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Development of a Simulator for Steam Turbine Generator Protection System Based on a Distributed Control System

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ABSTRACT

A steam turbine generator is a very complex machine and very dangerous because it has the potential to explode. Therefore, it should be equipped with a control system and protection system. A protection system for steam turbine generators is more complex than other facilities in the power-generating industry. Due to its complexity, a high-skill operator is required to operate the facility. In this study, a simulator of a protection system for a steam turbine generator based on a distributed control system DCS ABB 800xA has been developed. The system was developed considering eight parameters to ensure safety, including turbine speed, inlet temperature, vibration, turbine shaft position, steam drum tank level, and lubricating oil pressure. The system also provides a manual emergency push button to anticipate an uncontrollable condition. The developed simulator has been tested to ensure it works properly and protects the steam turbine generator from abnormal conditions. Tests were performed to check interlocking responses caused by a single variable. All the variables have been tested. Another test was performed to check the ability of the simulator to detect abnormal conditions and respond to those conditions. All the tests showed that the simulator system could operate properly. The simulator system is very comprehensive in detecting the potential of turbine trips. This system considered all the variables that were highly reported as the factors of the turbine malfunction. It is the main advantage of the proposed system. The developed system provides significant benefits for training the operator without interrupting the operation of power-generating facilities.

1. INTRODUCTION

Most manufacturing facilities have shifted to industrial automation systems in the last decades [1-3]. New technologies and architectural designs have come up with the expansion of industrial plants' organizational structures. Industrial machine systems must be highly reconfigurable to accept changes in processes and products as the global marketplace becomes more and more customer-driven. Rigid, static automation systems will eventually give way to more flexible varieties. Inherently flexible control systems are the focus of achieving such flexibility. There has been a noticeable shift in industrial control systems in recent years from centralized control to a much greater usage of distributed intelligence.

One of the machines primarily found in large industries is the steam turbine generator, which is used in the power generation industry, oil and gas processing, chemical industry, paper pulp industry, and many more. Steam turbine generators are very complex machines and very dangerous because they have the potential to explode. Therefore, designing a proper operating system and procedure is very important. Moreover, the facility must be operated by trained operators for safety reasons.

Steam turbine generators need to use a protection system to increase operation safety. The protection system aims to detect abnormal conditions and protect the steam turbine from potentially dangerous conditions. The protection system is also designed to take preventive action or shut down if there is an emergency condition. Many studies have been carried out to improve safety in the operation of steam turbine generators [4-13]. Wang and Liu [4] investigated the effect of adding filters on steam turbine control valves. These valves are usually between the boiler and the intermediate-pressure turbine in thermal power plants. They used the ANSYS CFX software package for this numerical simulation. Bolin and Engeda [7] studied various mechanisms of valve instability. Pondini et al. [8, 9] used Matlab/Simulink software to present a dynamic model for the control valve and steam turbine actuation system operating between the boiler and the medium-pressure turbine in a thermal power plant.

As automation technology develops, control technology is also used to operate various production facilities. It is aimed to improve safety and simplify complex processing processes. Distributed control systems (DCS) are one of the solutions to overcome the complexity of control systems of the steam turbine generator. Much research has been conducted to implement DCS in power-generating and distributing systems

[14-19]. Yulianto et al. [14] use risk-based maintenance strategies for DCS as power plant asset management. Implementing DCS in steam turbine generator operations is very helpful in increasing security and reducing complexity. DCS consists of various hardware and software connected by a communication network. DCS provides the ability to control and pivot processes concisely remotely. Besides a reliable control system, a safe process also needs an operator who understands the principles of the control system and is an expert in operating a steam turbine generator.

Several studies related to simulators in power plants were carried out [20-25]. Ulfiana et al. [20] developed a gas-fired power plant operation simulator using LabView as a simulation platform. They designed a simulation of the operational system for a gas-fired power plant but without implementing a protection system. Zabre et al. [21] developed a Combined Cycle Power Plant simulator for operator training. They also designed an operational system simulator where the operator can automatically monitor and control the system. However, the system did not implement a protection system. Agha et al. [22] researched resetting parameters of the unit 2 turbine protection system at Star Energy Geothermal Ltd. This research was focused on identifying the vibration protection system for the turbine. The model developed did not consider protection systems for temperature, pressure, and speed. Abu Bakar et al. performed another research on energy system simulators [23]. They built a Savonius turbine for educational purposes. Two models of the drag-driven vertical axis, 2-bladed and 3-bladed Savonius turbines, were constructed to generate electricity and integrated with a model house.

