Enhanced system reliability of HCS model as compared to existing systems in a typical thermal power plants

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***Abstract*–The paper presents a comprehensive study of various support systems for the cooling of large size generators in fossil fueled power plants. A novel 'Six Stage-hot Redundant Structure' (S2RS)– hydrogen cooling system (HCS) clubbed with highly reliable and efficient process instrumentation system is presented for the cooling of large generators in integrated gasification combined cycle power plants. The work includes a comparison between the proposed and the existing systems in terms of system reliability. The algorithm for system reliability evaluation of the S2RS–HCS is developed on MATLAB platform. The effectiveness of real-time featured proposed HCS is validated by computer simulation. The entire process instrumentation of the system is designed and simulated on real-time automation platform.**

Key words: Fossil-fuel power plant, hydrogen cooling system, human machine interface, redundancy, system reliability

1. Introduction

In recent scenario, Reliability is a main impact index for performance quality of a power plant. The designer's prime objective is to carry out the process with utmost efficiency of the system having maximum availability at minimum cost. Some of countries including Canada, China, Germany, India, Sweden, Switzerland, UK, USA, (and the list is ever increasing) have been practicing started on enhancing the reliability of power generations using advanced automation tools in one of another form. The system reliability of control and instrumentation (C&I) for hydrogen cooling system (HCS) is of prime importance at plant level (large size generators at the final stage of power plant) primarily due to the inadequacies of component reliability. Enhanced system reliability of the cooling process reduces the chances of system failure, and thus, requiring less time for maintenance and providing higher availability. Further, reduction in maintenance duration of the process allows it to be kept in active mode for longer durations.

2. Literature Review

Generating stations with power utility factor close to unity is essential with growing demand and its economic implications. Such operations require sophisticated automation system to provide highly productive, reliable and safe system as remarked by Kawai et al. (1999) and Liu et al. (2011). In turns, the efficiency of overall power generation system gets improved. Improved efficiency has its direct impact on reduction in emission of green house gases. Various authors Hammons (2006); Chakra borty et al. (2008); Facchiano (2009); Biswal et al. (2010); Garcia-Diaz and Gozalvez-Zafrilla (2011) have addressed various aspects on this issue. Efficiency improved by 1 percent may contribute in reduction of emitted CO_2 by 20,000 tons at the rate of 345 grams per kW hour as against 578 grams per kW hour has addressed by Arnold and Capener (2003).

Presently, major part of India's power requirement is fulfilled by conventional energy sources. As per data provided by the 'Institute for Energy Research' in year 2010, around 90 percent of the total power consumed in India is shared by fossil fuel based thermal, hydro, and nuclear power stations. Out of which almost two-third of the total power is produced by fossil fuel based power generating stations. India is the fourth largest coal (a type of fossil fuel) dependent country in the world.

The operations of fossil-fuel power plants require sophisticated automation system called supervisory control and data acquisition (SCADA) systems as they provide highly productive, reliable, and safe power generation. The SCADA systems have the capability to handle highly dynamic and composite structure like load distribution centers (LDCs). An automated power plant is the merge of two vital terms that is 'Power Plant' and 'Industrial Instrumentation'. A power plant is the collection of devices that make up the physical systems of generating power. Industrial instrumentation is the measurement of mechanical / non- electrical quantities such as pressure, level, flow, temperature, etc. by means of electrical methods with the help of signal conditioners. A broad power system instrumentation lay-out is shown in Fig 1 which highlights the further direction of the work presented.

In today's scenario, for the environment and climate point of view, combined cycle power plants (CCPPs) are among the world's safest fossil fuel plants. Coal is abundant and inexpensive compared to other fossil-energy sources, such as natural gas and oil. However, the environmental impact of combusting coal with air to generate electric power has crossed over the alarming zone. A range of pollutants including NO_x, SO_x, fly-ash, and heavy metals like mercury are produced. These need to be neutralized or separated out using expensive add- on equipment to meet current or emerging emission standards. Instead of releasing the hot waste gases from the gas turbine into the environment, CCPPs use these waste gases to generate steam for a down-stream steam turbine. Combination of two processes (gas and steam cycle) enormously improve efficiency up to 58 percent with the help of the latest automation system.

