bearings are provided in between the housing and ring for smooth movement of the ring. Pin holder will be bolted to the ring and will mesh with the slotted link through a pin. The slotted link will be fitted on the guide vane using a grub screw. When the linear actuator provides linear actuation, this motion will be converted to rotary motion of the guide vane through the movement of slotted link and thus the vane angle can be changed. The linear motion can be provided through suitable gearing arrangement, if rotary motor is used. Linear actuators will be used which have advantage over rotary motors, since no extra gearing setup needs to be done for actuation. Suitable self-lubricating material will be provided on the housing to prevent the friction / wear and tear of the sliding ring on the housing. This will ensure that the mechanism remains external lubrication free to provide oil-free air to the compressor which is the performance requirement. Two linear actuators can be provided on the ring to facilitate better accuracy and faster response time, however this will also add to the overall cost of the mechanism [1].

CASE STUDY

The FTA was applied to the newly designed linear motion mechanism for actuation of inlet guide vanes to test the reliability and safety. The fault tree diagram is shown in Figure 3.

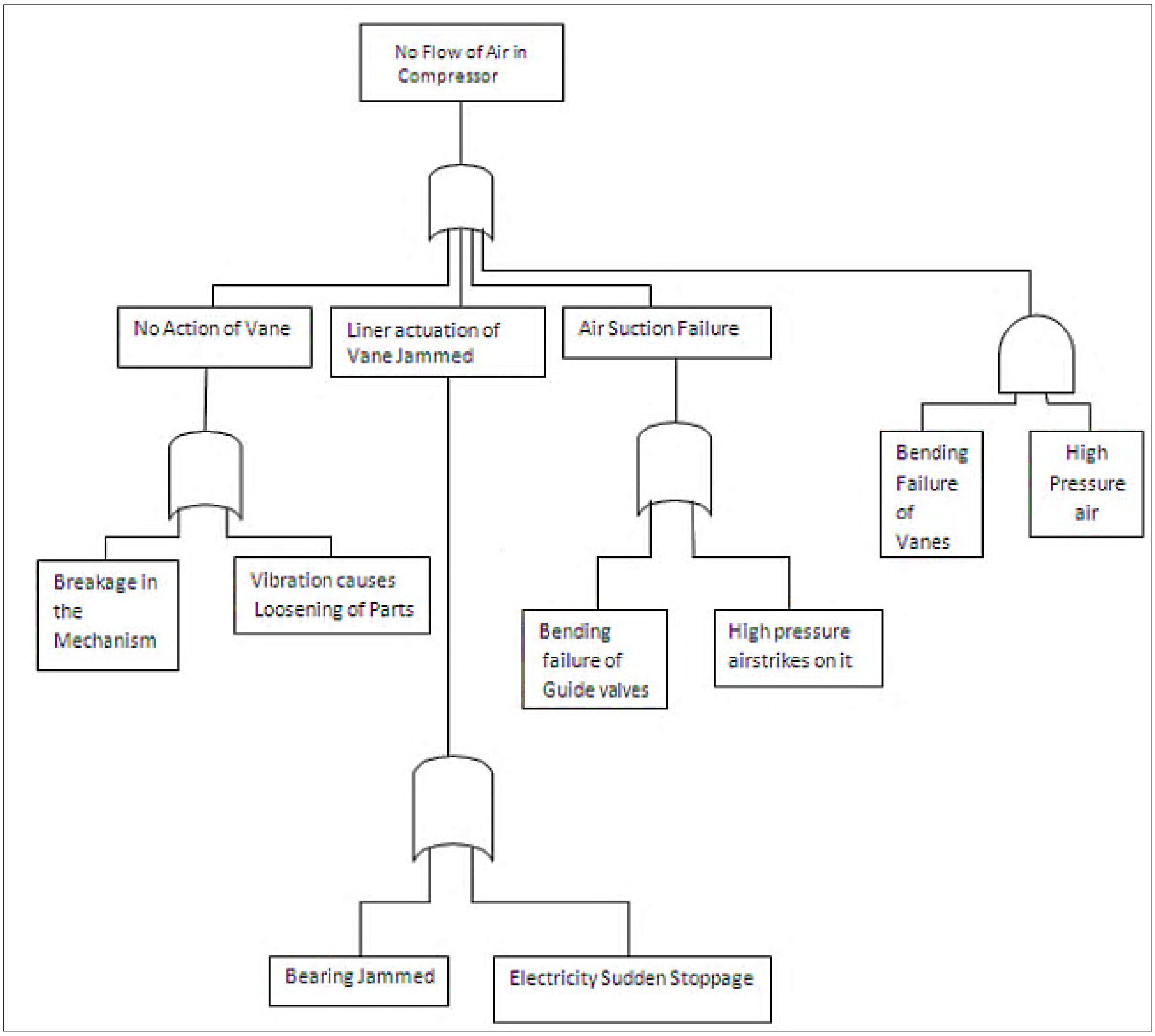


Fig. 3: *Fault Tree Diagram of Linear Motion Mechanism.*

Let,
Q = No flow of air in the compressor (top event);
A_1 = Breakage in the mechanism;
A_2 = Vibration causes loosening of parts;
B_1 = Bearing jammed;
B_2 = Electricity sudden stoppage;
C_1 = Bending failure of guide valves;
C_2 = High pressure air strikes on it;
D_1 = Bending failure of vanes;
D_2 = High pressure air.