Many studies were carried out to develop simulators to aid the operator in operating power plant systems, including identification of turbine vibration and protection systems. However, the protection system of steam turbine generators is more complex than all the systems that have been developed. Due to its complexity, a high-skill operator is required to operate the facility. However, it is not easy to train the operator using the actual facilities because they are continuously used in production. Hence, a simulator that can demonstrate the actual condition of the operation process is needed.

Therefore, in this research, a simulator of a protection system of a steam turbine generator based on a distributed control system based on DCS ABB 800xA was developed. The system was developed by considering many parameters to ensure the safety of the operation, such as turbine speed, inlet temperature, vibration, turbine shaft position, steam drum tank level, and lubricating oil pressure. The system also provides a manual emergency push button to anticipate an uncontrollable condition. The developed simulator is expected to help the operators learn and practice the protection system of steam turbine generators.

2. METHODOLOGY

Figure 1 presents a block diagram of the developed simulation system. The data input for this steam turbine generator simulation comes from the virtual instrument, which functions as a dynamic variable from monitoring equipment on the steam turbine generator. The dynamics variables are displayed on the Human Machine Interface (HMI) so that they can be monitored and controlled. All data input from the virtual instrument is processed using DCS ABB 800xA.

DCS ABB 800xA is software from ABB. DCS ABB 800xA has a soft controller, which is a controller that is manipulated virtually to replace the role of a physical controller. Data processing and programming are carried out using the control builder software. The simulation of the protection system on the steam turbine generator is created using this software, which is then uploaded to the soft controller. Before all data variables are displayed in the operator's workplace, these data pass through the OPC Server as a media for accessing and exchanging data between devices and applications. The data displayed on the Workplace Operator is in the form of an HMI graphic display.

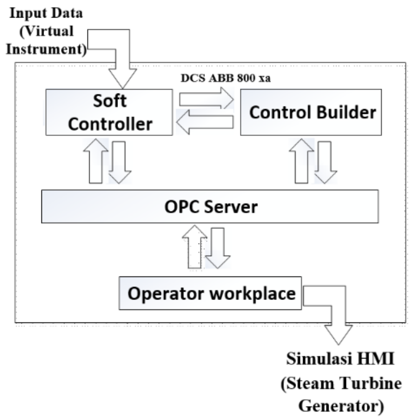

Figure 1. Block diagram of protection system for steam turbine generator

Figure 2 depicts the flowchart of the Steam Turbine Generator Simulation Protection System. Eight variables are input into the interlocking or protection system. The abnormal turbine condition for every variable indicated a potential turbine trip. When an abnormal condition occurs, the alarm is activated. Seven variables were used based on the API Standard 670 for the machinery protection system [26]. Another variable is the steam drum tank level of the boiler. It is important to control this variable to prevent the water in the boiler from overloading and overflowing into the turbine furnace. The threshold level for API standard-based variables was chosen based on the threshold recommended by the standard. Meanwhile, the threshold for the steam drum tank level was chosen as 99% of capacity. This level was decided by considering the safety of the system and the effectiveness of the operation. Nevertheless, the threshold of every variable could be modified by the instructor or operator for simulation purposes. The variables and their abnormal conditions are explained below.

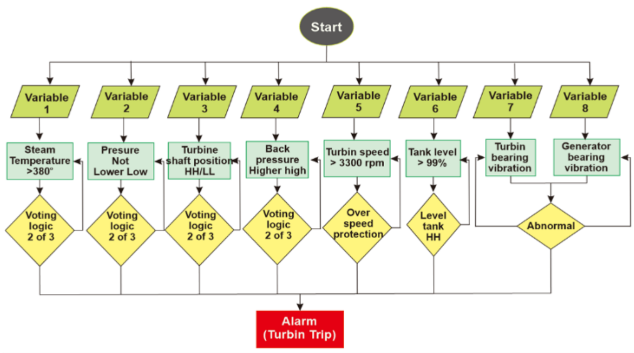

Figure 2. Flow chart of the protection system of the steam turbine generator

(1) Variable 1: Steam turbine inlet temperature

Steam turbine inlet temperature inputs A, B, and C are not Lower-Low (LL). The abnormal condition occurs when the temperature of at least two steam turbine inlet inputs is ≤ 380°C. The interlock of steam turbine temperature at the inlet position is not in a lower-low condition. It was implemented to prevent the steam temperature entering the turbine from dropping to lower than the specifications determined by the manufacturer. Controlling steam temperature entering the turbine was aimed at maintaining its performance and reliability. This interlocking system ensures that the steam temperature entering the turbine remains above the specification to avoid poor turbine performance and produce optimal power. If the temperature is lower than 380°C, then the interlock activates. This interlock is designed using voting logic 2 out of 3 (2oo3). The logic diagram of voting 2oo3 is shown in Figure 3.

