SIL Verification of Safety Instrumented System for Block Valve System in Gas Pipeline by Using Markov Model Methodology

P. Kongtong and, S. Chitwong

***Abstract*—This paper presents about methods for evaluation of safety integrity level (SIL) which is significant to reduce risk of failure of block valve in gas pipeline system by using Markov Model method which refer to International standard IEC 61508/61511. The reason of using Markov Model method is that it takes less time and more flexible than other methods to determine SIL. This method uses a qualitative approach showing Average Probability of Failure (PFDavg) rate data and repairing time from model to implement in further process.**

***Index Terms*—, tracking, biomimetic, redundancy, degrees-of-freedom Safety Instrumented Systems, Safety Instrumented Functions, Safety Integrity Levels, Markov Models, Probability of Failure on Demand**

I. INTRODUCTION

SAFETY Instrumented Systems (SIS) are not new. It has long been the practices to fit protective systems to industrial process plant where there is a potential threat to life or the environment. In example, to increase of energy consumption, safety system design in process of natural gas, which is flammable fluid, has generally been more significant. Natural gas pipeline in Thailand have been serviced to supply natural gas to consumer for 24 hrs./day for more than 25 years. The high pressure natural gas transfer itself to lower pressure. Pressure control valves are basically used to reduce pressure to proper with each area application. The natural gas pipelines are mostly routed through area of agriculture, community or highway where any fault of safety system design may become disaster to life or property. For this reason, risk assessment for control loop of this pressure control valve is highly significant to be reviewed in order to avoid hazard.

For hazardous process, safety instrumented system is significantly used to control reliability and safety of process. “Safety Integrity Level (SIL)” is used to define target probability of failure on demand (PFD) of a Safety Instrument Function (SIF) which is a guideline for safety design, installation and also preventive maintenance included. Dangerous failure such as instrument failure could make a severity consequence to property, environment and human which route cause of failure possibly came from several reasons whether failure of process instrument.

II. VERIFICATION METHODOLOGY

The method for SIL having various methodologies can be used to verify the SIL of SIS. The methods divided into two types are qualitative and quantitative methods.

Qualitative methods such as risk matrix are evaluation based on experience or knowledge of expert team to estimate the consequence of a hazard. Quantitative methods such as LOPA (Layer of Protection Analysis), FTA (Fault Tree Analysis), Markov Model evaluation are based on numerical data and mathematical analysis.

III. CASE STUDY

A. Determination of Safety Instrumented Function

In this work, safety instrumented function of block valve system protects over pressure in gas pipeline. The process operation of the block valve is receiving natural gas from station 1 in order to transmit to station 3. This SIF consists of three pressure transmitters (PT) having a two out of tree voting configuration serving as the inputs to the logic solver system. The logic solver will then signal to block valves with two solenoid valve (SOV) having one out of two voting configuration to close, shutting off the flow into the pipeline shown in Fig. 1.

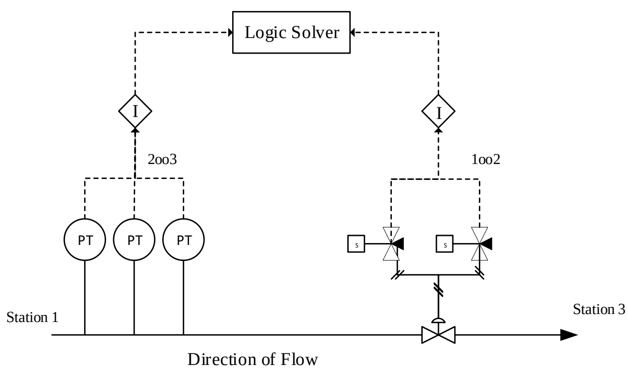

Fig. 1 Block Valve System

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Pawarisa Kongtong and Sakreya Chitwong are with the department of Instrumentation and Control Engineering, Faculty of Engineering, King Mongkut’s Institute of technology Ladkrabang, Ladkrabang, Bangkok 10520 THAILAND. (e-mail : pawarisa.kt@hotmail.com, sakreya.ch@kmitl .ac.th).

