Pure Cycle Cascaded Binary Geothermal Power Plant

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***Abstract*—Geothermal energy a 24×7, clean and naturally available energy is the next stage high density power generation resource that leads the power production market all over the world. Owing to its high positive impeccable advantages over the conventional energy sources it establishes pure cycle power production technology. Geothermal power plants are green power plants having relatively very few percent of sulphur-emission rates, carbon dioxide and nitrogen oxide emissions as compared to fossil power plants and also requires only a fraction of land that needed by other energy resources. Pure cycle cascaded binary geothermal power plant is a technology that is proposed for improving the utilization factor of the geothermal recourses and use factor of the generators. In this paper, two 300kW Organic Rankine Cycle Binary Cycle power plants which are integrated to form cascaded geothermal power plant is proposed keeping in view the reservoir temperature and estimated potential at Tatapani Geothermal Field. Plant one is a High Temperature Gradient Synchronous Generator having rotor with high temperature super conducting coil and provided with closed loop molten salt temperature controller and plant two is an Induction Generator. Both the plants are integrated in floating mode and are connected to an AC grid adopting reliably advanced synchronizing techniques.**

***Index Terms*—induction generator, molten salt, rankine cycle, synchronous generator**

I. Introduction

Pure Cycle power plant generates electrical power from low to medium temperature heat sources with zero emissions using an Organic Rankine Cycle turbine. An Organic Rankine Cycle, which is termed as ORC describes a model of the operation of steam heat engines most commonly found in power generation plants. Common heat sources for power plants using the Rankine cycle are coal, natural gas, oil, and nuclear fuels. The efficiency of a Rankine cycle is usually limited by the working fluid such as pentane, butane or R134a that is used in place of water-steam. Alternatively, the fluids having boiling points above water can also be used to have thermodynamic benefits. The difference between water and an exemplary organic fluid is that the critical point of organic fluids is reached at lower pressures and temperatures compared with water.

For low enthalpy geothermal resources [1], the binary ORC system is often used for generating electric power. The hot brine or geothermal steam is used as the heating source for an organic fluid which is used to drive the turbines. As suggested by Lamb et al (1980) the well head pressure fluid passes through hydraulic tapping unit and then in to the thermal recovery system which is a Rankine-Cycle unit using an organic fluid whose properties can be compatible with the site-specific wellhead and condensing temperature. In order to utilize the relatively high temperature and even moderate temperature geothermal resource, cascade connection of series of ORC plants is preferable, such that the water discharged by a unit which is still hot is utilized by a downstream unit of lower temperature requirements. In this cascading method, the source can be cooled down to lower temperature with respect to a single unit scheme, and electric power output can be optimized.

Tatapani Geothermal field in Surguja District, Chhattisgarh State, is a promising hot water reservoir in Central India along the Son-Narmada lineament [2]. Thermal manifestations in Tatapani consists of hot springs (50℃-97℃) in marshy ground, and hydro thermally altered clay zones covering an area of about 0.1 sq km. Geological Survey of India has carried out prospecting at Tatapani Geothermal Field for proving potential of geothermal resource by geochemical and geophysical methods and exploration by drilling. The geothermal resource at Tatapani is of low to intermediate enthalpy. The production wells at Tatapani indicate low-to-moderate production potential. The thermal water is free flowing (artesian flow) hence the energy required for pumping the water to the surface is also saved. The 1800 lpm hot water at 112℃ may be used for heating organic fluid in the heat exchangers. The inlet and outlet temperature of the fluid from heat exchanger may be 112℃ and 87℃, respectively. An Organic fluid binary cycle power plant is suitable for electricity generation at Tatapani due to low enthalpy of the thermal water. The binary-cycle pilot power plant may be planned in a cascading method to utilize the effluent water of 87℃, from the primary binary unit, for generation of additional electricity.

In this paper a 600kW binary-cycle power plant is considered for the generation of electricity from the geothermal energy at Tatapani. The total considered capacity of the plant considered is equally divided in to

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two units each having capacity of 300kW. First unit is suggested with Synchronous Generator having a rotor with high temperature super conducting coil [3] and provided with closed loop molten salt temperature controller and the second unit with Induction Generator [4]. The starting methods [5], synchronizing techniques [6] and integration of these two generating units for cascading and connection to a grid are presented.