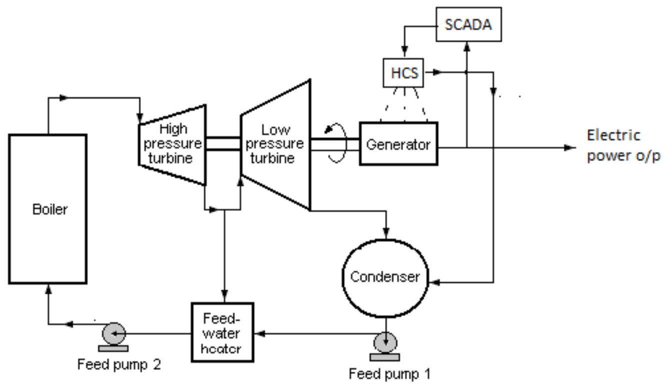

Figure 1 Block diagram of HCS based thermal power plant

In present work, special attention is given on requirements and benefits of heat recovery steam generator (HRSG) section of modern power plants (Lindsley (2000); Flynn (2003); Gay et al. (2006)). A HRSG is a heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used (in a process) to drive a steam turbine. A common application for an HRSG is in CCPPs, where hot exhaust from a gas turbine is fed to an HRSG to generate steam which in turn drives a steam turbine. This combination produces electricity more efficiently than either the gas turbine or steam turbine alone. At this stage, the focus of the research work is directed towards the role and importance of the HCS, which is vital for the efficient operation of large size generators. Large size generating sections are one of the critical components of a power plant. These generating sections require SCADA operated process C&I system for safe and reliable operation. As generating sections appear at the last stage of CCPPs, they act as an interface / bridge between rest of sections of the power plant and transmission system (sub-stations). As shown in Fig 1, generators cooling system is one among the eight major operations which is responsible for the efficient operation of generating stations.

3. Problem Formulation

A digitally automated HCS has proposed by Hargrove et al. (1992). In the follow up, a method for quick pressure relief of H2 cooled generator was introduced by Krützfeldt and Musil (2000), and Blatter et al. (2000) has also proposed a three stage cooling circuit for the cooling of generators. Adelmann et al. (2001) initiated a H2 cooling system which is used for cooling the stator of a water-cooled turbo-driven generator. Brosnihan et al. (2008) has furthered the work by proposing a modular system of air, H2, and carbon dioxide (CO2) through a gas manifold for monitoring of H2 cooled generators, where various modules employed are gas dryer, gas purity, overheat, and gas/generator monitoring modules. The cost reduction issues are implicitly focused on reducing operation and maintenance expenses, and minimizing investment in new plant set up like HCS. Here, fault tree analysis plays a key role to analyze system design and reliability of a dedicated process model. Biswal et al. (2012) proposed a process model of HCS which is reliable for the units of capacity up to 120-300 MW of a generating station.

Reliable operation of generators results to improve the efficiency of power plants by reducing the maintenance duration of the components. Enhanced system reliability of a process reduces the chances of system failure and hence, it requires less time for maintenance and provides increased availability. Thus, reduction in maintenance duration is proportional to longer operation of cooling system in active mode. In this way, HCS reduces the green house gases emission by enhancing the plant performances. At this stage, the scope of the present work has been directed towards designing a 'Process C&I model of the HCS' and evaluating the model in terms of system reliability. More significantly, some new P/I (Pneumatic – Current / Piping and Instrumentation) models have been developed with a view to advance 'the state of art' of processing units of Hydrogen (H2) for HCS. This very idea has inspired for further study in this direction.

4. System Reliability Evaluation

In general, fault avoidance methods prove to be less expensive than fault tolerance methods in evaluating system reliability. Where, fault avoidance methods are used to approach the modal life of components and fault tolerance methods approach redundant based improvement in system design. However, in case of fault avoidance methods; cost increases exponentially versus linear improvement in reliability performance of the system. Also, it is observed that behavior of components used in a system can be different than the characteristics of components used as an individual. Thus, in industrial applications like HCS, fault tolerance based methods are always preferred to evaluate the system reliability. Network reduction technique (NRT) is one of the methods of fault tolerance scheme which is used to evaluate the system reliability of the existing methods and the proposed scheme.