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IV. Units Evaluation method

A. Markov Model

Markov model is a technique to calculate safety integrity level by state transition diagram. The diagram from state to another state will be presented transition failure mode of each component. The corresponding transition rates are indicated on the arrows or transition arch is shown in Fig. 2.

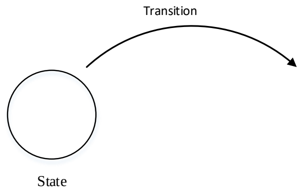

Fig. 2 Representation of Transition State

The two types of the system of Markov model are Restorable and Non-Restorable. Restorable shown in Fig. 3 the system containing state which can fail and can then be restore to initial state without necessary system failure. Non–Restorable shown in Fig. 4 is system containing state which can fail and cannot be restored to their up state without necessary system failure. The state transition diagram contains only transition direction towards system failure state.

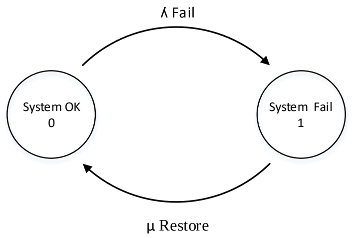

Fig. 3 Restorable component

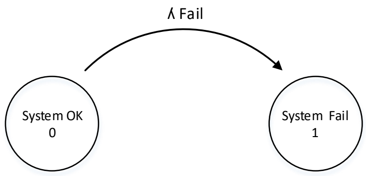

Fig. 4 Non- restorable component

B. State of Components

The state of a component is determined by list of the possible failure mode of each component to classify the degraded state (intermediate) and failure system states of block valve system. The initial state is a unique one which means no failure at all. The states are listed in Table I.

TABLE I, The state of a system

Components	Failure Mode	Resulting System State after a single failure
Pressure Sensor (S)	SD	Intermediate State
	SU	Intermediate State
	DD	Intermediate State
	DU	Intermediate State
Logic Solver (L)	S	Fail Safe
	D	Fail Dangerous
Solenoid Valve (A1)	SD	Fail Safe
	SU	Fail Safe
	DD	Intermediate State
	DU	Intermediate State
Block Valve (A2) +Actuator	S	Fail Safe
	D	Fail Dangerous

C. Probability of Failure

In block valve system, PFDavg is calculated by the state transition rates, repairs and restorations, which will be added into the models. Common cause failure can also be added into the calculation steps. It is capably simplified by a transition metric including failure modes of each component typically divided into four modes:

--Safe detected (SD)
--Safe undetected (SU)
--Dangerous detected (DD)
--Dangerous undetected (DU)

The λ parameter is the rate that the demand occurs.
The proof test interval (TI), the mean time to restore (MTTR), PFDavg defined as in Table II.

TABLE II, PFD Values of Component

Model Parameters	Pressure Transmitter	Logic Solver	Solenoid Valve	Valve +Actuator
λ^{SDC}	$4\text{x}10^{-10}$	-	5.05E x10-09	-
λ^{SUC}	$4\text{x}10^{-10}$	-	5.05E x10-09	-
λ^{SDN}	$1.96\text{x}10^{-8}$	$7.425\ \text{x}10^{-07}$	9.595E x10-08	7 x10E-08
λ^{SUN}	$1.96\ \text{x}10^{-8}$	$7.5\ \text{x}10^{-09}$	9.595E x10-08	7E x10-08
λ^{DDC}	$3\ \text{x}10^{-10}$	2.375x10-07	2.5E x10-09	1.07 x10E-07
λ^{DUC}	$1.2\ \text{x}10^{-09}$	1.25E x10-08	2.925E x10-09	2.27E x10-07
λ^{DDN}	$1.47\ \text{x}10^{-08}$	-	4.75E x10-08	-
λ^{DUN}	$5.88\ \text{x}10^{-08}$	-	5.558E x10-08	-
SFF%	0.6	0.99	0.721	0.309
Test Interval (Hours)	17,520	17,520	17,520	17,520
MTTR (Hours)	12	12	12	12