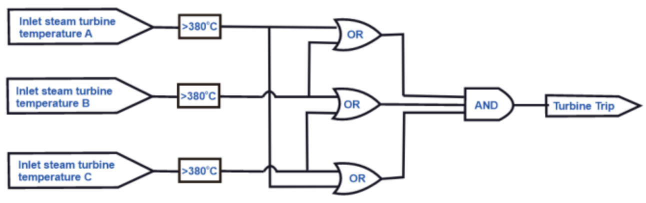

Figure 3. Logic diagram 2oo3 interlock caused by inlet steam turbine temperature

(2) Variable 2: Pressure switch oil

Pressure switch oil Lower-Low A, B, and C (LL). The abnormal condition occurs when two input turbine shaft positions are in LL condition. This interlock system is a protection mechanism designed to monitor and control the lube oil pressure in the system. The interlock system ensures that lubricating oil pressure remains within a safe and operational range to provide adequate lubrication to various components, such as bearings and gears. If the lubricating oil pressure is lower, the interlock activates and triggers a turbine trip (alarm). This interlock is designed using voting logic 2oo3, similar to the logic diagram as shown in Figure 3.

(3) Variable 3: Turbine shaft position

Turbine shaft positions A, B, and C are not higher-high/lower-low (HH/LL). The abnormal condition occurs when two input turbine shaft positions are in HH/LL. This system was designed to monitor and control the turbine shaft position. The interlock system was designed to ensure that the turbine shaft was within a safe and appropriate setpoint based on manufacturer specifications.

(4) Variable 4: Back pressure

Back pressure A, B, and C are higher-high (HH). An abnormal condition occurs when two back pressure inputs are in a higher-high (HH) condition. The system was designed to monitor and control the back pressure of steam. Based on manufacturer specifications, the interlock system was designed to ensure that the back pressure was within a safe and appropriate setpoint.

(5) Variable 5: Turbine speed

Turbine speed. Abnormal conditions occur when the turbine speed is ≥ 3300 R. The interlock system ensures the turbine shaft is within a safe and appropriate setpoint based on manufacturer specifications. It was designed to ensure that the turbine generator was rotated safely.

(6) Variable 6: Steam drum tank level

Steam drum tank level. An abnormal condition occurs when the steam drum tank level is ≥ 99%. The steam drum tank stores the feedwater, which is then converted to steam for the turbine's generation. The system was aimed at ensuring the water in the steam drum tank was at a safe level. If the water level is higher than 99%, it could be overloaded, and the water overflows into the turbine, adversely affecting the turbine.

(7) Variable 7: Turbine front or rear bearing vibration

Turbine front or rear bearing vibration is abnormal. The interlock system was designed to protect the turbine from fatal damage due to high vibration. This system is to ensure that the turbine operates in safe condition. The logic diagram for turbine and generator vibration is presented in Figure 4.

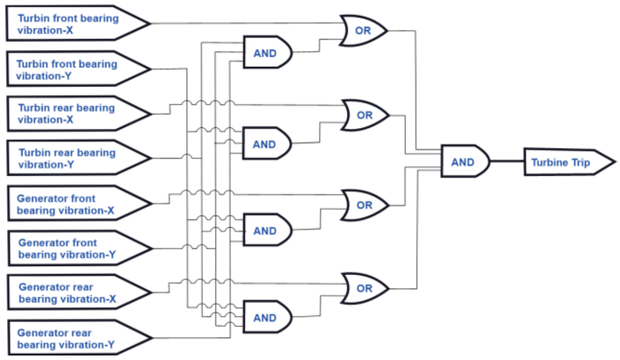

Figure 4. Logic diagram of interlock caused by turbine and generator vibration

The simulator also has a push-button for a manual emergency interlock system. This interlock ensures that the steam turbine generator can be stopped quickly and manually in an emergency case. It connects the emergency stop button to the protection system on the steam turbine generator to trigger protective action and quickly stop operation.

3. RESULT AND DISCUSSION

There are several aspects should be considered in developing the user interface in the operator workplace, such as:

- The HMI display should be user-friendly to ensure that the critical data is displayed clearly and easily understood.
- Appropriate colours, graphics, and icons should enhance clarity and attractiveness.
- The layout of interface elements should be arranged logically and orderly to make the system easy to use.

By considering those aspects, the display of the operator workplace was developed, as shown in Figure 5.

Several tests have been performed to ensure the simulator works appropriately and protects the steam turbine generator from abnormal conditions. Tests were also performed to check interlocking responses caused by a single variable. All the variables in this study have been tested. Every variable was tested several times for various cases. Another test was performed to check the simulator's ability to detect and respond to abnormal conditions.

