Petri Net based Approach for Achieving on-Line Fault Diagnosis and Performance Evaluation of Real-Time Industrial Processes

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ABSTRACT
The main aim behind this paper is to develop, design and implement on-line fault diagnosis on real-time industrial processes with suitable performance measures. For this purpose, the system is modeled using Petri nets. The system considered for study here is the Sulphur Recovery Unit (SRU) of Chennai Petroleum Corporation Ltd (CPCL), Chennai. SRU is one of the most important units in the refining process for extraction and removal of sulphur from the products in-order to improve the efficiency. So, in this paper, the sub-units, valve sequence system of Main Clause Recovery Concept (MCRC) converters and vaporized Liquefied Petroleum Gas (LPG) header system of SRU are considered for study. Fault diagnosis algorithms are being developed based on the above idea along with the evaluation of appropriate performance measures.

Keywords: Fault Diagnosis; Estimation; MCRC Converter; Vaporized LPG Header; Sulphur Recovery Unit (SRU); Performance Evaluation.

1. INTRODUCTION
Due to the advancement of Technology in Science and Commerce, there has always been a thrust to improve the efficiency of the Process or System to the demands of the end users. In this regard, Fault Diagnosis and Identification (FDI) plays an important role and has been one of the most concentrated areas of research, design and development.

The main idea behind this paper is thus to design, develop and implement algorithms for achieving FDI in real-time industrial chemical processes along with the evaluation of performance measures.

The Chemical Process considered here is the Sulphur Recovery Unit (SRU) of refinery process of Chennai Petroleum Corporation Ltd (CPCL), Chennai. SRU unit forms an important and essential unit in refining process, where extraction and removal of sulphur from the products of refining are carried out to improve the purity and efficiency of the products. SRU comprises several sub-units working together to achieve the purest form of the products, thereby reducing the content of elemental sulphur. In this paper, the working of Main Clause Recovery Concept (MCRC) converters along with the vaporized liquefied petroleum gas (LPG) header unit is considered for study.

Refining process industry comprises various components of boilers, heat exchangers, cooling towers, etc., and the flow of the fuel/gas is done through a series of pumps and valves, controlled through control units placed at various locations in the industry. The control units take appropriate control actions through the help of numerous sensors for controlling flow, level, pressure, temperature, etc. System normally monitored through automatic/manual means it is subjected to frequent malfunction and has to be rectified so as to improve the efficiency and avoid frequent breakdowns. Moreover, the faults or malfunctions that frequently occur in the system are either due to valve or sensor failures. Since valves and sensors are an integrated part of every sub-unit of the process, it becomes quite difficult to identify and detect the faults arising due to these failures. Hence, it is utmost necessary to develop algorithms for achieving effective fault diagnosis to detect valve and sensor failures.

In literature, there have been several schemes and designs developed and available to achieve fault diagnosis. The most primitive of the approaches is based on analytical model approaches [1], but failed to provide useful results due to the inefficiency in providing exact modeling of physical process. Hence, state model techniques [2], even though highly regarded as the prime and mostly considered techniques for achieving FDI, requires high precision in estimating [3] the plant and fault models.

Here, in this paper, the concept of Petri nets is used for modeling the systems as Discrete Event Systems (DES) [4] rather than continuous systems [5] for the sake of simplicity. The faults occurring in valves are classified as transition faults, and the ones occurring in sensors are classified as place faults in Petri net environment. The normal condition of an event is considered to be observable, and is thus modeled. Once the fault has occurred, the corresponding event is termed as unobservable, and thus the system is again modeled based on the un-observable nature.

2. SYSTEM DESCRIPTION
The process design of SRU is based on the MCRC technology, which is licensed by M/s Delta Hudson Engineering Ltd. It is a combination of clause process and the extension of clause reaction upto the temperature at which the product sulphur starts condensing on the catalyst. Extension of clause reaction upto sulphur dew point enhances sulphur recoveries beyond 99%. As sulphur condensation on the catalyst leads to its activity reduction, regeneration of such portion of the catalyst bed is required.

2.1 Clause Section
Each train of the SRU consists of one thermal reactor, i.e., the Main Combustion Chamber (MCC) and four catalytic converters. The first catalytic converter is a conventional clause converter,

while the last three are MCRC converters that alternate between a sub-dew point mode and a regeneration mode. With such a four-converter MCRC configuration, sulphur recovery higher than 99 % is achievable. The salient feature of the MCRC process is that regeneration takes place on line.

