Development of an Integrated Condition Monitoring System on Critical Parameters of a Micro Steam Power Plant

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Abstract- In order to improve the efficiency and implement preventive or condition-based maintenance it is essential that a system that signals early warning of failure is provided so that appropriate restoration decision is made to forestall such failure. An Integrated Condition Monitoring System (ICMS) is developed to monitor parameters responsible for health condition of a 5 kW micro steam power plant. ICMS was designed to monitor those critical parameters that their abrupt change in values beyond design thresholds can lead to catastrophic failure. These parameters are steam temperature, steam pressure, steam mass flow rate, current, and voltage. The system was developed by using appropriate sensors programmed on Arduino UNO. Test was carried out in five replicates and the outcomes compared with the design/threshold values. The experimental results were within the limits of threshold values indicating that the plant's health condition is normal. Results also show that the sensors' capacities and performance are adequate with data variations in all cases less than 5%. Hence, the device is efficient, and has ability to predict imminent failure thereby safe cost and time of carrying out breakdown maintenance.

Indexed Terms- Condition monitoring, Micro steam power plant, critical parameter, maintenance efficiency

I. INTRODUCTION

The abundance of palm kernel shell which was identified as biomass and its high calorific value (i.e. GCV 3800-4200Kcal/kg) [1], palm kernel shell has gained its status as a biofuel resource because it is cheap and readily available [2, 3]. These characteristics has made it better as fuel for powering the steam micro-power plant can be useful fuel in steam plant fuel in place of fossil fuel for power plants and its assemblage such as turbine, boiler and generator operational parameters such as temperature and pressure can move to an abnormal condition, it causes a very high damage on the power plant so there is need to prevent such [4]. Few authors identified that the rapid increase in the global energy crisis, combined with the concerns about environment issues has led to an extensive promotion of nuclear and renewable energy, for most parts of the world [4, 5]. Hence, the need for an alternative source of energy, palm kernel shell was found to be a well-known biomass product because of its higher heat energy or calorific value [6]. The steam rotary motion serves as driver to alternator which in turn generates electricity [7]. Predictive maintenance as one of optimization action has emerged to provide condition-based early warning [7]. In power generation industry condition monitoring provides early warning of asset failure in combustion turbines, including steam turbines. In order to improve a power plant's operational reliability, fault diagnostic accuracy and condition monitoring precision, it is necessary to validate the acquired data, isolate any failed sensor and recover the failed critical measurement in control or fault diagnosis mechanisms [8]. Preventing sensor failure would provide a return on the investment, by minimizing potential down-time [8].

The steam turbine has been in use for the past century and is available in virtually any capacity ranging from a few (hp) kW to a several hundred (hp) kW. It is highly reliable, needs little maintenance and extremely long service life. Steam turbines are custom built, hence efficiency and operating characteristics can be optimized for each application [9]. Retrofitting as team turbine into a facility's steam system can be done quite easily, minimizing installation costs. Most facilities that have a steam plant usually are unaware of their potential to cogenerate.

II. POWER PLANT COMPONENTS

The plant consists of three major components which are; steam generator (boiler), turbine and alternator. These components were assembled as a whole micro power plant after modification of an earlier developed power plant.

A micro steam generator of 5 kW earlier developed by [10] and later improved upon by [11] was deficient in the area of identification of critical parameters (for monitoring the operational health of the system), increased losses due to location of the steam reservoir outside the whole component which affected the operational monitoring parameters (i.e. temperature, pressure and steam flow rate), our new system involved the identification as well as monitoring operational/ critical parameters and reduction of heat losses to boost the measured operational parameters and at the same time digitized the system by developing an instrumentation strategy to capture operational parameters on a real-time basis.

Micro turbine of 5 kW capacity earlier developed by [12] was deficient in the area of measurement of critical operational parameters (i.e. inlet temperature, inlet pressure, flow rate of steam and their corresponding outlet values) in his design, and at the same time deficient at real time measurement and monitoring approach of these parameters. All these parameters were well monitored in the new design and as well provided devices for the real time measurement of the operational parameters.