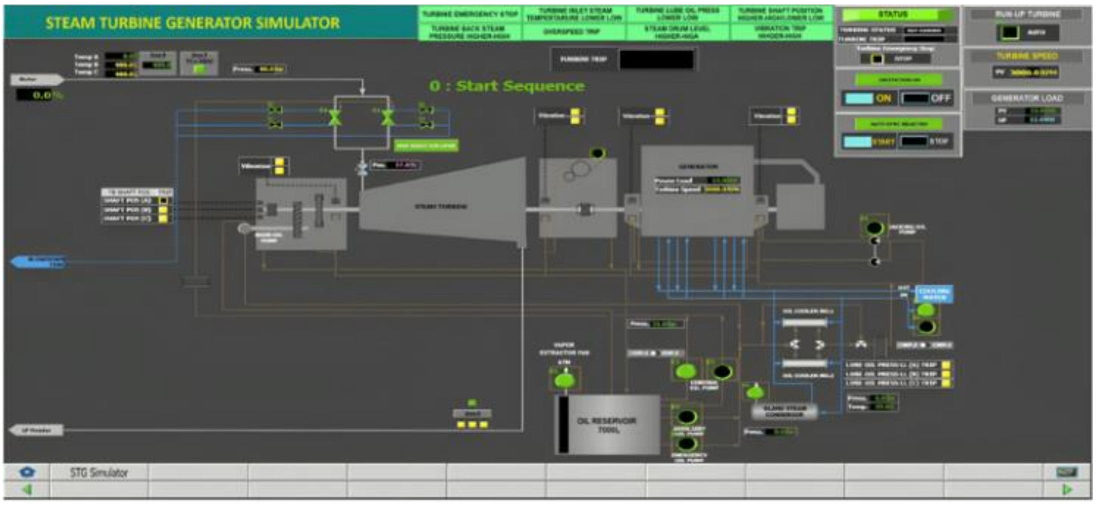

Figure 5. HMI design of steam turbine generator

3.1 Testing on manual emergency push button

Even though the operation was developed by implementing automatic systems, manual procedures for emergency cases should be provided. The test ensures that the emergency push button has been performed appropriately. The operator should press the emergency push button manually. Before the push button is pressed, the system is operated in normal condition, indicated by the green color on the notification bar of all variables, as shown in Figure 6(a). After the emergency is pressed, the colored notification bar changes to red, followed by the alarm blinking. In this case, the Interlocking is active. The test on this feature has been performed many times, and the system works correctly for all the tests.

3.2 Testing on the interlocking caused by steam turbine temperature

This test was performed to check the function of the interlocking system due to the steam turbine temperature. The interlock system is active when the steam temperature enters the inlet is less than 380°C, and this condition occurred minimum at two of three inlets. Eight temperature variations have been tested; the result is shown in Table 1.

Table 1 shows that the alarm is inactive, and the indicator is green when there is only one inlet where the temperature is less than 380°C, as shown by tests 1 and 5. The same condition also occurred when the temperature at all the inlets was more than 380°C, as shown by test no. 4. On the contrary, the locking system is active, which is indicated by the red color notification bar and alarm blinking when the temperature of the steam at two inlets is less than 380°C, as shown by tests no. 2, 3, and 4. The notification bar on the operator workplace is presented in Figure 6(b). The same system response was shown by tests 7 and 8 when the temperature at all the inlets is less than 380°C.

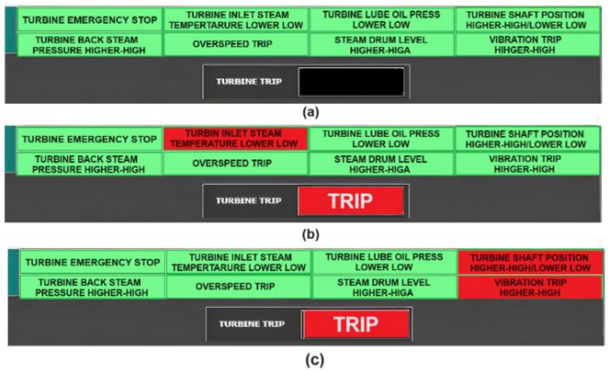

Figure 6. Notification bar, (a) normal condition, (b) turbine trip caused by steam tempeature, and (c) turbine trip caused by turbine shaft position and vibration

Table 1. Data of interlocking test on steam turbine temperature

Test No.	Inlet Temp. A (°C)	Inlet Temp. B (°C)	Inlet Temp. C (°C)	Nilai 2oo3	Alarm (Blinking)	Color of Indicator
1	390	390	300	390	No	Green
2	390	300	300	300	**Yes**	**Red**
3	300	390	0	300	**Yes**	**Red**
4	390	410	400	390	No	Green
5	400	400	0	400	No	Green
6	400	0	0	0	**Yes**	**Red**
7	0	0	0	0	**Yes**	**Red**
8	250	300	350	350	**Yes**	**Red**

3.3 Testing on the interlocking caused by pressure switch lube oil

This test was performed to ensure that the interlock caused by lubricating oil pressure works correctly. The interlock occurs when at least two out of three of the lubricating oil pressures are in a lower condition. Then, the interlock system activates and triggers the turbine trip, indicated by the red alarm blinking on the operator's workplace display. Eight pressure variations for all three switches have been tested, and the results are presented in Table 2.