Weibull's distribution described in equations (1)-and-(2) is considered for all the systems; proposed and the existing, for resolving the design issues and evaluating the system reliability and bring out comparison between the proposed and the existing methods. For carrying out comparison at common platform, all the existing models and the one proposed are simplified using NRT with hot-redundancy concept based on (3). Typical hazard rate $\lambda(t)$ as given by equation (3) below is considered for the evaluation of system reliability based on philosophy of $k-out-of-n:G$. Equations (1)-and-(2), represents relationship between Reliability functions $\Re(t)$ and the hazard rate $\lambda(t)$. $\Re(t)$ represents reliability of components

Used in process models (with hot redundant unit(s), in days). $\Re_s(t)$ is the overall system Reliability of HCS. 'θ' is the slope parameter and 'η' is the scale parameter of the two- parameter Weibull distribution function. $\Re_s(t)_{series}$ is the reliability of components are Connected in series, while presents reliability hot redundant components. 'n'is number of redundant components'.

$$\left.\begin{array}{l}\Re(t)=e^{-(t/\eta)^{\theta}} \\ \lambda(t)=\left\{(\theta/\eta)*(t/\eta)^{\theta-1}\right\}\end{array}\right\} \quad (1)$$

$$\left.\begin{array}{l}\Re_s(t)=\sum_{i=0}^{k}\left\{\int_0^t \lambda(t)dt\right\}^i \exp\left(-\int_0^t \lambda(t)dt\right) \\ (i!)^{-1}=\sum_{i=0}^{k=1}\frac{e^{-\lambda.t}(\lambda.t)^i}{i!}\end{array}\right\} \quad (2)$$

$$\left.\begin{array}{l}\Re s(t)=1-(1-R(t))^n \\ \Re s(t)_{series}=R_a*R_b \\ \Re s(t)_{parallel}=R_a \Box R_b=1-\left\{(1-R_a)*(1-R_b)\right\}\end{array}\right\} \quad (3)$$

Further, R_{TA} represents the reliability of reservoir T-HA. Similarly, R_{TB} represents the reliability of tank T-HB and R_{TC} represents T-HC. Reliability of different heat exchangers is represented by R_{HE} series, for example, reliability of heat exchanger HE1A and so on. Reliability of super insulated vacuum line (SIVL) is represented by RSI. Further, each stage is connected serially in forward direction, whereas, within the stage, each block is connected in parallel mode. RHE1A is couple with RHE1B, RHE2A is coupled with RHE2B, and RHE3A is coupled with RHE3B. Out of this, one unit of each pair is active at a time.

4.1 System by Hargrove et al. (1992)

Authors introduced a system relating to the H2 cooled generators in an electrical power station. The reliability model of the system is given by.

$$\left.\begin{array}{l}\Re_1(t)=R_X*R_{TB}*R_{HE1}*R_{HE2}=\Re 1 \\ \because R_X=R_{TA}\Box R_{SI}\end{array}\right\} \quad (4)$$

4.2 System by Krützfeldt and Musil (2000)

Authors proposed an idea for quick pressure relief in a H2 cooled generator system. The reliability model of the system is represented by

$$\left.\begin{array}{l}\Re_2(t)=R_{TA}\cdot R_{TB}\cdot R_{HE1}\cdot R_{\gamma}=\Re 2 \\ \because R_{\gamma}=R_{HExk}\Box R_{HEyk},\ y\le 2\ and\ 0\le k\le 1\end{array}\right\} \quad (5)$$

4.3 System by Blatter et al. (2000)

Blatter et al. introduced a three stage H2 cooling system for generators. The reliability model is articulated by (6).

$$\left.\begin{array}{l}\Re_3(t)=R_{TA}\cdot R_{TB}\cdot R_{\beta}\cdot R_{\gamma}=\Re 3 \\ \because R_{\gamma}=R_{HExk}\Box R_{HEyk}=R_{\beta}\end{array}\right\} \quad (6)$$

4.4 System by Adelmann et al. (2001)

The system has a container for compensating coolant which is arranged in a parallel section with the cooling circuit. The reliability model is expressed by (7).

