International Journal of Scientific Engineering and Technology Research

ISSN 2319-8885
Vol.03,Issue.12
June-2014,
Pages:2703-2709

www.semargroup.org,
www.ijsetr.com

Design of 20 MVA Three-Phase Turbo-Alternator Used in Geothermal Energy Production

ZIN MAR AUNG[1], KYAW SAN LWIN[2]

[1]Dept of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar, E-mail: zinmaraung.ep@gmail.com.

[2]Dept of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar, E-mail: kyawsanlwin75@gmail.com.

Abstract: There are various resources of power to produce electricity in Myanmar. They are biomass, solar, wind, water and geothermal energy. Geothermal energy uses geothermal reservoirs but in a different way as is the case with carbon dioxide storage. At depths varying from several hundreds of meters to several kilometers geothermal energy is used to provide heat. From a depth of 6 kilometers and deeper geothermal energy is used to produce electricity by means of superheated steam. By combining carbon dioxide storage and geothermal energy and integrate them in a system where carbon dioxide is used as working fluid for a geothermal system. A geothermal plant is use high speed steam turbine and synchronous generator. In this thesis, the essential features of geothermal power plant and the selections of the turbine and generator are explained. Moreover, this paper treats of the design calculation of a three-phase turbo-alternator for a dry steam geothermal power plant.

Keywords: Produced Electricity, Geothermal Energy, Dry Steam Plant, Synchronous Generator, Turbo-Alternator.

I. INTRODUCTION

Geothermal power is an alternative source of energy that harnesses the heat from within the Earth in order the generate electricity and space heating. Twenty-four countries were producing electricity from geothermal resources, with a total geothermal installed capacity exceeding 10892 MWe, with electricity generation of 66184.1 GWh, based on 2010 data. With the expansion of the direct usage of this geothermal water, this could be another step in meeting the energy needs of developing countries. The Earth itself is continuously heated through radiation from within itself and with the gathered rainfall and snowmelt which is supplied each year new geothermal reservoirs are created. The production from these individual reservoirs can be sustained for many decades and perhaps even centuries. With essentially zero emissions during the capturing process, geothermal energy is classified as a renewable resource. Geothermal energy is derived from heat within the earth, usually in the form of underground steam or hot water.

The sources of geothermal energy are due to the molten rocks. That is found beneath the surface of the earth known as magma. Most magma remains below the earth's crust and heats the surrounding rocks and subterranean water. Some of this water comes all the way up to the surface through fault sand cracks in the earth as hot springs or geysers. When this rising hot water and steam is trapped in permeable rocks under a layer of impermeable rocks, geothermal reservoirs are formed. The thermal energy of these reservoirs can be taken from different depths through wells hundreds to thousands of feet deep Geothermal energy is considered a renewable energy source because heat is continuously produced inside the earth and is cost effective, and environmentally friendly, with very low carbon emission, and, unlike solar and wind, geothermal power is immune from weather changes.

II. ADVANTAGES OF GEOTHERMAL ENERGY SYSTEM

The advantages of geothermal energy system relative to each other may be summarized as follows:

- Clean energy.
- Renewable electricity.
- Direct use.
- Fewer places.
- Proven technology.
- Low operating and maintenance cost.
- No pollution and global warming.
- No dependent on the weather condition.
- No wastage and generation of by-products.
- No fuel required; energy cost not an issue.
- Have been built in the deserts, in the middle of crops, and in the mountain forests.
- Base-load power; 24/7/365 days a year.

II. TYPES OF GEOTHERMAL POWER PLANT

There are three basic types of geothermal energy generation plants in use today. With all three of these methods, the left over condensed steam and geothermal fluids are returned to the Earth in order to generate more heat.

A. Dry Steam Geothermal Plant

A dry steam plant has production wells that are drilled down to the geothermal reservoir. Since steam is used directly, the cost of boilers and boiler fuel eliminated, providing energy at a very low cost. However, the technology is bounded by the extremely rare resources of dry steam. The superheated pressurized steam (180˚C < T < 280˚C) is brought to the surface at high speeds and passed through a steam turbine to generate electricity. The steam passes through a condenser and is converted into water. The condensate is then re-injected into the ground through wells. Pumps support these processes with condensate re-injection pumps (CRIP), cooling water pumps (CWP) and auxiliary pumps. Since steams are used directly, the cost of boilers and boiler fuel eliminated, providing energy at a very low cost. However, the technology is bounded by the extremely rare resources of dry steam as shown in fig 1.