II. Choice of Binary Fluids

The fluids as listed in Table I are given in the order of rising critical temperature T_c and normal boiling temperature T_s, 1 bar P_c is the critical pressure and P_s the vapor pressure at 20 ℃. The higher the vapor pressure of a liquid at a given temperature, the lower will be the normal boiling point (i.e., the boiling point at atmospheric pressure) of the liquid. The boiling point of a liquid is the temperature at which the vapor pressure of the liquid equals the environmental pressure surrounding the liquid. A liquid in a vacuum environment has a lower boiling point than when the liquid is at atmospheric pressure. A liquid in a high pressure environment has a higher boiling point than when the liquid is at atmospheric pressure. In other words, the boiling point of liquids varies with and depends upon the surrounding environmental pressure.

In this ORC, R134a is opted as a binary fluid because it is widely used with excellent results in the heat pumps and cooling/refrigeration industry, which involves inverse Rankine cycle machines. R134a is available in the market. The necessary parts for the corresponding Rankine cycle machine are also available in the market. CARRIER, the multinational air-conditioning manufacturer has developed a low cost 200kWe geothermal binary power unit using R134a as working fluid. The plant was installed in the "Chena" geothermal field in Alaska, USA, utilizing 74 ℃ water. Two units have been installed, which commenced operation in August 2006 and December 2006 respectively.

TABLE I. List of Working Fluids

Fluid	T_c [℃]	P_c [bar]	T_s, 1bar [℃]	P_s, 20 ℃ [bar]
R134a	101,1	40,6	-27,1	5,7
R227ea	101,7	29,3	-16,5	3,9
R236fa	124,9	32,0	-1,4	2,3
R245fa	154,1	36,4	14,9	1,2

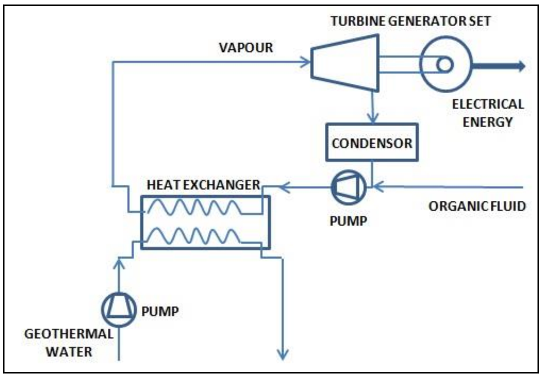

Figure 1. Rankine cycle geothermal power plant

III. Selection of Rankine Cycle Parameters

The Rankine cycle plant is schematically presented in Fig. 1.

A. *Geothermal Heat Exchanger (Evaporator)*

Among all the types of heat exchangers Plate type exchangers are preferred to shell and tube exchangers, as far as it concerns the geothermal heat transfer, because the geothermal water usually contains dissolved particles or ions (silica SiO_2 or salts such as calcium carbonate $CaCO_3$), which tend to be deposited on the surfaces and cause fouling of the heat exchanger. It is obvious that it is easier to clean them from the plates rather than the tubes, as a plate heat exchanger can be easily dismantled and cleaned either mechanically or chemically. But owing to heat transfer rate and construction, shell and tube type heat exchangers are preferable and based on the type of flow of fluid in the heat exchanger, counter type of flow is best suitable as it has high heat transfer rate. Hence shell and tube heat exchangers with counter flow type are opted in our study, assuming there is no deposition of dissolved particles or ions.

B. *Cooling Heat Exchanger (Condenser)*

It is a device in which steam condenses into liquid i.e. when exhausted steam from the turbine is allowed to pass through it then steam gets converted into liquid. The process of phase conversion of a substance can be carried out in it. Generally shell and tube condenser is preferred in geothermal binary power plants.

C. *Turbine*

A turbine is an electromechanical device which rotates on its own axis when steam or vapor is enforced on to it and converts mechanical energy into electrical energy when coupled with the shaft of a generator. Every turbine has its own functional performance based on their construction. Among all the types of turbines variable phase turbine can be best suited for geo thermal power plants. The Variable Phase Turbine (VPT) is comprised of a set of individual, fixed nozzles and an axial impulse rotor [7]. The two-phase nozzle is the thermodynamic energy conversion element of the VPT. Enthalpy is converted to two-phase kinetic energy in a near isentropic expansion. Expanding gas breaks up the liquid phase into small droplets. Momentum is transferred from the gas to the droplets by pressure and shear forces. The small diameter of the droplets results in a close coupling of the gas and liquid, producing efficient acceleration of both phases. The inlet to the nozzle can be liquid, two-phase, supercritical, or vapor. Two-Phase kinetic energy is efficiently converted to shaft power by reversing the direction of the tangential component of the flow velocity in an axial impulse turbine.