A 5 kW capacity alternator earlier developed by [13, 14, 15] was deficient in the area of measurement of critical operational parameters (i.e. temperature, pressure, and their corresponding outlet values) in the design and at the same time deficient at real time measurement and monitoring approach of these parameters. All these parameters were well monitored in the new design and as well provided devices for the real time measurement of these parameters. In addition, our new system apart from monitoring action can predetermine health condition of the plant and hence predicting imminent failure for planned maintenance activities. On this basis, unexpected failure is stopped and thereby saving cost of break down maintenance of micro steam power plant.

III. MATERIALS AND METHODS

Figure 1 shows the steps of achieving the study which includes parameter identification, model development which is sub-divided into simulation and interface, interface development. Likewise, procurement of materials is sub-divided into sensor position calibration, sensor which both leads to experimentation then experimentation, verification and validation.

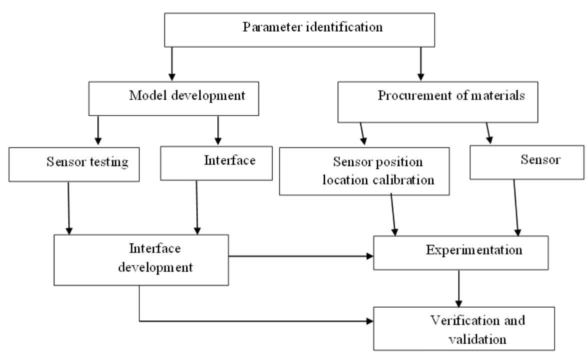

Figure 1: Block Diagram of Research Procedure

3.1 The Circuit Diagram for Boiler Parameter Monitoring

The circuitry diagram for boiler parameter monitoring is shown in Figure 2. Results of the primary parameters sensor of the boilers are transmitted to the device unit (Arduino UNO) which is powered by a 5V battery. This pin was connected to the device unit for processing of the raw data after which it is been transmitted to the monitoring device via the transmitter cable.

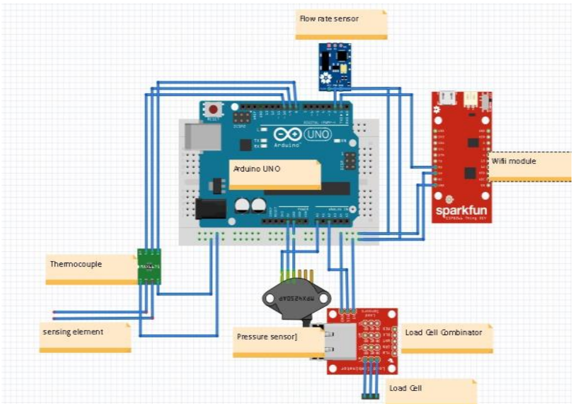

Figure 2: Boiler Sensors Circuitry

3.2 The Circuit Diagram for Turbine Parameter Monitoring

The circuit diagram for turbine parameter monitoring is shown in Figure 3. The sensor having a sensing element which sends signal obtained from the turbine to the device unit through the digital processing. There is a connection pin on the device for processing of the acquired data before transmission to the monitoring device via the cable.