$$\left.\begin{array}{l}\Re_4(t)=R_{TA}\cdot R_S\cdot R_y\cdot R_{\beta}=\Re_4 \\ \because R_S=R_{TB}\Box R_{TC}=R_{\beta}\end{array}\right\} \quad (7)$$

4.5 System by Brosnihan et al. (2008)

Brosnihan et al. proposed a modular system for the monitoring of hydrogen-cooled generator. It included a skid platform for the monitoring of air, H2, and CO2. Reliability model of the system is provided in (8).

$$\Re_5(t)=R_{TA}\cdot R_{TB}\cdot R_{HE1}=\Re 5 \quad (8)$$

4.6 System proposed by Biswal

The proposed method is designed and supported with a redundant module for uninterrupted supply of H2 (Biswal et al. (2012)). The reliability of the system improves with increasing number of redundant components. Here, matrix of storage tanks has been judiciously selected for the storage of LH2 as reservoirs, and for cold converters; T-HB and T-HC. Reliability model of the system is provided in (9).

$$\left.\begin{array}{l}R_S=R_Y*R_{TB},R_T=R_Z*R_{TC},R_a=R_S\Box R_T \\ \because R_{\beta}=R_{HE3A}\Box R_{HE3B}=R\gamma \\ \therefore \Re_6(t)=R_X*R_a*R_{\beta}*R_{\gamma}=\Re 6\end{array}\right\} \quad (9)$$

The proposed method is a type of standby system where active redundancy has been considered. However, it requires smart and proven choice for selecting the number of components as a redundant module. In this proposal, matrices of hydrogen storage and processing tanks are judiciously selected so that they contribute to improve reliability and are cost-effective models. In both the proposed models (A) (Section III-D1) and (B) (Section III-D2), the number of standby component is chosen as k = 1. It has two fold benefits: enhanced system reliability and cost effectiveness. Thus, improvement in system reliability of the proposed method as compared to that of existing systems is one of the essences of this paper. The reliability model of the proposed method for evaluating the overall system reliability of HCS is shown in Fig. 2

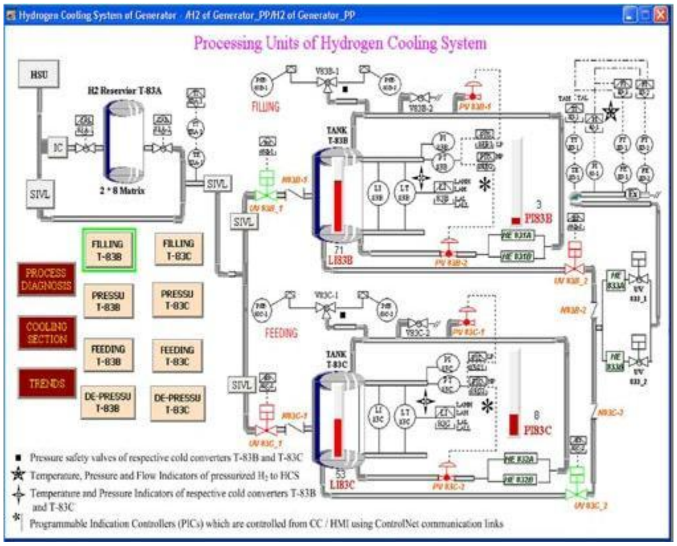

Figure 2 Proposed processing unit of S3RS-HCS

The algorithm is summarized in six steps: steps 1-6.

1) From control center, digital outputs are generated and guided to operate On-off valves. Simultaneously pressure values are operated by analog outputs.