2.2 MCRC Section

In the MCRC section, there are three catalytic stages along with respective sulphur condensers. Operating conditions in two of the three MCRC reactors are aimed in such a way that the adsorption of produced sulphur takes place on part of the catalyst present in the reactor. Such adsorption of sulphur of the catalyst is achieved by maintaining temperature in the corresponding reactors lower than the sulphur dew point. Removal of sulphur from product gases of clause reaction is done by the way of adsorption on catalyst to increase the sulphur conversion by moving clause reaction in forward direction. Additionally, lower reaction temperature also helps thermodynamic equilibrium to shift towards higher sulphur equilibrium concentrations. Thus, overall higher sulphur conversions are easily achieved by reducing the operating temperature in the catalytic reactors. However, deposition of sulphur on active site of catalyst prohibits its further activity. To regenerate the activity of such catalyst sites, sulphur present on such sites needs to be desorbed.

Desorption of sulphur is carried out by operating the reactors at temperature higher than sulphur vaporization temperature. The need for operating sulphur loaded catalyst at higher temperatures is met by operating one of the three MCRC reactors at any given time under regeneration mode. Each MCRC reactor operates in sequence under (1) Regeneration mode (Mode I), (2) Sub dew point mode-1 (Mode II) and (3) Sub dew point mode-2 (Mode III).

As mentioned above, MCRC section includes the three sub dew point sulphur converters. These converters alternate between a sub dew point mode of operation and a regeneration mode. For the purpose of discussion, the converter operating in the regeneration mode is said to be in the sulphur converter II position and the converters operating in the sub-dew point mode are said to be in the No. III and No. IV positions. The reheated gas from the clause section enters the No. II position sulphur converter and regenerates the catalyst bed by vaporizing sulphur which was previously adsorbed onto the catalyst when this converter occupied the No. III and IV positions. Clause conversion continues in this converter even while it is regenerating. The exit gas is cooled to remove elemental sulphur and flows directly (without reheat) to the No. III position sulphur converter that is operating in sub-dew point mode. The gas mixture from converter flows to condenser, and the balance gas from condenser directly flows to No. IV position sulphur converter, where additional sulphur is produced and adsorbed onto the catalyst.

The adsorbed sulphur onto the catalyst is removed from the same converter in the next cycle. Approximately for every 24 hours, one of the three MCRC converters is changed from sub dew point mode to regeneration mode, and another one is changed from regeneration mode to sub dew point mode. The cycle time is changed depending on the loading of sulphur onto the catalyst bed during actual operation.

2.3 Initial Firing

For start-up of main and line burners, and as supplementary fuel for line burners in case of low hydrogen sulphide (H_2S) content of acid gas, vaporized LPG is used. Liquid LPG from battery Limits is received in LPG vaporizer drum, and is vaporized by means of LP steam flowing into the internal coil of the drum. The vaporized LPG is sent to vaporized LPG K.O. Drum, where entrained liquids are separated and from where it is distributed to main burners and to line burners of both the trains.

3. SYSTEM MODELING

As mentioned in the earlier section, system modeling is done using Petri nets, considering the whole process as a discrete event system. The presence of a token in a place denotes the condition for starting an operation or event, firing of a transition denotes the start of the event and movement of the token from one place to another represents condition after the operation or event is completed. Based on these conditions, the modeling of the system is done.

Figures 1 and 2 represent the equivalent systems for valve sequence operations of MCRC cycle1 to cycle3 and vaporized LPG header train modeled using Petri nets. The dark circles represent the actual valves that are present in the unit. The white circles represent the conditions for the valve, i.e., whether open or closed. Thus, presence of token in the respective white circles shows that the corresponding valves are to be kept open or closed.

Once successful modeling of the system is completed, the algorithms for fault diagnosis are developed and the corresponding fault (valve failure, sensor failure etc.) can be detected and identified.