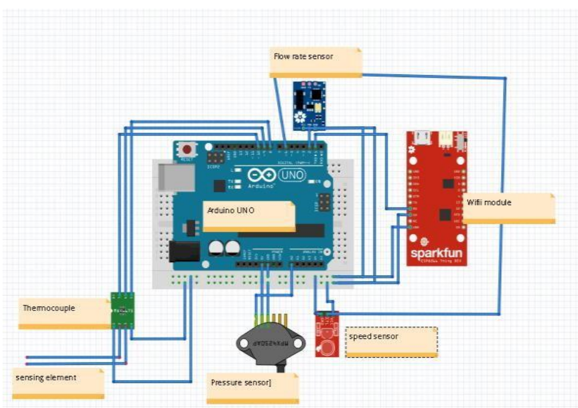

Figure 3: Turbine Sensors Circuitry

3.3 The Circuit Diagram for Alternator Parameter Monitoring

The circuit diagram for generator/alternator parameter monitoring is shown in Figure 4. The sensor is mounted on the generator. The current sensor has three different pins which are analog pin, power pin and the ground pin. This pin was connected to the device unit for processing of the raw data after which it is been transmitted to the monitoring device via the transmitter cable.

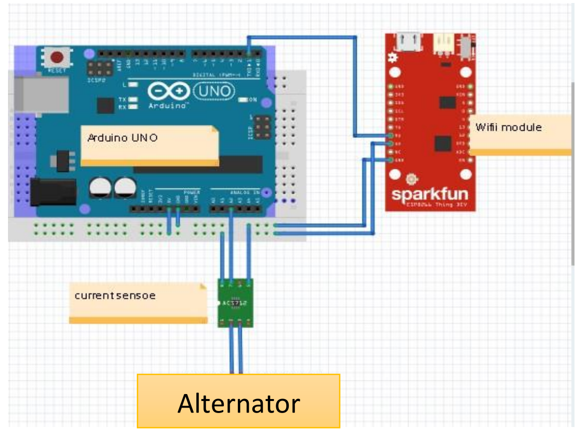

Figure 4: Alternator Sensors Circuitry

3.4 System-Plant Integration Process

All three major components i.e. steam generator (boiler), turbine and alternator were assembled in series and connected together with appropriate materials such as pipes, belt and mounted on a rigid bed. The steam generator was designed with a ½ inch riser pipe and superheater and with same size of gate valve which is used for the regulation of steam flow to the turbine based on demand and design consideration. All exposed pipes were lagged accordingly to prevent heat losses due to conduction and convection and all connected joints were fastened together with the aid of appropriate wrench size and sealed to air tight with application of thread tapes to prevent leakages and heat losses. After the set up was in place all pre-determined locations of the various sensors were drilled, welded and brazed with the aid of drilling machine, electric welding machine and Oxy-acetylene and were surface grinded with grinding machine with abrasive finish to achieve smooth surfaces at the punctured area, thereafter the sensors were mounted appropriately and sealed to air tight to prevent leakages and heat losses.

3.5 System Parameters Monitoring Process on Steam Power Plant

The system was designed to monitor the three major components of the steam plant which are boiler, turbine and alternator. Figure 5 shows critical parameters monitoring process on the steam power.

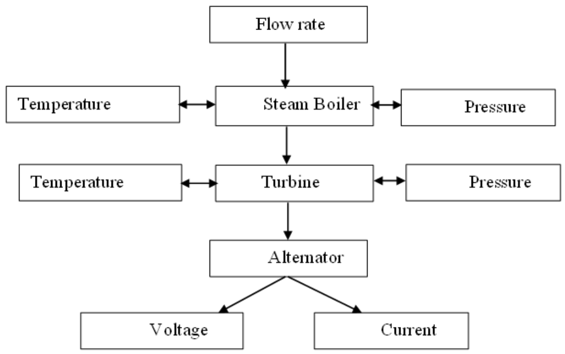

Figure 5: Steam Power Plant Parameters Monitoring Process

3.6 System Control Modeling Process

Expected threshold/designed parameters (Temperature, Pressure, Flow rate, Voltage and Current) of the system are given as T_e ,P_e , F_e ,V_e , I_e while the actual parameter measured by the incorporated sensors are given as T_a ,P_e , F_a ,V_a , I_a respectively, all these parameters and their conditions of operation based on pre-determined values are modeled as contained in Table 1.

Table 1: Steam power plant monitoring and control modeling.