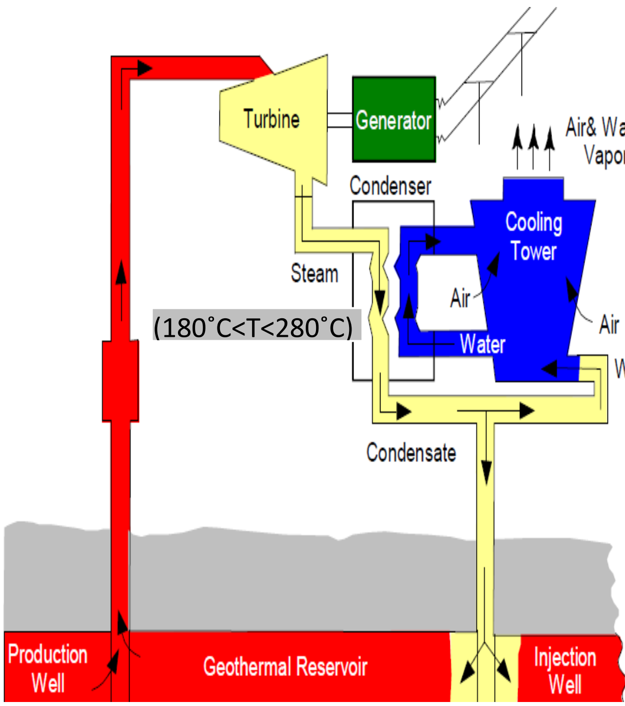

Fig.1. Process Diagram of Dry Steam Geothermal Power Plant.

B. Flash Steam Geothermal Plant

Geothermal reservoirs that contain hot, pressurized water are much more common and provide energy for all domestic geothermal power production. In a flash steam plant, pressurized water is heated using geothermal resources. The hot and high-pressure liquid (185˚C<T<220˚C) is converted into steam by flashing the extracted liquid through reducing the pressure. Before fluids enter the plant, the pressure of the fluid is reduced until it begins to boil, or flash. This process produces both steam and water as shown in fig 2. The fluid is separated into steam and brine. This water is injected back down into the reservoir again and the steam is used to drive the turbine, which powers a generator. After passing through the turbine, the steam enters a condenser and is cooled to a liquid state, then pumped back down into the reservoir.

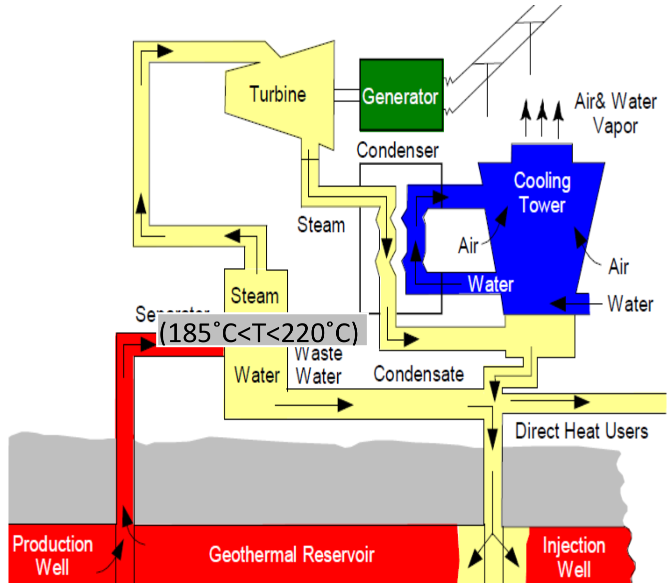

Fig.2. Process Diagram of Flash Steam Geothermal Power Plant.