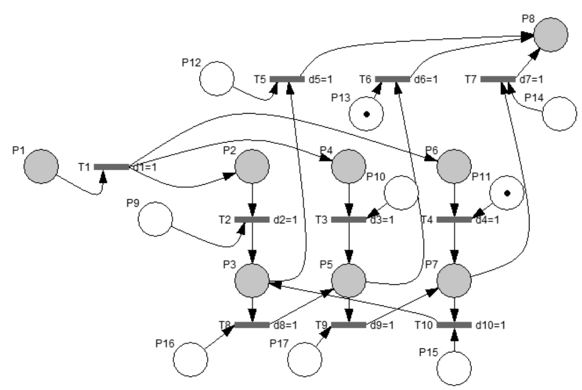

Fig. 1: Petri net model of MCRC valve sequence

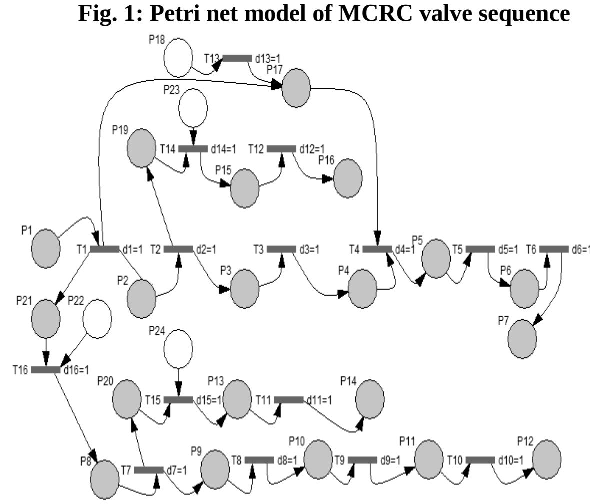

Fig. 2: Petri net model of vaporized LPG header train

Table 1: Description of places/transitions and conditions for model shown in Fig. 1

P/T	Description	P/T Condition Yes-Token present No- Token absent ON-Firing enabled OFF-Firing disabled		
		Cycle 1	Cycle 2	Cycle 3
P1	Process Flow gas	Yes	Yes	Yes
T1	Valve 1 ON	ON	ON	ON
P2, P4, P6	Flow gas ready	No	No	No
P3, P5, P7	Mode I, II, III	No	No	No
T2, T3, T4	Inlet valve 1, 2, 3	ON	OFF	OFF
T8, T9, T10	Intermediate valve 1, 2, 3	ON	ON	OFF
T5, T6, T7	Outlet valve 1, 2,3	OFF	OFF	ON
P9, P10, P11	Inlet Valve 1, 2, 3 condition	Yes	No	No
P12, P13, P14	Outlet valve 1, 2, 3 condition	No	No	Yes
P15, P16, P17	Intermediate valve 1, 2, 3 condition	Yes	Yes	No

Table 2: Description of places/transitions and conditions for model shown in Figure 2

S. No	P/T	Description
1.	P1	KO drum output
2.	P2, P3	Valve 1 condition and operation
3.	P4, P10	Valve 2 condition and operation
4.	P5, P11	Valve 4 condition and operation
5.	P6, P7	Pressure switch and Reaction furnace condition
6.	P8, P9	Alternate Valve 1 line condition and operation
7.	P12	Furnace operation
8.	P13, P14	Flare output for alternate line
9.	P15, P16	Flare output for main line
10.	P17, P18	Flow transmitter output and condition
11.	P19, P20	Condition for flare operation and main and alternate lines
12.	P21, P22	Conditions for valve 1 in alternate line
13.	P23, P24	Condition for valve 3 in flare output of main and alternate lines
14.	T1-T6	Main line valves
15.	T7-T10	Alternate line valves
16.	T11, T15	Flare output valves of main line
17	T14, T12	Flare output valves of alternate line
18.	T13	Condition for Flow Transmitter
19.	T16	Condition for valve 1 in alternate line

4. FAULT DIAGNOSIS AND IDENTIFICATION

This section describes the methods of fault detection and proposed algorithm for achieving fault diagnosis.

4.1 Fault Detection

As mentioned in the earlier section, Petri net is a powerful tool for system description. Nevertheless, it can be a useful tool for process monitoring also. The problem of process monitoring in any process plant can be stated as follows: The measurement signals come from the system at constant scanning rate. While processing these data, a computer based system should decide on-line in real-time if an error has occurred or not. To perform this, the computer program needs to know the "total" process description.