D. *Generators*

In this paper two 300kW ORC Binary Cycle power plants, one modeled with an Induction Generator and the other with Synchronous Generator are integrated to form cascaded geothermal power plant keeping in view the reservoir temperature and estimated potential at Tatapani geothermal field.

An induction generator is an asynchronous generator that is mechanically and electrically similar to an induction motor and is often referred as motor-generator. It requires reactive power to generate real power in its generating mode of operation. From the moment the transition of induction machine from motoring mode to generating mode happens, rotor magnetic field which was developed due to induction effect during the motoring mode gets declined. But without rotor magnetic field electrical power generation is not possible. Hence in order to magnetize the rotor field winding, lagging currents at nearly Zero Power Factor has to be supplied. This lagging current will effectively magnetize the rotor field winding and chains in power generation. Thus a lagging reactive power is to be injected into the rotor winding for supporting the action of induction generator. The lagging reactive power can be supplied by a capacitor bank or by a synchronous condenser. Over-excited synchronous machine is often referred as synchronous condenser.

Synchronous generators are principally alternating current generators. They generate electric power only at synchronous speed. The driving speed of the prime-mover coupled to its shaft should be always steady. For geothermal applications, where the temperature and pressure of the binary fluid are not constant, properly designed geared turbines are to be opted. In this case molten salt closed loop control system is proposed so as to achieve constant system temperatures.

IV. Pure Cycle Cascaded Binary Geothermal Power Plant

Assuming the discharge temperature of 112°C and effluent water temperature of 87°C for binary cycle plant, the reservoir may have capacity to sustain production about 3.5MW for a period of 20 years, from energy in liquid. The estimated area of the reservoir is 7.2 sq km at the thermal gradient of 50°C/km, and at the depth of 1.5km.

In this schema, the total considered capacity of the plant is 600kW and is equally divided in to two units each having capacity of 300kW. First unit is an upstream unit suggested with synchronous generator having a rotor with high temperature super conducting coil and provided with closed loop molten salt temperature controller and the second unit is a downstream unit with induction generator such that the water discharged by first unit is utilized by it and also synchronous generator feeds reactive power to the induction generator. Both the plants are cascaded such that total generating capacity about 600kW is possible. There are different techniques and methods used to run a geothermal power plant using the generators as discussed in the previous section. The functional operation of a proposed geothermal power plant can be clearly understood with the help of a flow chart as shown in Fig. 2. The synchronous generator having a rotor with high temperature super conducting coil, which is referred as HTS Synchronous generator supplies Induction Generator with reactive power. To meet the demand of the Induction Generator for lagging VARs as well as to permit the Induction Generator to have a smaller power factor corresponding to a relatively large air gap, HTS Synchronous Generator generates sufficient reactive power. Plant 1 corresponding ORC plant with synchronous generator with 300kW is integrated with plant 2 corresponding ORC plant with induction generator with capacity 300kW, i.e. capacity forming Pure Cycle Organic Rankine Cycle Cascaded Binary Power Plant which is illustrated in Fig. 3**.**