The various possible reasons for failure of air to pass into the air compressor are shown in the fault tree diagram in Figure 3 whereas, Figure 4 shows the framework for proposed fault diagnostic of IGV.

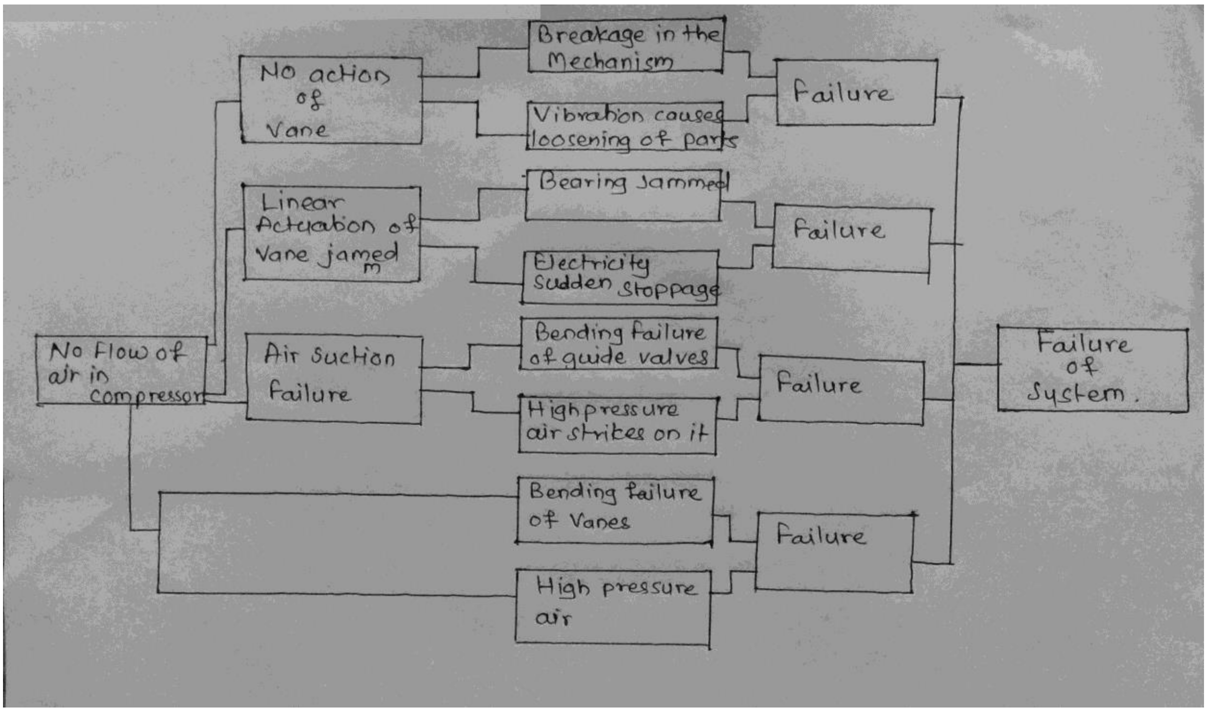


Fig. 4: *Framework for Proposed Fault Diagnostic of IGV.*

Qualitative Analysis

Minimal cut set method was used for qualitative analysis. The method of finding the minimal cut set can be divided into two types—upstream and downstream [5]. However, based on the logical sequence of potential failure cycle the downstream approach is adopted in this paper. The idea of downstream can be explained as, according to two adjacent terms in fault tree, logic 'or' gate increases the number of cut sets and logic 'and' gate increases the capacity of the cut set [5]. Figure 5 shows the qualitative analysis of IGV.