C. Binary Cycle Geothermal Plant

A binary cycle plant transfers heat from the hot geothermal fluid (105˚C<T<185˚C) that is sent through a heat exchanger to vaporize a secondary working fluid such as pentane, iso-butane in the Rankine Cycle, or ammonia in the Kalina Cycle. Rather than flashing the geothermal fluid to produce steam, this type of power plant uses heat exchangers to transfer the heat of the water to another working fluid that vaporizes at lower temperatures. This vapor drives a turbine to generate power, after which it is condensed and circulated back to the heat exchangers. This type of geothermal plant has superior environmental characteristics compared to the others because the hot water (which tends to contain dissolved salts and minerals (fig 3)) is never exposed to the atmosphere before it is injected back into the reservoir.

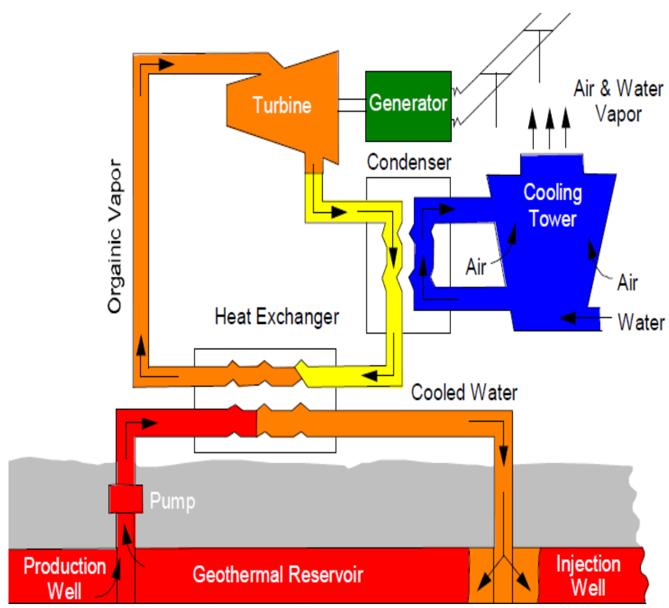

Fig.3. Process Diagram of Binary Geothermal Power Plant.

III. CASE STUDY OF DRY STEAM POWER PLANT

The base case for dry steam power plant produces 0.48 MW per doublet with a runtime of 7750 hours per year. This totals an electricity production of 3.7 GWh per year without carbon dioxide emissions. When the same amount of electricity would have been produced using natural gas fired power plants the total carbon dioxide emissions would equal 1100 ton. This results in a total avoidance of 36000 ton carbon dioxide over the full 50 years lifetime of the system. This adds 36 % of total carbon savings to a carbon dioxide storage project. The main output of the system is shown in the amount of electricity produced, which is the goal of the system. The system's output can be described using all of the following aspects:

- Electrical output
- Thermal input
- Efficiency
- Well spacing
- Flow (mass and volume)

Several variables have to be defined before an output can be calculated. These variables are mainly location specific variables as properties of the reservoir. Complete lists of variables that influence the output of the system are:

- Reservoir
    - Depth
    - Reservoir height
    - Geothermal gradient
    - Rock permeability
- Turbine
- Lifetime
- Wells
- Diameter

The impact of these variables on the system will be described below in the sensitivity analysis. However, before a sensitivity analysis can be performed, a base system needs to be defined.

IV. BASE SYSTEM

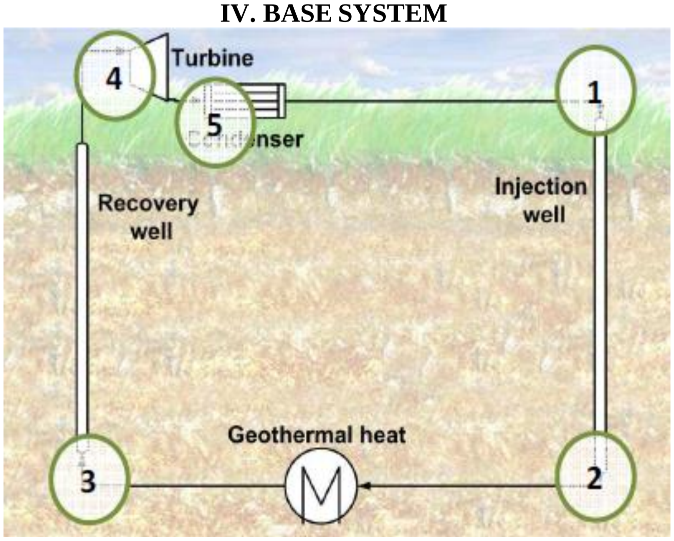

Fig.4. Systematic representation of the system.