D. Notation

PFD_{avg}	Average Probability of Failure on Demand
λ_S	Failure Rate of Sensor
λ_L	Failure Rate of Logic Solver
λ_{A1}	Failure Rate of Solenoid Valve
λ_{A1}	Failure Rate of Block Valve combines Actuator
λ^{SDC}	Safe Detected Common Cause Failure Rate
λ^{SUC}	Safe Undetected Common Cause Failure Rate
λ^{SUN}	Safe Undetected Normal Mode Failure Rate
λ^{SDN}	Safe detected Normal Mode Failure Rate.
λ^{DUN}	Dangerous Undetected Normal Mode Failure Rate
λ^{DUC}	Dangerous Undetected Common Cause Failure Rate
λ^{DDN}	Dangerous Detected normal mode failure rate
λ^{DDC}	Dangerous Detected Common Cause Failure Rate
μ_0	Restoration Rate
μ_{SD}	Restoration Rate for Shutdown

E. Calculating

Markov model illustrated in Fig. 5 is calculated by steady state probability solutions. The system has twelve states initial 0 to 11 and there are transition arcs of 41 between the states. It is assumed that system is operating in states 0.

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Since twelve states exist, the P-matrix has a dimension of 12x12.

Each of the states from the Fig. 5 is identified by three units. State 0 represent system OK in fully operation. State 1, 2, 3 and 4 represent the system has firstly degrade (Intermediate State). State 5, 6, 7 and 8 represent the system has secondary degrade. State 9 represent system fail safe state. State 10 represent system fail dangerous undetected state. State 10 represent system fail dangerous detected.