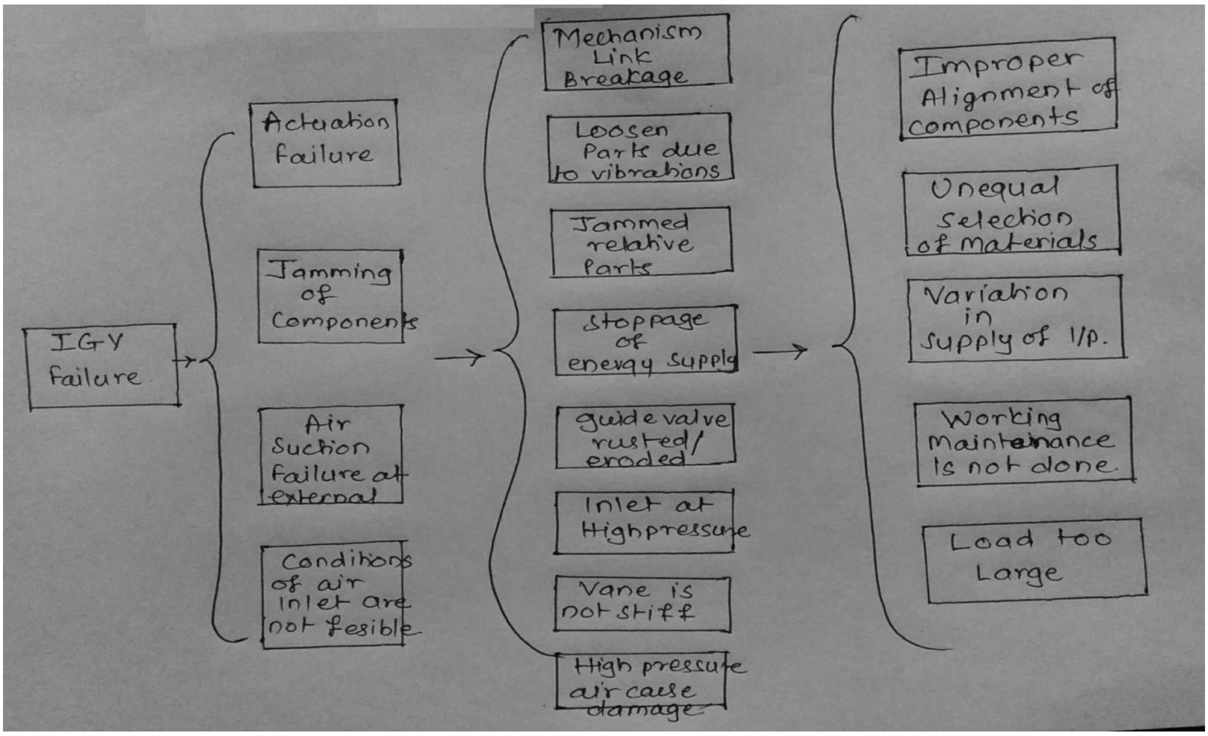


Fig. 5: *Qualitative Analysis of IGV.*

$$Q = (A_1 \cap A_2) \cap (B_1 \cap B_2) \cap (C_1 \cap C_2) \cap (D_1 \cap D_2) \quad (4)$$
$$Q = (A_1 . A_2) \cap (B_1 . B_2) \cap (C_1 . C_2) \cap (D_1 . D_2) \quad (5)$$
$$Q = (A_1A_2) . (B_1B_2) . (C_1C_2) . (D_1D_2) \quad (6)$$
$$Q = A_1A_2B_1B_2C_1C_2D_1D_2 \quad (7)$$

Eq. (7) shows the minimal cut set of the FTA of IGV. It can be seen that all the potential failures should occur simultaneously for the top event to occur.

Quantitative Analysis

The main aim to carry out quantitative analysis is to find the characteristics quantities of the top event and the importance of the basic event, which can determine the weakness of the system [5]. The various steps involved in quantitative analysis are:

1. Calculate the probability of top event

The probability of occurrence of top event with 'AND' gate can be calculated by the following formula [5]:

$$\boldsymbol{p(x) = \cap_{i=1}^{n} p(x_i) = \prod_{i=1}^{n} p(x_i)} \quad (8)$$

The probability of occurrence of top event with 'OR' gate can be calculated by following formula [5]:

$$\boldsymbol{p(x) = \cup_{i=1}^{n} p(x_i) = 1 - \prod_{i=1}^{n}[1 - p(x_i)]} \quad (9)$$

CONCLUSION

IGV is one of the key components of centrifugal air compressor, whose failure will directly hamper the safe operation of the compressor. In this paper, a newly designed mechanism for IGV actuation was subjected to FTA. With greater understanding of the failure modes of the IGV, the design can suitably modified to prevent the potential failures and lead to a safer design.

FUTURE SCOPE

The quantitative analysis of IGV will be carried out.

REFERENCES

1. Tibrewala AP, Padave TJ, Wagh TP, *et al.* Flow Analysis of Upstream Fluid Flow using Simulation for Different Positions of Optimized Inlet Guide Vane in Centrifugal Air Compressor. AJER. 2014; 3(2): 148–56p.
2. Gharahasanlou AN, Mokhtarei A, Khodayarei A, *et al.* Fault Tree Analysis of Failure Cause of Crushing Plant and Mixing Bed Hall at Khoy Cement factory in Iran. *Case Studies in Engineering Failure Analysis*, 2014; 2: 33–8p.
3. Duan RX, Zhou HL. A New Fault Diagnostic Method based on Fault Tree and Bayesian Networks'. *2012 International Conference on Future Electrical Power & Energy Systems*. *Energy Procedia*. 2012; 17: 1376–82p.
4. Ortmeier F, Schellhorn G. Formal Fault Tree Analysis—Practical Experiences. *Electronic Notes in Theoretical Computer Science*. 2007; 185:139–151p.
5. Zhi-Ling Y, Bin W, Dong SH, *et al.* Expert System of Fault Diagnostic for Gear box in Wind Turbine. *The 2nd International Conference on Complexity Science & Information Engineering*. *Systems Engineering Procedia*. 2012; 4:189–95p.