The base system is designed by using average temperature values. The variables of the base system can be found in Table I. The whole system is designed as a steady state closed cycle. The numbers are rounded and can change for different locations.

TABLE I. Variables Used for Base System for Dry System Power Plant

Variable	Value	Unit
Reservoir depth	2000	m
Reservoir height	100	m
Geothermal gradient	31	K/km
Permeability	10^{-13}	m^2
Turbine efficiency	80	%
Running hours per year	7750	hr/yr
Lifetime	50	yr
Well diameter	0.2	m

The base system design as stated above results in a system which extracts 14.5 MW of heat from the soil and turns it into 0.48 MW electrical output resulting in a 3.3% overall efficiency. To maintain this output for at least 50 years with a runtime of 7750 hours per year, the wells need to be at least 1400 m apart from each other. The properties at the different parts of the system for the base case of the Netherlands can be seen in Table II. The numbers in Table II can be seen in Fig 4.

TABLE II: Properties of Carbon Dioxide at the Start of the Different Steps in the System for the Base Case

No.	Location	Pressure	Temp:	Density	Enthalpy	Entropy
		Bar	K	kg/m^3	kJ/mol	kJ/mol/K
1	Injection well	74.5	296.0	788	-1.855	0.106
2	Reservoir	264.2	305.0	929.3	-1.855	0.103
3	Recovery well	244.2	347.5	715.0	2.276	0.116
4	Turbine	93.05	317.3	474.3	2.276	0.110
5	Condenser	74.05	303.9	303.9	2.137	0.119

A. Turbine

Like all conventional thermal power plants, a geothermal plant fig 5 uses a heat source to expand a liquid to vapor/steam. This high pressure vapor/steam is used to mechanically turn a turbine-generator. At a geothermal plant, fuel is geothermal water heated naturally in the earth, so no burning of fuel is required. At many power plants, a steam turbine is used to convert the thermal energy extracted from pressurized steam into useful mechanical energy. Mechanical energy is then converted into electricity by the generator. Geothermal plants rely upon one or a combination of three types of conversion technology, binary, steam, and flash, to utilize the thermal energy from the hot subsurface fluids and produce electricity. After the thermal energy has been used to turn the turbine, spent steam is condensed back to a liquid and injected into the ground where it is reused in the geothermal system, prolonging the lifetime of a geothermal plant. Electricity is then transported by transmission lines into the regional grid. In the turbine part, the carbon dioxide is adiabatically expanded. The output of this component is electricity generation. In the turbine the carbon dioxide expands from supercritical state to gas. Without entropy losses, the output of the turbine can be calculated using enthalpy differences and mass flow.

Increasing the last stage blade (LSB) size and exit diameter from the turbine will result in improving economies of scale. Stress corrosion cracking (SCC) in the last stage blade is often cited as the limiting factors in the blade length (due to the reduction in stress levels that are required) however erosion due to water droplets is also a factor that limits size. Improved methods of countering SCC would undoubtedly lead to increased LSB sizes. Titanium blades have been developed by some leading manufacturers in the industry, displaying improved corrosion resistance. However these have not gained widespread acceptance due to concerns about their performance in relation to erosion resistance. At the opposite end of the spectrum, there is reputedly intriguing ongoing work to develop small, 'high speed' turbine wheels that rotate at thousands of rpm a concentrated power extraction.

Fig.5. Turbine of dry steam power plant.