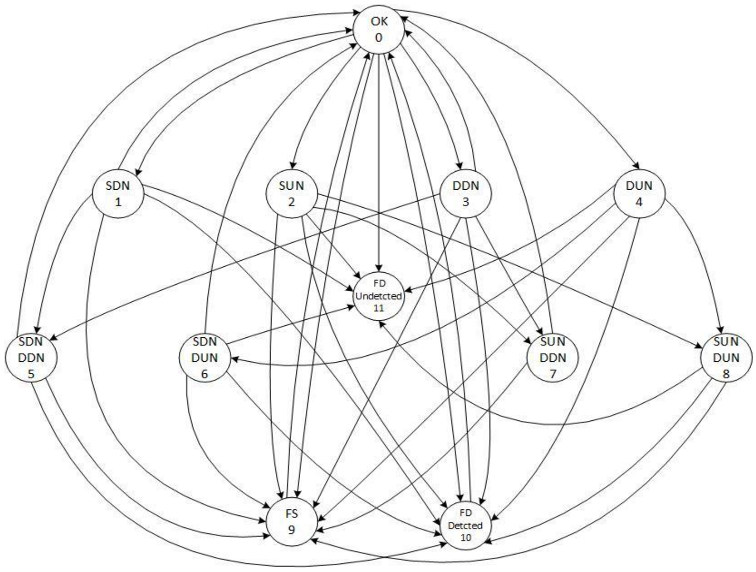

Fig. 5 Markov model of block valve system

$\lambda_{0,0} = 1-(\lambda_{0,1} + \lambda_{0,2}\ \lambda_{0,3} + \lambda_{0,4} + \lambda_{0,9+}\ \lambda_{0,10+}\ \lambda_{0,11})$
$\lambda_{1,0} = \mu_0$
$\lambda_{0,1} = 3\lambda_S^{SDN}$
$\lambda_{1,1} = 1-(\lambda_{1,5}+ \lambda_{1,6}+ \lambda_{1,9}+ \lambda_{1,10}+ \lambda_{1,11})$
$\lambda_{1,5} = 2\lambda_S^{DDN}$
$\lambda_{1,6} = 2\lambda_S^{DUN}$
$\lambda_{1,9} = \lambda_S^{SC}+2\lambda_S^{SN}$
$\lambda_{1,10} = \lambda_S^{DDC}$
$\lambda_{1,11} = \lambda_S^{DUC}$
$\lambda_{0,2} = 3\lambda_S^{SUN}$
$\lambda_{2,2} = 1-(\lambda_{2,7}+\lambda_{2,8} +\lambda_{2,9}+\lambda_{2,10}+\lambda_{2,11})$
$\lambda_{2,7} = 2\lambda_S^{DDN}$
$\lambda_{2,8} = 2\lambda_S^{DUN}$
$\lambda_{2,9} = \lambda_S^{SUC}+2\lambda_S^{SUN}$
$\lambda_{2,10} = \lambda_S^{DDC}$
$\lambda_{2,11} = \lambda_S^{DUC}$
$\lambda_{0,3} = 3\lambda_S^{DDN} +\lambda_L^{DD}+ 2\lambda_{A1}^{DDN}+\lambda_{A2}^{DD}$
$\lambda_{3,0} = \mu_0$
$\lambda_{3,3} = 1-(\lambda_{3,5}+ \lambda_{3,7}+ \lambda_{3,9} +\lambda_{3,10})$
$\lambda_{3,5} = 2\lambda_S^{SDN}$
$\lambda_{3,7} = 2\lambda_S^{SUN}$
$\lambda_{3,9} = \lambda_S^{SUC}+\lambda_S^{SDC}+ \lambda_{A1}^{S}$
$\lambda_{3,10} = \lambda_S^{DC}+2\lambda_S^{DN}+ \lambda_{A1}^{DD}$
$\lambda_{0,4} = 3\lambda_S^{DUN} +\lambda_L^{DU}+ 2\lambda_{A1}^{DUN}+\lambda_{A2}^{DU}$
$\lambda_{4,4} = 1-(\lambda_{4,6} + \lambda_{4,8} +\lambda_{4,9} + \lambda_{4,10} +\lambda_{4,11})$
$\lambda_{4,6} = 2\lambda_S^{SDN}$
$\lambda_{4,8} = 2\lambda_S^{SUN}$
$\lambda_{4,9} = \lambda_S^{SDC}+\lambda_S^{SUC}+\lambda_{A1}^{S}$
$\lambda_{4,10} = \lambda_S^{DDC}+2\lambda_S^{DDN} +\lambda_{A1}^{DD}$
$\lambda_{4,11} = \lambda_S^{DUC}+2\lambda_S^{DUN} +\lambda_{A1}^{DU}$
$\lambda_{5,5} = 1-(\lambda_{5,9} +\lambda_{5,10})$
$\lambda_{5,0} = \mu_0$
$\lambda_{5,9} = \lambda_S^{S}$
$\lambda_{5,10} = \lambda_S^{D}$
$\lambda_{6,6} = 1-(\lambda_{6,9} +\lambda_{6,10})$
$\lambda_{6,0} = \mu_0$
$\lambda_{6,9} = \lambda_S^{S}$
$\lambda_{6,10} = \lambda_S^{DD}$
$\lambda_{7,7} = 1-(\lambda_{7,9} +\lambda_{7,10})$
$\lambda_{7,0} = \mu_0$
$\lambda_{7,9} = \lambda_S^{S}$
$\lambda_{7,10} = \lambda_S^{D}$
$\lambda_{8,8} = 1-(\lambda_{8,9} +\lambda_{8,10})$
$\lambda_{8,9} = \lambda_S^{S}$
$\lambda_{8,10} = \lambda_S^{DD}$
$\lambda_{0,9} = 3\lambda_S^{SDC}+3\lambda_S^{SUC}+\lambda_L^{SD}+\lambda_L^{SU}+\lambda_{A1}^{SDC} + \lambda_{A1}^{SUC}+2\lambda_{A1}^{SDN} +2\lambda_{A1}^{SUN}+\lambda_{A2}^{SD}+ \lambda_{A2}^{SU}$
$\lambda_{9,9} = 1$
$\lambda_{0,10} = 3\lambda_S^{DDC}+ \lambda_L^{DD}+\lambda_{A1}^{DDC} +\lambda_{A2}^{DD}$
$\lambda_{10,10}= 1$
$\lambda_{0,11} = 3\lambda_S^{DUC} +\lambda_L^{DU}+ \lambda_{A1}^{DUC} +\lambda_{A2}^{DU}$
$\lambda_{11,11}= 1$