Table 2. Interlocking test result caused by pressure switch lube oil

Test No.	Press. Switch Lube Oil A	Press. Switch Lube Oil B	Press. Switch Lube Oil C	Alarm (Blinking)	Color of Indicator
1	On	On	On	No	Green
2	On	On	**Off**	No	Green
3	On	**Off**	**Off**	**Yes**	**Red**
4	**Off**	On	On	No	Green
5	**Off**	**Off**	On	**Yes**	**Red**
6	**Off**	On	**Off**	**Yes**	**Red**
7	On	**Off**	On	No	Green
8	Off	**Off**	**Off**	**Yes**	**Red**

Table 2 shows that the alarm is inactive, and the indicator is green when there is only one or no switch oil in lower low pressure, as shown by tests 1, 2, 4, and 7. On the contrary, the interlocking system is active, indicated by a red notification bar and alarm blinking when there are two or more pressure switches lube oil in lower low pressure, as shown in tests 3, 5, 6, and 8.

3.4 Testing on interlocking caused by turbine shaft position

This test was carried out to ensure that the interlock system caused by the turbine shaft position follows the design. The main purpose of controlling this variable is to protect the turbine from damage that may occur when the turbine shaft is in an unsafe position. The interlock system is active and alarm-blinking when the shaft is in a higher-high or lower-low position.

Table 3 shows that the alarm is inactive, and the indicator is green when there is only one or no turbine shaft in higher-high/lower-low conditions, as shown by tests 1, 2, and 4. On the contrary, the interlocking system is active, indicated by a red notification bar and alarm blinking when there are two or more turbine shafts in higher-high/lower-low positions, as shown in tests 3, 5, and 6.

Table 3. Interlocking test result caused by turbine shaft position

Test No.	Turbine Shaft Position A	Turbine Shaft Position B	Turbine Shaft Position C	Alarm (Blinking)	Color of Indicator
1	On	On	On	No	Green
2	On	On	**Off**	No	Green
3	On	**Off**	**Off**	**Yes**	**Red**
4	Off	On	On	No	Green
5	Off	**Off**	On	**Yes**	**Red**
6	Off	**Off**	**Of**f	**Yes**	**Red**

3.5 Testing on interlocking caused by overspeed

The test was performed to check the system in monitoring the turbine speed and conducting interlocking when the speed is over the specification (≥ 3300). Six tests were carried out, and the results are presented in Table 4. From Table 4, when the turbine speed is below 3300 rpm, as shown in test no. 1, 2. 3, and 4, then the notification bar is green without blinking. On the other hand, when the speed is more than 3300 rpm, the alarm blinks, and the notification is red color. It indicates that the system is in abnormal condition.

Table 4. Interlocking test result caused by turbine speed

Test No.	Speed (RPM)	Alarm (Blinking)	Color of Indicator
1	3000	No	Green
2	3100	No	Green
3	3200	No	Green
4	3290	No	Green
5	3300	**Yes**	**Red**
6	3350	**Yes**	**Red**

3.6 Testing on the interlocking caused by steam drum tank level

This test was aimed to ensure the interlocking system worked well when monitoring the steam drum tank level. The Interlocking is active when the steam drum tank level is higher-high, which is ≥ 99%. Six tests were carried out, and the results are presented in Table 5. The test showed that the alarm was not blinking, and the notification bar color was red when the tank level was below 99%, as shown in tests 1 to 4. However, when the tank level reaches 99% or more, as can be seen in test 5 and test 6, then the alarm blinks with the red color notification bar. In this case, the operation is abnormal, and the turbine could be tripped.

Table 5. Interlocking test result caused by turbine speed

Test No.	Steam Drum Tank Level (%)	Alarm (Blinking)	Color of Indicator
1	90	No	Green
2	95	No	Green
3	97	No	Green
4	98	No	Green
5	99	**Yes**	**Red**
6	100	**Yes**	**Red**

3.7 Testing on the interlocking caused by bearing vibration

This test was performed to check the ability of the simulation system to detect abnormal conditions due to vibration on the turbine and generator bearings. Two conditions cause the Interlocking to be active. The first is that at least two bearings in the turbine and generator are in an off condition. An off condition means that the bearing is working improperly. The second is the off condition, which occurred in the X and Y axes. Interlocking is active when the two conditions are fulfilled at the same time.