B. Efficiency

Efficiency is broadly defined as the ratio of the output to the input of any system. All thermal power plants have a fraction of waste heat. While efficiency is an important measure of power generating facility performance, comparing efficiency values for geothermal and other renewable technologies, as well as for fossil fuels, poses significant challenges. The public interest in energy efficiency arose as a fossil fuel issue: that is, the less fuel used per output, the fewer emissions and the greater quantity of depleting fuels conserved. Burning fossil fuels to generate electricity contributes to climate change, health problems, and ecosystem damage. As fossil fuel resources become scarcer, costs skyrocket. That’s why efficiency, maximizing the energy output from a quantity of burned fossil fuel, is so important for traditional power plants. For renewable energy use, in contrast to fossil fuel use, efficiency is primarily an economic concern.

Maximizing the output per input of available energy is still important, but the public issues are confined primarily to land use, not climate change, health and conservation issues. Unlike geothermal and other renewables, fossil fuel use is not sustainable even if managed properly and used efficiently. At a geothermal facility, the fuel source is not burned. That means air emissions are substantially lower than at a fossil fuel facility. Because the geothermal resource, the fuel source, doesn’t have to be shipped from far-off locations, there is no environmental impact related to transportation as with traditional resources. The geothermal resource is continuously available and highly reliable. Geothermal power plants regularly inject geothermal liquids back through the reservoir, thereby improving the lifetime of the plants. While both conventional plants and geothermal plants must reject heat to the surroundings, geothermal plants result in more heat rejection per unit of useful power output than conventional plants. Besides more obvious distinctions related to emissions and sustainability, other technology and resource differences must be considered when comparing efficiencies.

V. DESIGN THEORY

Design of electrical machines mainly consists of obtaining the dimensions of the various parts of the machine to suit given specifications, using available material economically and then to furnish these data to the manufacture of the machine. The aim of the designer is to obtain:

- Lower cost
- Smaller size
- Wider temperature limit
- Lower weight
- Better performance under no load and loaded conditions
- Minimum losses

A. Main Dimensions of Stator Frame

Output equation,

$$Q = 3V_{ph} I_{ph} \times 10^{-3}\,\text{kVA} \quad \textbf{(1)}$$

Armature ampere turns per pole,

$$AT_a = \frac{1.35 T_{ph} I_{ph} K_w}{P} \quad \textbf{(2)}$$

Generated e.m.f per phase,

$$E_{ph} = 4.44\, f\, \phi\, T_{ph}\, K_w \quad \textbf{(3)}$$

Thus, turns per phase,

$$T_{ph} = \frac{E_{ph}}{4.44\, f\, K_w \phi} \quad (4)$$

Where, air gap flux per pole,

$$\phi = B_{av} \times \frac{\pi DL}{P} \quad (5)$$

Sectional area of conductor,

$$a_s = \frac{I_s}{\delta_s} \quad (6)$$

Flux density in stator teeth at gap surface,

$$B_t = \frac{\phi}{b_t \times L_{ic} \times N_t} \quad (7)$$

Thus, width of the teeth,

$$b_t = \frac{\phi}{B_t \times L_{ic} \times N_t} \quad (8)$$

Width of the slot,

$$b_s = \tau_s - b_t \quad (9)$$

Mean length of stator turn,

$$l_{mt} = (2L + 2.5\, \tau_p + 0.05 \times kV + 0.15)\ m \quad (10)$$

Resistance of stator winding,

$$R_s = \frac{\rho\, l_{mt} T_{ph}}{a_s} \quad (11)$$

Average loss factor,

$$K_{dav} = 1 + (\propto h_c)^4 \frac{m^2}{9} \quad (12)$$

$$\propto = \sqrt{\frac{\text{copper width in the slot}}{\text{slot width}}} \quad (13)$$

Eddy current loss = $(K_{av}-1) \times$ Copper losses (14)

Resistance drop,

$$IR = I_{ph} \times R_s \times \text{Average loss factor} \quad (15)$$

Total leakage flux,

$$\phi_L = \phi_s + \phi_0 \quad (16)$$

Slot leakage flux,

$$\phi_s = 2\sqrt{2}\mu_0 I_{ph} T_c L_s \lambda_s$$

Over hang leakage flux,

$$\phi_s = 2\sqrt{2}\mu_0 I_{ph} T_0 L_0 \lambda_0 \quad (17)$$

Flux density in stator core,

$$B_c = \frac{0.5\phi}{A_c} \quad (18)$$

Sectional area of stator core,

$$A_c = d_c \times L_i \quad (19)$$

Thus, depth of stator core,

$$d_c = \frac{\phi}{2 B_c L_{ic}} \quad (20)$$

Outer diameter of stator core,

$$D_o = D + 2(d_c + h_c) \quad (21)$$

B. Design of Field System

Length of the air gap,

$$L_{gs} = \frac{l_g}{\cos\left(\frac{\pi x}{\tau_p}\right)} \quad (22)$$

Sectional area of pole body, $A_p = \frac{\phi_p}{B_p}$

For rectangular pole:

Cross-sectional area of pole body, $A_p = 0.95\, L_p\, b_p$

0.95 has been taken as the stacking factor.

Width of the pole body,

$$b_p = \frac{A_p}{0.95 L_p} \quad (23)$$

Armature ampere turns per pole,

$$AT_a = \frac{1.35\, I_{ph} T_{ph} K_w}{P} \quad (24)$$

Full load field ampere turns,

$$AT_f = (1.7 \text{ to } 2)\, AT_a \quad (25)$$

Copper losses per coil = $(I_f)^2 R_f$

$$= (I_f)^2 \left[\frac{\rho L_{msf} T_f}{a_f}\right] \text{watts} \quad (26)$$

Total copper areas in the field coil = $a_f\, T_f$

$$= (d_f \times h_f)\, S_f \quad (27)$$

Flux in core section,

$$\phi_y = \frac{1}{2}\phi \quad (28)$$

Flux density in the core may be assumed varying from 1.0 to 1.2 Tesla.

Cross-section area of core,

$$A_c = \frac{\phi_c}{B_c} \quad (29)$$

Thus, depth of core,

$$d_c = \frac{A_c}{L_c} \quad (30)$$

Total ampere turns for gap,

$$AT_g = 0.796\, B_g\, K_g\, l_g \times 10^6 \quad (31)$$

Total ampere turns for the teeth,

$$AT_t = H_t \times h_s \quad (32)$$

Ampere turns for core,

$$AT_c = H_c \times L_c \quad (33)$$

Total ampere turns for rotor core = $H_y \times l_y$ (34)

Voltage per field coil, $V_c = \frac{(0.8 \text{ to } 0.85) \text{ exciter voltage}}{(\text{number of field coils})}$ (35)

Number of field coils will be equal to the number of poles.

Mean length of turn of field coil,

$$l_{mtf} = 2(l_p + b_p) + \pi(d_f + 2t_i) \quad (36)$$

Resistance of field coil,

$$R_f = \frac{\rho l_{mtf} T_f}{a_f} \quad (37)$$

Sectional area of field conductor,

$$a_f = \frac{\rho l_{mtf} T_f}{V_c} \quad (38)$$

Number of turns in field winding,

$$T_f = \frac{\text{Full load field ampere turns}}{\text{Field currents}} \quad (39)$$

Resistance of the field winding,

$$R_f = \frac{\rho l_{mtf} T_f}{a_f} \quad \textbf{(40)}$$

Copper losses = $(I_f)^2 R_f$ **(41)**

C. Design of Three-Phase Synchronous Generator

Design a 20 MVA, 11 kV, 3000 r.p.m, 50 Hz, star connected non-salient pole type, three-phase turbo-alternator, giving the complete information about its various parts and satisfying the design with respect to performance. Suitable and justified assumptions may be made for various design data. The design data sheet of this generator is shown in Table III.

VI. CONCLUSION

This paper was intended for three-phase synchronous generator design for dry steam geothermal power plant. In this design, 16 MW synchronous generators are considered. The selection of synchronous generator for a geothermal scheme is considered by turbine speed, drive system, power rating and environmental aspects. To control the speed of turbine, governors are used. The design should be carried out based on the given specification, using available materials economically.