The state of transition matrix is shown in Fig. 6

$$P=\begin{bmatrix}
1-\Sigma & 3\Lambda_S^{SDN} & 3\Lambda_S^{SUN} & 3\Lambda_S^{DDN}+\Lambda_L^{DD}+2\Lambda_{A1}^{DDN}+\Lambda_{A2}^{DD} & 3\Lambda_S^{DUN}+3\Lambda_L^{DU}+\Lambda_{A1}^{DUN}+\Lambda_{A2}^{DU} & 0 & 0 & 0 & 0 & 3\Lambda_S^{SDC}+3\Lambda_S^{SUC}+\Lambda_L^{SD}+\Lambda_L^{SU}+\Lambda_{A1}^{SDC}+\Lambda_{A1}^{SUC}+2\Lambda_{A1}^{SDN}+2\Lambda_{A1}^{SUN}+\Lambda_{A2}^{SD}+\Lambda_{A2}^{SU} & 3\Lambda_S^{DDC}+\Lambda_L^{DD}+\Lambda_{A1}^{DDC}+\Lambda_{A2}^{DD} & 3\Lambda_S^{DUC}+\Lambda_L^{DU}+\Lambda_{A1}^{DUC}+\Lambda_{A2}^{DU} \\
\square_0 & 1-\Sigma & 0 & 0 & 0 & 2\Lambda_S^{DDN} & 2\Lambda_S^{DUN} & 0 & 0 & 2\Lambda_S^{SC}+2\Lambda_S^{SN} & \Lambda_S^{DDC} & \Lambda_S^{DUC} \\
0 & 0 & 1-\Sigma & 0 & 0 & 0 & 0 & 2\Lambda_S^{DDN} & 2\Lambda_S^{DUN} & 2\Lambda_S^{SUC}+2\Lambda_S^{SUN} & \Lambda_S^{DDC} & \Lambda_S^{DUC} \\
\square_0 & 0 & 0 & 1-\Sigma & 0 & 2\Lambda_S^{SDN} & 0 & 2\Lambda_S^{SUN} & 0 & \Lambda_S^{SUC}+\Lambda_S^{SDC}+\Lambda_{A1}^{S} & \Lambda_S^{DC}+2\Lambda_S^{DN}+\Lambda_{A1}^{DD} & 0 \\
0 & 0 & 0 & 0 & 1-\Sigma & 0 & 2\Lambda_S^{SDN} & 0 & 2\Lambda_S^{SUN} & \Lambda_S^{SDC}+\Lambda_S^{SUC}+\Lambda_{A1}^{S} & \Lambda_S^{DDC}+2\Lambda_S^{DDN}+\Lambda_{A1}^{D} & \Lambda_S^{DUC}+2\Lambda_S^{DUN}+\Lambda_{A1}^{DU} \\
\square_0 & 0 & 0 & 0 & 0 & 1-\Sigma & 0 & 0 & 0 & \Lambda_S^{S} & \Lambda_S^{D} & 0 \\
\square_0 & 0 & 0 & 0 & 0 & 0 & 1-\Sigma & 0 & 0 & \Lambda_S^{S} & \Lambda_S^{DD} & 0 \\
\square_0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-\Sigma & 0 & \Lambda_S^{S} & \Lambda_S^{D} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-\Sigma & \Lambda_S^{S} & \Lambda_S^{DD} & 0 \\
\square_{SD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-\Sigma & 0 & 0 \\
\square_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-\Sigma & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