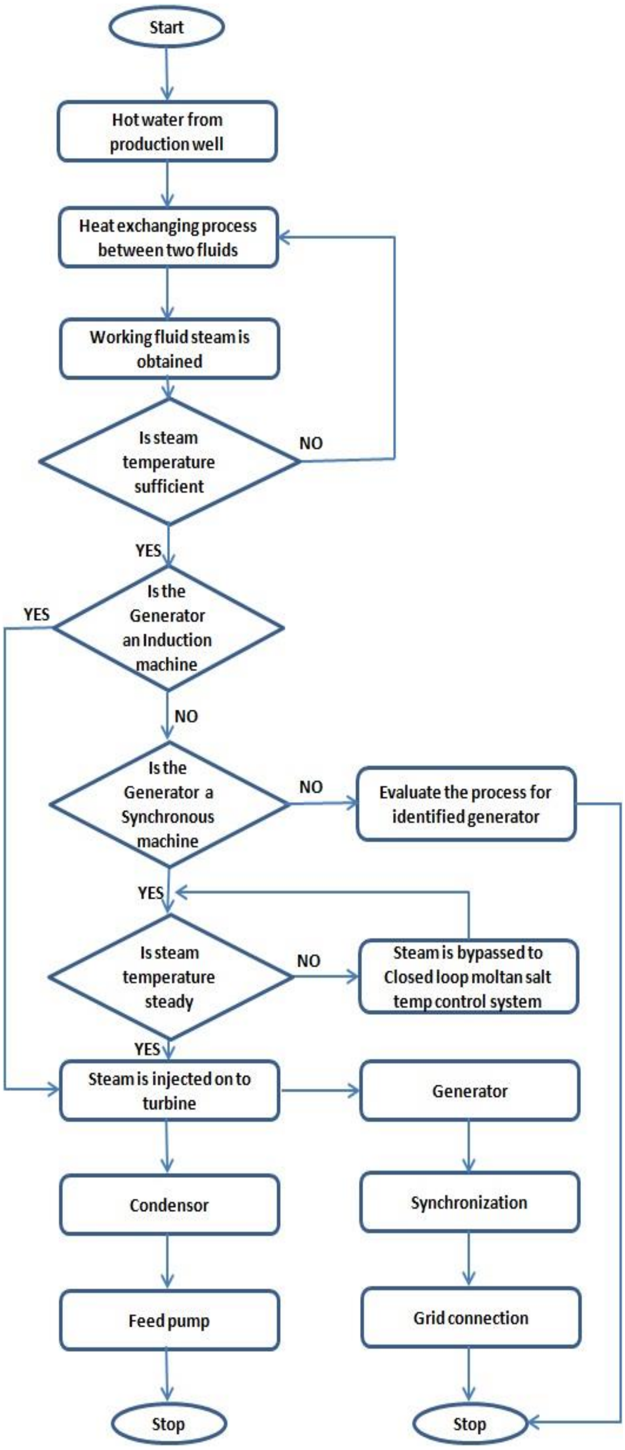

Figure 2. Flow chart

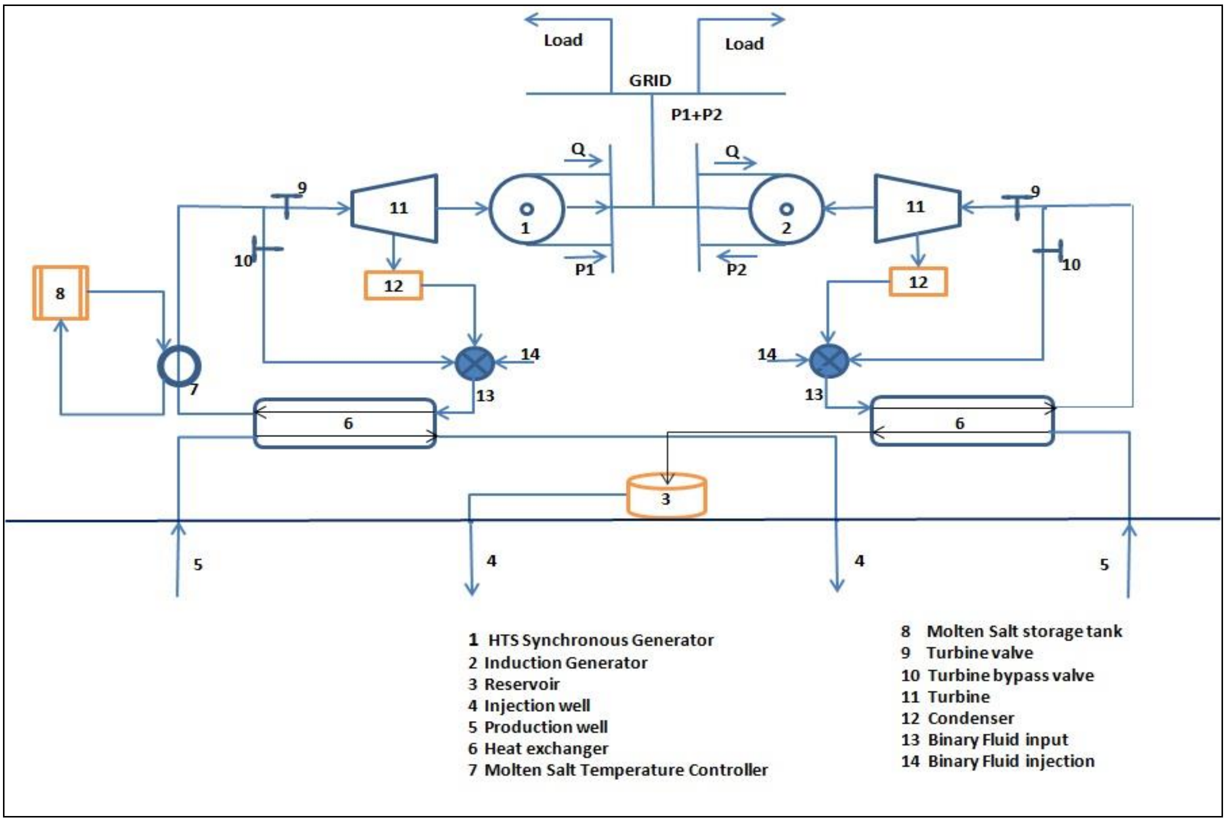

Figure 3. Pure cycle cascaded geothermal power plant

A. *Description of Plant with Synchronous Generator*

Two wells called injection well and production well are to be drilled up to1.5kms with regular spacing between each other. Through the injection well water from the reservoir is pumped into the earth and through the production well hot water will be brought to the earth surface with the help of a pump. The hot water (at 87-112 ℃) obtained from the production well is made to pass through the heat exchanger in the shell side. On the other side of the heat exchanger i.e. in the tube side, binary fluid, R134a refrigerant is made to pass through, in which heat exchanging process takes place between the two liquids. The steady temperature and pressure of the binary fluid is accomplished by accommodating proper provision for charging and discharging molten-salt storage system as illustrated in the flow chart in Fig. 2. In the proposed technology, the binary fluid with high temperature deviation is diverted to molten salt containers by the closed loop molten salt temperature control system, in which the molten salt either gets charged or starts discharging so as to maintain steady temperature within the system tending to steady speed of the turbine which is driving the synchronous generator. Molten salt storage system is actuated for discharging with appropriate discharging rate, if the system temperature is less than the steady temperature.

Molten salt can be kept hot enough by the charged temperature for days together and possibly weeks, and that this practice currently works better than storing electricity in batteries. The Molten salt storage system is efficient thermal energy storage system having the provision of charging and discharging the temperatures through a closed loop control action that can be achieved by temperature sensors and transducers within closed loop molten salt temperature control system. By opting suitable technology the generator which is coupled to a turbine can be made to run as a synchronous generator by controlling the speed of all the equipments. Initially the speed of the generator is measured by using a speed sensor. It is aware that the generator speed depends on the turbine speed and the turbine speed depends on the binary fluid pump speed and the binary fluid temperature. Molten salt closed loop control system with additional pump speed control functionality takes care