S/N	Probable Conditions	Parameters model	Resulting machine status
1	Condition (1)	if $T_a \leq T_e$	then the plant normal
2	Condition (2)	if $T_a \geq T_e$	then the plant needs maintenance
3	Condition (3)	if $P_a \leq P_e$	then the plant normal
4	Condition (4)	if $P_a \geq P_e$	then the plant needs maintenance
5	Condition (5)	if $F_a \leq F_e$	then the system normal
6	Condition (6)	if $F_a \geq F_e$	then the plant needs maintenance
7	Condition (7)	if $V_a \leq V_e$	then the system normal
8	Condition (8)	if $V_a \geq V_e$	then the plant needs maintenance
10	Condition (9)	if $I_a \leq I_e$	then the system normal
11	Condition (10)	if $I_a \geq I_e$	then the plant needs maintenance

IV. RESULTS AND DISCUSSION

4.1 Parameters Monitoring of Micro Steam Power Plant

Table 2 contains the list of monitored parameters and their respective sensor types.

Table 2: Parameter measured and sensor types selected

S/N	Parameter	Unit	Sensor Type
1	Boiler Pressure	Pa	BMP180
2	Turbine Pressure	Pa	BMP180
3	Voltage	Volts	ZMPT101B
4	Steam Boiler Temperature	^oC	K-Type thermocouple
5	Steam Turbine Temperature	^oC	K-Type thermocouple
6	Outlet steam flow rate from boiler	Kg/s	YF-S201
7	Inlet steam flow rate to turbine	Kg/s	YF-S201
8	Current Generated	Ampere	ACS712

A total number of 8 sensors were used to collect data from the steam power plant as shown in Table 2. These sensors on ICMS system were applied for extracting necessary data on steam power plant through a transmission cable. The set-up outcome of the experiment for data acquisition on boiler, turbine and alternator critical parameters (temperature, pressure, steam mass flow rate, voltage and current) is shown in Figure 6.

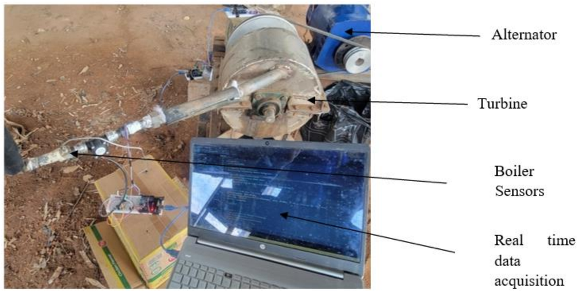

Figure 6: Assemblage of Sensors for Real Time Data Acquisition

Integrated Condition Monitoring System (ICMS) in monitoring action on a steam power plant is shown in Figure 6. The outcomes from temperatures, pressure, flow rate, current and voltage are displayed on the screen.

4.2 Experimental Data Results

The outcomes of the inlet and outlet steam plant parameters taken in steps of five minutes interval are as shown in Tables 3 and 4. The Table 3 shows inlet: temperature, pressure, mass flow rate, current and voltage. The experimental results for the five replicates shows that all sensors utilized are adequate with a minimum and maximum standard deviation of 0.550 (flow rate: YF-S201 sensor) and 8.598 (K-Type thermocouple sensor), respectively. Maximum and minimum percentage variations of data acquisition of 5.27% and 0.28% were returned by current (ACS712) and flow rate (YF-S201) sensors, respectively. In all cases, sensors' data acquisition ability is accurate since the percentage variation in all the processes was less than 10% (Table 3).