Suppose, it is possible to map the structure of the total process using a Petri net, the transport of physical conservation quantity can be represented by firing of tokens. If the conservation quantity takes only few discrete values, and if the measured signals are not noisy, comparison is made and using the property of reachability, the errors are identified. This is carried out by finding the initial marking and comparing it with the new marking vectors developed after firing of tokens. Any change in the sequence will result in an error in the corresponding element of the marking vector which gives indication of faulty nature of the process.

Even when the signals received from the system are noisy, the property of observability is considered as the criterion for diagnosis where suitable threshold limit has to be satisfied. If the error measured as mentioned above is higher than the limit, then it indicates that a fault has occurred. Then, suitable diagnosis is done to classify the faults.

4.2 Fault Monitoring Algorithm

With regard to the types of faults considered earlier and its equivalent in Petri net environment, the following criterion is adopted.

Step (i): Initial token content per place is found out by determining the initial marking vector denoted by $M_i(0)$.

Step (ii): Actual number of tokens arising in the running of the process is found out which is denoted by $M_i(k)$.

Step (iii): The difference between the marking vectors are calculated, i.e., $M_i(k)$-$M_i(0)$.

Step (iv): If the difference is 0, then the system is considered as fault free.

Step (v): If not, the corresponding place fault is occurred and algorithm is developed to identify the faulty place/transition.

Figures 3 and 4 show the development of system for fault diagnosis modeled in MATLAB environment. The presence of a place fault is diagnosed by considering and checking the reachability of markings. For diagnosing the transition faults, evaluation of performance measures are considered. Likewise, Figures 5 and 6 show the views of the simulation results obtained for a faulty and non-faulty process. The view of the algorithm developed in MATLAB environment is shown in Figure 7.