Four tests were performed, and the results are provided in Table 6. In test 1, there are two Off conditions on the X-axis and Y-axis of the turbine bearing. In this case, the Interlocking is inactive because abnormal conditions only occur in the turbine. The first condition to activate interlocking still needs to be fulfilled. The Interlocking is also inactive in test 2 because the Off conditions are only on the X-axis of the turbine bearing and generator bearing. In this case, the second condition to activate the interlocking system still needs to be fulfilled. Test 3 and test 4 fulfil the two conditions of the interlocking system. The Off conditions were found on the turbine and generator; moreover, the Off conditions were found on the X-axis and Y-axis.

Table 6. Interlocking test result caused by turbine speed

Bearing	Test 1	Test 2	Test 3	Test 4
Turb. Front bearing Vibration-X	**Off**	**Off**	On	**Off**
Turb. Front bearing Vibration-Y	**Off**	On	On	On
Turb. Rear bearing Vibration-X	On	Off	**Off**	On
Turb. Rear bearing Vibration-Y	On	On	On	**Off**
Gen. Front bearing Vibration-X	On	**Off**	On	On
Gen. Front bearing Vibration-Y	On	On	**Off**	On
Gen. Rear bearing Vibration-X	On	**Off**	On	On
Gen. Rear bearing Vibration-Y	On	On	On	**Off**
Alarm (Blinking)	No	No	**Yes**	**Yes**
Color of Indicator	Green	Green	**Red**	**Red**

3.8 Testing on the interlocking caused by all variables

Complete and comprehensive tests were performed to check the effect of all the variables. Three tests were conducted, and the results are provided in Table 7. From this table, it can be seen that test 1 produces regular operation; meanwhile, test 2 and test 3 produce interlocking and turbine trips. Two factors caused the Interlocking on test 2; the first is two of the three turbine shaft positions in higher high or lower low (HH/LL) conditions. The second is two bearing vibrations, rear bearing vibration X and front bearing Vibration Y. The notification bar on the operator workplace is shown in Figure 6.

Meanwhile, five factors caused by test 3 are pressure Switch Lube Oil, Turbine Back Steam Pressure, Overspeed, Steam Drum Level Tank, and turbine bearing vibration. Several tests have been performed to ensure the simulator works appropriately and protects the steam turbine generator from abnormal conditions. Tests were also performed to check interlocking responses caused by a single variable. All the variables in this study have been tested. Every variable was tested several times for various cases. Another test was performed to check the simulator's ability to detect and respond to abnormal conditions.

The series of tests demonstrate that the developed system could operate well as a simulator of an automatic turbine protection system. The developed simulator system is very comprehensive in detecting the potential of turbine trips. This system considered all the variables that were highly reported as the factors causing the turbine malfunction. It is the main advantage of the proposed system over other simulators. Dulai and Bica [27] developed a system for steam turbines only to control the turbine speed. Meanwhile, Hirkude et al. [28] modelled and simulated on the load-governing system of a steam turbine.

The proposed simulator is easily operated. The system could be connected to real steam power generating facilities to obtain the real data, or the operator could input and modify the data and the threshold of all variables for training purposes. The developed simulator could be implemented in various steam power generating facilities, as long as the real facilities provide the data for all the variables.

Table 7. Interlocking test results caused by all variables

Variable		Test 1	Test 2	Test 3
No.	**Name of Variable**			
1	Inlet Steam temperature A	390	390	300
	Inlet Steam temperature B	390	300	300
	Inlet Steam temperature C	300	390	0
2	Pressure Switch Lube Oil A	On	On	On
	Pressure Switch Lube Oil B	On	On	**Off**
	Pressure Switch Lube Oil C	On	**Off**	**Off**
3	Turbine shaft position A	On	**Off**	On
	Turbine shaft position B	On	On	**Off**
	Turbine shaft position C	On	**Off**	On
4	Turbine Back Steam Press. A	On	On	On
	Turbine Back Steam Press. B	On	On	Off
	Turbine Back Steam Press. C	On	**Off**	**Off**
5	Overspeed	3000	3100	3300
6	Steam Drum Level Tank	97	98	99
7	Turb. Front bearing Vibration-X	On	On	On
	Turb. Front bearing Vibration-Y	On	On	**Off**
	Turb. Rear bearing Vibration-X	On	**Off**	**Off**
	Turb. Rear bearing Vibration-Y	On	On	On
8	Gen. Front bearing Vibration-X	On	On	**Off**
	Gen. Front bearing Vibration-Y	On	**Off**	On
	Gen. Rear bearing Vibration-X	On	On	On
	Gen. Rear bearing Vibration-Y	On	On	On
	Alarm (Blinking)	No	**Yes**	**Yes**
	Color of Indicator	Green	**Red**	**Red**