Table 3: Experimental results of ICMS on power plant analysis

Sensor Type	1	2	3	4	5	Average	Standard Deviation	Percent (%) variation
K-Type thermocouple	255.49	277.42	263.40	272.12	277.38	270.16	8.598	3.18
K-Type thermocouple	259	280	272	268	271	270.16	6.782	2.51
ACS712	10.65	12.33	12.33	11.82	12.00	11.78	0.621	5.27
ZMPT101B	239	245	241	244	240	241.80	2.315	0.96
BMP180	0.14129	0.14472	0.14230	0.14360	0.14462	0.14331	0.1322	0.92
BMP180	0.141	0.144	0.14420	0.14210	0.14360	0.14298	0.1233	0.86
YF-S201	18.58	20	19.20	19.88	18.90	19.31	0.550	0.28
YF-S201	18.58	20	19.20	19.88	18.90	19.31	0.550	0.28

The threshold/design and experimental results shown in Table 4 revealed the experimental results were within the limits of threshold values. Results also show that the sensors' capacities selected can adequately accommodate the possible data variations from real-time monitoring of the micro steam plant's critical parameters.

Table 4: Comparison of Expected Threshold /Design and Experimental values

	Sensor Type	Sensor Unit	Design /Threshold value	Experimental value	Sensor Capacity
1	K-Type thermocouple	^{0}C	400	270.16 ± 8.598	0-600
2	K-Type thermocouple	^{0}C	276.1	270±6.782	0-600
3	ACS 712	Amps	22.73	11.78±0.621	0-30
4	ZMP T101 B	Volts	240	240.80±2.315	0-3000
5	BMP 180	MPa	0.45	0.14331±0.001332	0.0-1.1
6	BMP 180	MPa	0.1	0.14298±0.001233	0.0-1.1
7	YF-S201	kg/s	.0275	19.31±0.550	1-30
8	YF-S201	kg/s	0.0275	19.31±0.550	1-30

On the basis of the experimental results presented in Table 4, the ICMS system is capable of monitoring health condition of the steam power plant. Since all the data acquired by the sensors during series of experiment carried out fell within acceptable range (Table 5), then, no imminent failure is expected within two (2) hours duration of performing each experiment, which was repeated five times. Once the condition of the plant is normal, there is no need to plan for preventive maintenance ahead, thereby saving the cost of both preventive and breakdown maintenance.

Table 5: Decision on Health Condition of the Steam Power Plant using ICMS

Parameters	Boiler Outlet temperature, ^{0}C	Boiler Outlet pressure, MPa	Steam mass flow rate out of boiler, kg/s	Turbine Inlet temperature, ^{0}C	Turbine Inlet pressure, MPa	Alternator voltage, Volts	Alternator current, Amperes
Max. Real time value	276.95	0.1443	0.0275	276.95	0.1443	239.35	13.75
Maximum expected threshold value	400	4.2	0.028	400	0.028	240	22.73
Decision (Normal/ Abnormal	Normal	Normal	Normal	Normal	Normal	Normal	Normal

CONCLUSION

The micro steam power plant's health condition can effectively be monitored through integration of ICMS to acquire performance data on critical parameters for comparison with threshold/design data of such parameters. The study has demonstrated that automation of steam power plant operation with regard to the monitoring of its temperature, pressure, steam flow rate, current and voltage parameters using the ICMS has enabled prediction of well-being of a 5 kW power generating plant which comprises a steam boiler, turbine and an alternator. The result generated from the ICMS referred to as experimental value is within the limit of the design/threshold value as well falls within the range of the sensor capacity value hence the ICMS performance is satisfactorily meets the design specifications.

From the results obtained from the ICMS it can be concluded that:

i. All the operating parameters namely temperature, pressure, steam flow rate, current and voltage can be monitored real time and the system is capable of isolating defective component for preventive maintenance planning ahead to forestall breakdown.
ii. The results show the sensors' capacities are adequate to performance their intended functions.
iii. The expected threshold/design values are within the limits of operational parameters of the steam power plant. There is no call for alarm as regarding the failure of the plant very soon
iv. Data acquired by the sensors accurately fell below the 10 % variation allowance. Hence, the system performance is satisfactory.
v. Further study should look intot how artificial intelligent can be integrated into the monitoring system by training the data acquired from the system after long time of its operations, so that it can respond well to change of environment and unplanned future conditions.

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