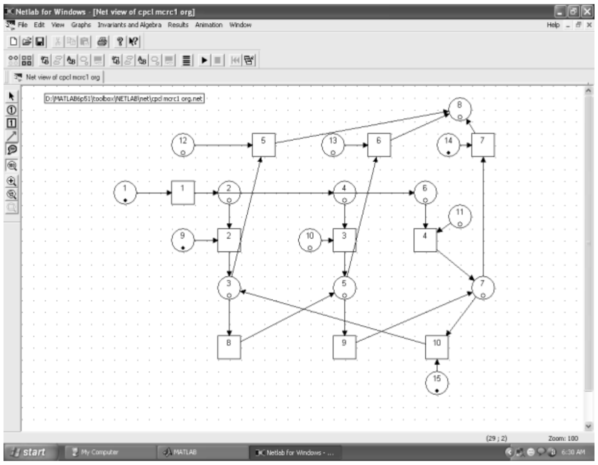

Fig. 3: View of original model of MCRC valve sequence 1

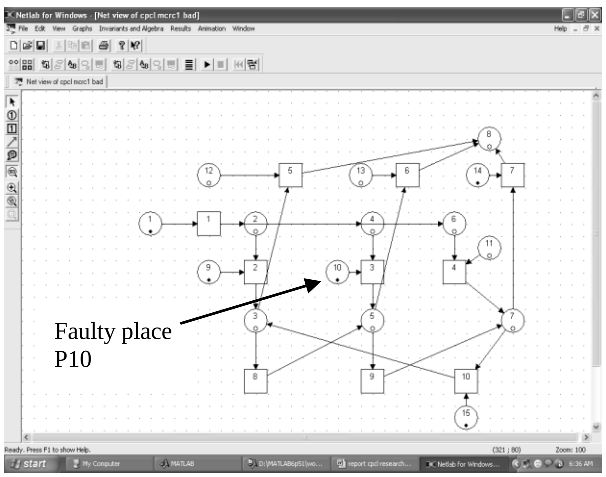

Fig. 4: View of fault model of MCRC valve sequence 1

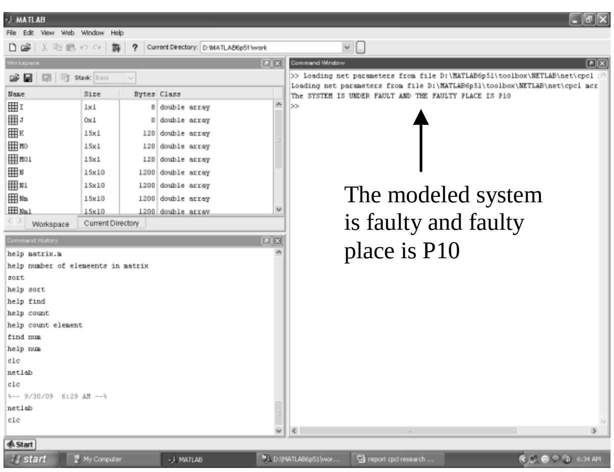

Fig. 5: View of Simulation result developed in MATLAB for Faulty process

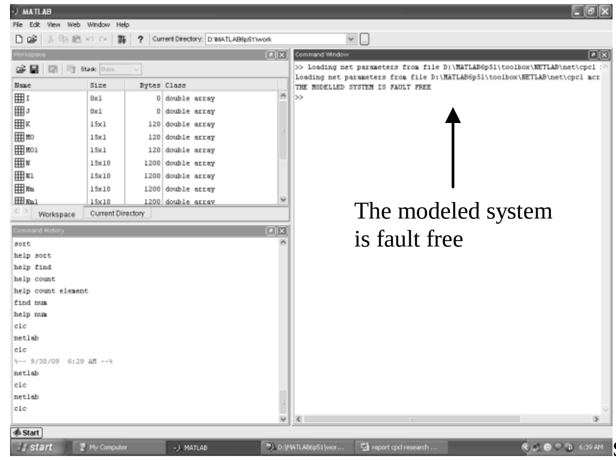

Fig. 6: View of Simulation result developed in MATLAB for Non-Faulty process

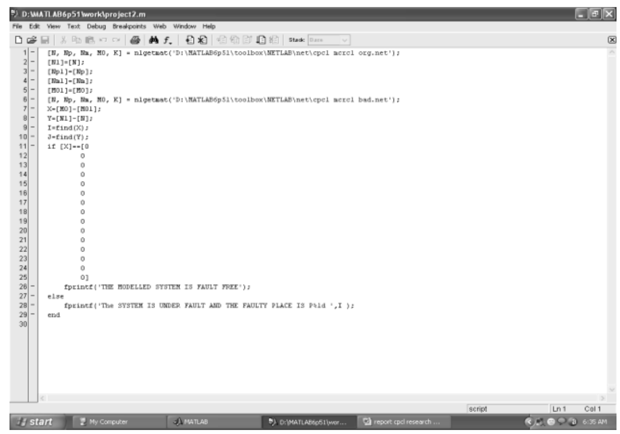

Fig. 7: View of algorithm developed for FDI in MATLAB

5. NUMERICAL RESULTS AND DISCUSSION

For the purpose of simulating the processes modeled using Petri nets as shown in Figure 8, SIRPHYCO software [6] is utilized. The simulation window shows the time taken for firing of each valve to operate in the MCRC sequence. Moreover the graphs also depict the sequence of operation i.e. initially P3 is marked followed by P5, P7 and finally outputted through P8. Similar graphs can be obtained by considering the other valve sequences of the MCRC.

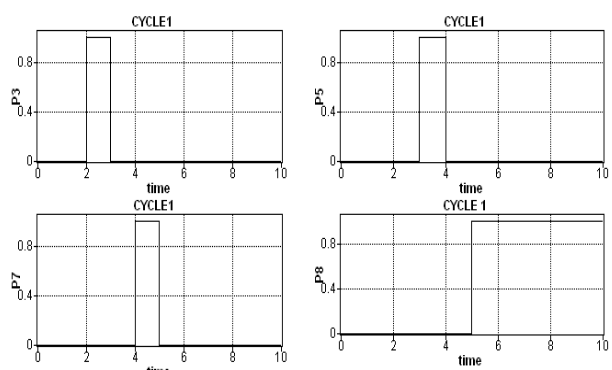

Fig. 8: Results for MCRC valve sequence 1

The marking evolution of the places considering the valve sequences 2 and 3 are simulated and shown in Figures 9 and 10 respectively.