4. CONCLUSIONS

This study developed a simulator for the protection system of a steam turbine generator based on a distributed control system using DCS ABB 800xA. The system was developed considering eight variables to ensure safety operation, including turbine speed, inlet temperature, vibration, turbine shaft position, steam drum tank level, and lubricating oil pressure. The system also provides a manual emergency push button to anticipate an uncontrollable condition. The developed simulator has been tested to ensure it works appropriately and protects the steam turbine generator from abnormal conditions. Tests were performed to check interlocking responses caused by a single variable. All the variables have been tested, and the results show that the system responds correctly based on the design threshold value. Another test was performed to check the ability of the simulator to detect and respond to abnormal conditions on all variables simultaneously. It is the main advantage of the proposed system compared to others. All the tests showed that the simulator system could operate properly. The simulator could be used as a monitoring system or an instrument for training the operator. Training the operator using this instrument can be conducted without interrupting the power plant facilities in the production area. The simulator could be used for various types of the steam generator facilities since the facilities could provide the data for all the variables.

Currently, the vibration signal from the generator is still in the form of a digital signal, ON/OFF only. In the future, an analog vibration sensor type will be applied. Hence, the system could display a vibration value graph as a function of time. This study is part of a research project to develop a control and protection system for a steam power plant. To complete the project, a control and protection system for the boiler and generator will be developed in the future.

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REFERENCES

[1] Lu, Y., Xu, X., Wang, L. (2020). Smart manufacturing process and system automation–A critical review of the standards and envisioned scenarios. Journal of Manufacturing Systems, 56: 312-325. https://doi.org/10.1016/j.jmsy.2020.06.010

[2] Ghobakhloo, M. (2018). The future of manufacturing industry: A strategic roadmap toward Industry 4.0. Journal of Manufacturing Technology Management, 29(6): 910-936. https://doi.org/10.1108/JMTM-02-2018-0057

[3] Wollschlaeger, M., Sauter, T., Jasperneite, J. (2017). The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. IEEE Industrial Electronics Magazine, 11(1): 17-27. https://doi.org/10.1109/MIE.2017.2649104

[4] Wang, P., Liu, Y. (2017). Influence of a circular strainer on unsteady flow behavior in steam turbine control valves. Applied Thermal Engineering, 115: 463-476. https://doi.org/10.1016/j.applthermaleng.2016.12.073

[5] Wang, P., Liu, Y. (2017). Unsteady flow behavior of a steam turbine control valve in the choked condition: Field measurement, detached eddy simulation and acoustic modal analysis. Applied Thermal Engineering, 117: 725-739. https://doi.org/10.1016/j.applthermaleng.2017.02.087

[6] Mazur, Z., Campos-Amezcua, R., Urquiza-Beltrán, G., García-Gutiérrez, A. (2004). Numerical 3D simulation of the erosion due to solid particle impact in the main stop valve of a steam turbine. Applied Thermal Engineering, 24(13): 1877-1891. https://doi.org/10.1016/j.applthermaleng.2004.01.001

[7] Bolin, C., Engeda, A. (2015). Analysis of flow-induced instability in a redesigned steam control valve. Applied Thermal Engineering, 83: 40-47. https://doi.org/10.1016/j.applthermaleng.2015.02.043

[8] Pondini, M., Signorini, A., Colla, V. (2017). Steam turbine control valve and actuation system modeling for dynamics analysis. Energy Procedia, 105: 1651-1656. https://doi.org/10.1016/j.egypro.2017.03.539

[9] Pondini, M., Colla, V., Signorini, A. (2017). Models of control valve and actuation system for dynamics analysis of steam turbines. Applied Energy, 207: 208-217. https://doi.org/10.1016/j.apenergy.2017.05.117

[10] Wang, P., Ma, H., Quay, B., Santavicca, D.A., Liu, Y. (2018). Computational fluid dynamics of steam flow in a turbine control valve with a bell-shaped spindle. Applied Thermal Engineering, 129: 1333-1347. https://doi.org/10.1016/j.applthermaleng.2017.10.104

[11] Gao, Q., Ding, L., Huang, D. (2019). Experimental and numerical study on loss characteristics of main steam valve strainer in steam turbine. Applied Thermal Engineering, 147: 935-942. https://doi.org/10.1016/j.applthermaleng.2018.07.031