of the pump speed in addition to steady temperatures and if the generator runs at synchronous speed then the turbine speed can also be made to run at synchronous speed by varying the speed of the pump which in turn varies the speed of the fluid flow through heat exchanger due to which the force exerted by the steam from the outlet of the heat exchanger varies thereby varying the relational speed of the turbine.

Thus both the turbine and the generator are made to run at synchronous speed and hence can be connected to the grid without any electronic means viz., cycloconverters, thus avoiding injection of nonlinearities and thereby harmonics in to the system.

B. *Description of Plant with Induction Generator*

Basic orientation of this plant is also similar to the power plant with synchronous generator. But in this case initially induction generator is run as a motor by connecting it to the synchronous generator through interconnecting switch. Induction motor drives the coupled turbine in freewheeling mode until binary fluid vapor at desired temperature and pressure is acted on the turbine blades. Once the speed of the turbine becomes just greater than the synchronous speed, synchronous generator will take care in supplying lagging reactive power to induction machine. Now induction machine starts acting as induction generator. As soon as generating mode is achieved synchronizing channels are introduced in to the system, so as to maintain frequency and voltage balance between the synchronous generator and the induction generator.

V. Conclusion

Geothermal power plants are suitable for deployment in all types of terrain and environment. If the geothermal resource is typically above 150 °C, a direct flash steam plant can be used. For lower resource temperatures binary plant either with steam (flash plant) or hydrocarbon (binary plant) working fluids can be used. In view of its pure cycle green energy resource and 24×7 availability next stage power production will no doubt draws the concentration of the power producers in addition to the utility towards development of geothermal power plants worldwide. Hence the pure cycle cascaded binary geothermal power plant technology proposed in this paper will exhibit an optimistic path for effective utilization of the geothermal reservoir temperatures and constrained electrical generators that can be used for précising the system thereby improving the utilization factor of the recourses and use factor of the generators.

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