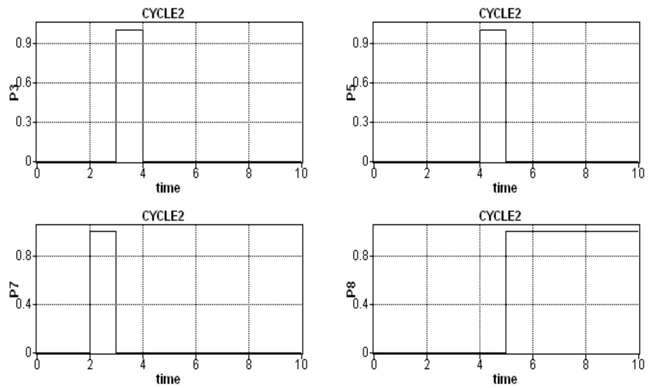

Fig. 9: Results for MCRC valve sequence 2

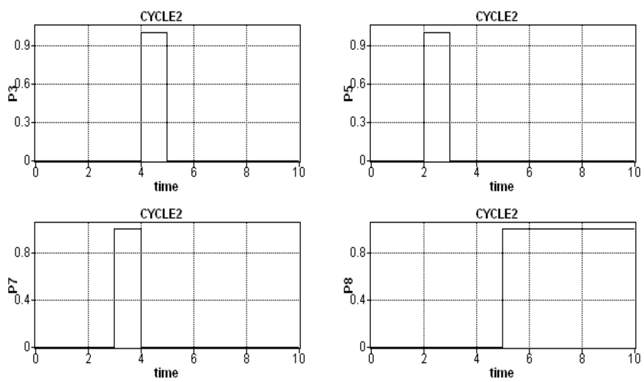

Fig. 10: Results for MCRC valve sequence 3

The performance of the modeled system is determined by considering the system as a random process, and by fitting a distribution constant for the transitions. The distribution constant types Constant, Uniform, Exponential, Lognormal, Gamma and Weibul are considered in this paper, and applied to the transitions which are used for modeling the inlet, intermediate and outlet valves of the MCRC sequence. The results are simulated using the PETRINET2.3 toolbox [7] and results are tabulated in Tables 3-5. The performance measures obtained in this paper are service sum, service rate, service distance, service time, and utilization which give the total description about the performance of transitions. For example, it can be seen from the values of the utilization performance index that the performance of transitions T7, T8, and T2 are improved by considering Gamma, Uniform and Lognormal functions respectively. Similar studies can be made using the other measures which are highly useful in understanding the system behaviors.

Table 3: Performance measures for transition T7

Measure	Serv ice sum	Ser vice rate	Ser vice distance	Ser vice time	Utili zation
Constant	1	0.0192	52	50	0.9615
Uniform	1	0.0134	74.55	72.03	0.9661
Exponential	1	0.0236	42.45	40.98	0.9653
Lognormal	1	0.0051	192.97	184.93	0.9583
Gamma	1	0.0073	136.54	133.53	0.9778
Weibul	1	0.0194	51.457	49.603	0.964

Table 4: Performance measures for transition T8

Measure	Serv ice sum	Ser vice rate	Ser vice distance	Ser vice time	Utili zation
Constant	1	0.0192	52	50	0.9615
Uniform	1	0.0134	74.56	0.406	0.9782
Exponential	1	0.0235	42.45	0.118	0.9682
Lognormal	1	0.0052	192.98	1.595	0.976
Gamma	1	0.0073	136.54	0.002	0.978
Weibul	1	0.0194	51.457	0.471	0.9733

Table 5: Performance measures for transition T2

Measure	Serv ice sum	Ser vice rate	Ser vice distance	Ser vice time	Utili zation
Constant	1	0.0192	52	0.5	0.981
Uniform	1	0.0134	74.56	0.624	0.987
Exponential	1	0.0236	42.45	0.352	0.976
Lognormal	1	0.0052	192.98	3.637	0.995
Gamma	1	0.0073	135.54	2.012	0.993
Weibul	1	0.0194	51.457	0.3719	0.981

6. CONCLUSIONS

In this paper, the total description of the process monitoring for achieving FDI is attempted, and the results are obtained along with the evaluation of performance measures. For this purpose, the MCRC and vaporized LPG header train sub-units of SRU are considered for study and modeled using Petri nets. The proposed scheme is very useful in diagnosing valve and sensor failures which are common phenomenon in process industries.

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