Fig. 6 Transition matrix of block valve system

Substituting the given failure rates and other parameter into the transition matrix is the P-matrix resulted in Fig. 7

$$P=\begin{bmatrix}
0.999997 & 0.00000005880 & 0.00000002250 & 0.00000044310 & 0.00000052705 & 0 & 0 & 0 & 0 & 0.00000128630 & 0.00000034790 & 0.00000024603 \\
0.083333 & 0.999999772 & 0 & 0 & 0 & 0.00000002940 & 0.00000011760 & 0 & 0 & 0.00000007920 & 0.00000000030 & 0.00000000120 \\
0 & 0 & 0.999999812 & 0 & 0 & 0 & 0 & 0.00000002940 & 0.00000011760 & 0.00000003960 & 0.00000000030 & 0.00000000120 \\
0.083333 & 0 & 0 & 0.99999891380 & 0 & 0.00000003920 & 0 & 0.00000003920 & 0 & 0.00000075080 & 0.00000025700 & 0 \\
0 & 0 & 0 & 0 & 0.99999891380 & 0 & 0.00000003920 & 0 & 0.00000003920 & 0.00000075080 & 0.00000007970 & 0.00000017730 \\
0.083333 & 0 & 0 & 0 & 0 & 0.99999891380 & 0 & 0 & 0 & 0.00000004000 & 0.00000007500 & 0 \\
0.083333 & 0 & 0 & 0 & 0 & 0 & 0.99999994430 & 0 & 0 & 0.00000004070 & 0.00000001500 & 0 \\
0.083333 & 0 & 0 & 0 & 0 & 0 & 0 & 0.99999985000 & 0 & 0.00000007500 & 0.00000007500 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.99999991150 & 0.00000007350 & 0.00000001500 & 0 \\
0.041667 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0.083333 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

Fig. 7 Numeric transition matrix

V. RESULTS

The transition matrix is calculated by the result of PFD_{avg} of 0.16413. The PFD_{avg} an achieved SIL level for low demand application is SIL 1 as Table III.

Due to SIL level being SIL1, no need to improve, but the enhanced design of the block valve design is a fail-close and solenoid valve de-energized to trip.

TABLE III, SAFETY INTEGRITY LEVELS

Current PFD_{avg}	SAFETY INTEGRITY LEVEL (SIL)	PFD_{avg}
	4	.0001 - .00001
	3	.001 - .0001
	2	.01 - .001
0.16413	1	.1 - .01

Table V shows the PFD_{avg} with respect to change in test interval of the block valves. In this system, Fig. 8 shows a plot of probability of failure on demand as a function of operating time interval.

TABLE V, RESULTS OF PFD

ime Interval (Month)	3	6	9	12
PFD_{avg}	0.000593763	0.001565583	0.003537514	0.007770226
Time Interval (Month)	15	18	21	24
PFD_{avg}	0.016968965	0.037012553	0.080710488	0.17598927

VI. CONCLUSION

We proposed a method verifying the SIL which user can apply to other units in the requirements for verification SIF and implement to improve more thorough hazard and risk analysis to determine their needs more accurately.

The entire verification method will be obvious that the safety of operation reduces the risk. A loss, that will occur, can contribute to plan maintenance work, inspection, and to increase reliability.

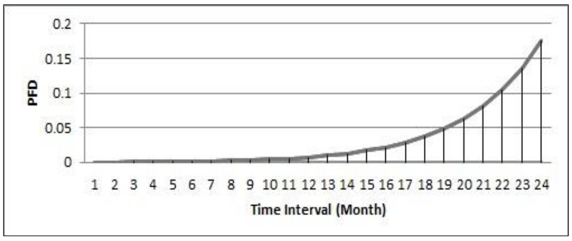

Fig. 8 Plot PFD as a function of operating time interval

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