TABLE III: Design Data Sheet of 20 MVA Turbo-Alternator

Specification	Symbol	Unit	Value
Full load output	Q	kVA	20000
Line voltage	V	kV	11
Phase	-	-	3
Frequency	f	Hz	50
Pole	-	-	2
Speed	N_s	r.p.m	3000
Turbine	-	-	High
			speed
MAIN DIMENSIONS			steam
Internal diameter of stator	D	m	
Output coefficient	K′	-	0.8
Gross length of stator core	L	m	260
Pole pitch	τ_p	m	2.4
			1.256
STATOR WINDING			
Flux per pole	Ø	Wb	
Turns per phase	T_{ph}	-	1.63
Total stator slot	s	slot	18
Conductor per slot	-	conds/slot	36
Slot length	L_s	cm	3
Slot pitch	τ_s	cm	215
Stator conductor section	a_s	mm^2	6.98
With of the slot	b_s	cm	328
Depth of the slot	h_s	cm	3.9
Resistance of stator per	R_{ph}	ohm	8.65
phase	W_{Cu}	kW	0.0105
Copper losses in stator	W_{eddy}	kW	36.6
winding	W_{stray}	kW	10.9
Eddy current losses in	W_{stator}	kW	7.125
conductors	W_{st_teeth}	kW	54.625
Stray load losses	W_{st_core}	kW	35.4
Total losses of stator	-	p.u	369
winding	$\phi_{leakage}$	Wb	0.00225
Iron losses in the stator	D_0	m	0.10143
teeth	SCR	-	1.873
Iron losses in stator core	v	m/sec	0.75
Effective resistance	L_g	mm	120
Total leakage flux			1.85
Outer diameter of stator			
core	D_r	cm	
Short circuit ratio	a_f	mm^2	76.3
Peripheral speed	R_f	Ω	84
Air gap length	I_f	Amps	0.41
	T_f	Turn/pole	219
FIELD SYSTEM			224
Rotor diameter			
Sectional area of field	$W_{fld\text{-}cu}$	kW	
conductor	-	kW	79.1
Resistance of field	-	kW	10.786
winding	W_{iron}	kW	160
Field current	W_{total}	kW	404.4
Field turns per pole	η	percent	708.911
	-	˚C	95.75
PERFORMANCE			44
ANALYSIS			
Rotor copper losses			
Exciter losses			
Friction and windage			
losses			
Total iron losses			
Total full load losses			
Efficiency			
Stator temperature-rise			

VII. ACKNOWLEDGMENT

The author wishes to express her deepest gratitude to her teachers, Department of Electrical Power Engineering, Mandalay Technological University. Similar thanks to all for their instructions and willingness to share their ideas throughout all those years of study.

VIII. REFERENCES

[1] Marco Baresi, Ruggero Bertani, “Geothermal Electricity”, European Technology Platform, Philippe Dumas – European Geothermal Energy Council, EU, (2012).

[2] Sulzer, “Cost-efficient Pumping Solutions for Geothermal Power Plants”, Sulzer Pumps for Geothermal Power Generation, (2011).

[3] D.H.M. Janse, “Combining Geothermal Energy with CO_2 Storage”, Master thesis, Intermediate Report, Sustainable Development, Track Energy and Resources, Utrecht University, (2010).

[4] Ethan Goffman, “Geothermal Energy: Drilling Beneath the Surfaceof Energy Dilemma”, Discovery Guide, ProQuest, (2009).

[5] Alyssa Kagel, “The State of Geothermal Technology”, Part II: Surface Technology, A Publication by the

Geothermal Energy Association for the U.S., Washington, D.C., January (2008).
[6] John W. Lund, “100 Years of Geothermal Power Productions”, Geo-Heat Center, (2004).
[7] Mike Long, P. E., Bill Lewis, P. E., Marshall Ralph, “Geothermal Power Production”, Power Engineers, Hailey, USA, (2004).
[8] Dr. Ronald Dipoppo, “Small Geothermal Power Plants”, University of Massachusetts Dartmouth, USA, (1999).
[9] Agarwal, R. K., “Principles of Electrical Machine Design”, (1999).
[10] Dr. Mittle V.N. and Atvind Mittle, “Design of Electrical Machines”, Standard Publishers Distributors, (1998).
[11] Deshpande, M.V., “Design and Testing of Electrical Machines”, Wheeler publishing, (1983).
[12] Say, M.G. “Performance and Design of Alternating Current Machines”, Pitman and Sons, Ltd., 3rd Edition, University of London, (1976).