[12] Glinka, G., Shen, G. (1991). Universal features of weight functions for cracks in mode I. Engineering Fracture Mechanics, 40(6): 1135-1146. https://doi.org/10.1016/0013-7944(91)90177-3

[13] Averous, N.R., Stieneker, M., Kock, S., Andrei, C., Helmedag, A., De Doncker, R.W., Hameyer, K., Jacobs, G., Monti, A. (2017). Development of a 4 MW full-size wind-turbine test bench. IEEE Journal of Emerging and Selected Topics in Power Electronics, 5(2): 600-609. https://doi.org/10.1109/JESTPE.2017.2667399

[14] Yulianto, D.T., Isman, R.M., Ihsan, S.N., Susanto, H.G. (2021). Implementing risk-based maintenance strategies for distributed control system as power plant asset management. IOP Conference Series: Materials Science and Engineering, 1096(1): 012108. https://doi.org/10.1088/1757-899X/1096/1/012108

[15] Shi, G., Wang, J., Gao, J. (2021). Research on nuclear turbine control and protection system based on DCS integrated technical solution. International Conference on Nuclear Engineering, 85246: V001T02A006. https://doi.org/10.1115/ICONE28-64191

[16] Chang, X., Qiu, X. (2023). Robust gas-path fault diagnosis with sliding mode applied in aero-engine distributed control system. Sustainability, 15(13): 10278. https://doi.org/10.3390/su151310278

[17] Mahish, P., Pradhan, A.K. (2019). Distributed synchronized control in grid integrated wind farms to improve primary frequency regulation. IEEE Transactions on Power Systems, 35(1): 362-373. https://doi.org/10.1109/TPWRS.2019.2928394

[18] Yamashita, D., Tsuno, K., Koike, K., Fujii, K., Wada, S., Sugiyama, M. (2019). Distributed control of a user-on-demand renewable-energy power-source system using battery and hydrogen hybrid energy-storage devices. International Journal of Hydrogen Energy, 44(50): 27542-27552. https://doi.org/10.1016/j.ijhydene.2019.08.234

[19] Kroposki, B., Bernstein, A., King, J., Vaidhynathan, D., Zhou, X., Chang, C.Y., Dall'Anese, E. (2020). Autonomous energy grids: Controlling the future grid with large amounts of distributed energy resources. IEEE Power and Energy Magazine, 18(6): 37-46. https://doi.org/10.1109/MPE.2020.3014540

[20] Ulfiana, A., Abdi, C.S., Jannus, P. (2019). Gas power plant operation simulator using LabVIEW in energy conversion laboratory of Jakarta State Polytechnic. In Proceeding of 8th Annual Southeast Asian International Seminar (ASAIS), pp. 57-60.

[21] Zabre, E., Roldan-Villasana, E.J., Romero-Jiménez, G., Cruz, R. (2009). Combined cycle power plant simulator for operator's training. In Proceedings of the World Congress on Engineering and Computer Science (Vol. 2). San Francisco, USA.

[22] Agha, M., Sihana, S., Effendy, N. (2013). Kajian ilmiah penyetelan ulang parameter sistem proteksi turbin unit 2 di star energy geothermal ltd. Teknofisika, 2(3): 75-82. https://journal.ugm.ac.id/teknofisika/article/view/5822.

[23] Bakar, N.A.A., Mu'in, N.A., Kamaruddin, N.M. (2022). Design and development of savonius turbine for STEM education. Journal of Advanced Research in Applied Sciences and Engineering Technology, 28(2): 334-347. https://doi.org/10.37934/araset.28.2.334347

[24] Yu, Q., Li, X., Wang, Z., Zhang, Q. (2020). Modeling and dynamic simulation of thermal energy storage system for concentrating solar power plant. Energy, 198: 117183. https://doi.org/10.1016/j.energy.2020.117183

[25] Zhang, Q., Wang, Z., Du, X., Yu, G., Wu, H. (2019). Dynamic simulation of steam generation system in solar tower power plant. Renewable Energy, 135: 866-876. https://doi.org/10.1016/j.renene.2018.12.064

[26] Standard, A.P.I. (2014). Machinery Protection Systems. API Standard 670

[27] Dulau, M., Bica, D. (2014). Simulation of speed steam turbine control system. Procedia Technology, 12: 716-722. https://doi.org/10.1016/j.protcy.2013.12.554

[28] Hirkude, J., Kerkar, S., Borkar, M. (2021). Modeling and simulation of the load governing system of steam turbine. In Advances in Fluid and Thermal Engineering: Select Proceedings of FLAME 2020, pp. 327-338. https://doi.org/10.1007/978-981-16-0159-0_29