2) To execute the filling event as Fill_T83B/Fill_T83C
   - $UV83B-1/UV83C-1 \rightarrow O$ • $UV83B-2/UV83C-2 \rightarrow C$
   - $PV83B-2/PV83C-2 \rightarrow C$ • $PV83B-1/PV83C-1 \rightarrow CNT$

3) To execute the pressurization event as Pres_T83B/Pres_T83C
   - $UV83B-1/UV83C-1 \rightarrow C$ • $UV83B-2/UV83C-2 \rightarrow C$
   - $PV83B-1/PV83C-1 \rightarrow C$ • $PV83B-2/PV83C-2 \rightarrow CNT$

4) To execute the feeding event as Feed_T83B/Feed_T83C
   - $UV83B-1/UV83C-1 \rightarrow C$ • $UV83B-2/UV83C-2 \rightarrow O$
   - $PV83B-1/PV83C-1 \rightarrow C$ • $PV83B-2/PV83C-2 \rightarrow CNT$

5) To execute the depressurization event as Depres_T83B/Feed_T83C
   - $UV83B-1/UV83C-1 \rightarrow C$ • $UV83B-2/UV83C-2 \rightarrow C$
   - $PV83B-2/PV83C-2 \rightarrow CNT$ • $PV83B-1/PV83C-1 \rightarrow O$

6) Go to step 2 to attempt the next iteration.

5. Result and Discussions

Figs. 2(a) and 2(b) depict the two different sets of tests performed to evaluate system reliability performance of the proposed method vis-à-vis the other methods. The abscissa represents the samples collected at different instants of time For example; the 10th sample is at the highest limit of threshold value of component reliability of various components. The ordinate represents the system reliability performance of the proposed method (R6) over the methods (R1, R2, R3, R4 and R5) that is, the ordinates shows relative improvement of R6 than that of the existing systems in percentage.

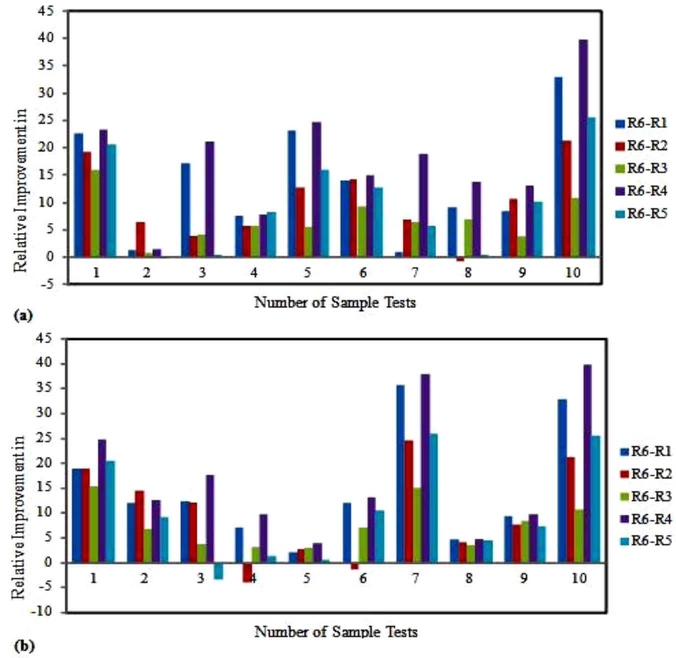

Figure 3 Histogram shows improvement in system reliability of R6 over R1, R2, R3, R4 and R5. (a)-And-(b) represent two different test sets Test I and Test II.

At upper limits of threshold values, the R6 has shown 32.85% improvement in system reliability as against that of R1. Similarly, R6 has obtained 21.34%, 10.83%, 39.77% and 25.66% improvement as against that of R2, R3, R4 and R5 respectively. However, maximum improvement in system reliability of R6 when compared with that of R1 has varied from 23.2% to 35.79% as shown in Fig 2. Similarly, these values corresponding to improvement in reliability of R6 with respect to R2, R3, R4 and R5 have varied from 18.9%–19.2%, 15.45–15.96%, 24.7%–37.92% and 20.67%–25.92% respectively. Thus, it can be summarized that the proposed S2RS-HCS model exhibits superiority over all oIther existing models in terms of system reliability.

6. Conclusions

S2RS-HCS model is designed for cooling of the large generators. It has been shown that it is reliable and cost-effective for the capacity of nx250-300 MW units and above. At upper limits of threshold values, the proposed model (R6) has shown (32.85%, 21.34%, 10.83%, 39.77% and 25.66%) significant enhancement in system reliability as against that of the existing systems R1, R2, R3, R4 and R5 respectively. In this way, the R6 enhances the gainful application of the HRSG sections of CCPPs and will have its direct impact on plant performance.

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