THERMAL ANALYSIS OF
AIR COOLED SYNCHRONOUS GENERATOR

Jehan Shazly

Department of Electrical Engineering, Fayoum University, Egypt (e-mail: jehanshazly2001@gmail)

Mohammed S. Sediek

A student research with the Department of Electrical Engineering, Fayoum University, Egypt (e-mail: eng.ms1987@gmail.com).

Magdy B. Eteiba

Department of Electrical Engineering, Fayoum University, Egypt (e-mail: eteiba@yahoo.ca)

Abstract: This paper describes a study of the steady state and transient temperature rise of Siemens air cooled synchronous generator, which is driven by gas turbine, whose rated power 313 MVA at 3000 rpm. The modeling technique is the finite-element method. The temperature rise is mainly due to power losses, which are used as input data of thermal analysis to predict the temperature distributions. All considerable parameters that influence synchronous generator operation have been involved. The numerical solutions, which are obtained from thermal model, are compared with actual measurements that obtained from kureimat station in Egypt, and with Siemens test report.

Key words: Air cooled synchronous generator, heat conduction equation, finite-element method, convection and radiation.

1. Introduction

Three phase synchronous generators are the primary source of all the electrical energy we consume. The heating of the stator and field windings of a synchronous generator is the most significant limit in its operation [1]. The capability curve is used to prevent overloading by limiting the synchronous generator operation. The capability curve depends on factors; from these factors is the temperature that, the generator capability curve expresses the stator and rotor heat limit and any external limits of the generator. Therefore, large generator designs need a cooling medium that has good heat transfer properties and low windage and friction characteristics [2].

The power level, at which the heating limit usually occurs, is much lower than the maximum power that the generator is mechanically and magnetically able to supply. So, large synchronous generator has been realized by most of researcher and engineers. In general, a typical synchronous generator can supply up to 300 % of its rated power until its windings burn up. Therefore, the thermal analysis of turbo-generator is important [3].

The proposed model involves figuration and solution of the heat conduction equation of a two

dimensional mathematical thermal model to study steady-state and transient thermal performance inside a 3-phase air cooled synchronous generator using the finite-element technique.

Boundary conditions in the heat transfer process such as the convective and radiative heat transfers are prevailing in the present study. Different loading, ambient temperature, and cooling conditions have also been considered. The Finite Element Method (FEM) is used in analysis because it is a powerful computational technique for approximate solutions to a variety of "real-world" engineering problems having complex domains subjected to general boundary conditions. Finite element analysis has become an essential step in the design or modeling of a physical phenomenon in various engineering disciplines [4]. The numerical simulation of the heat transfer analysis was implemented using ANSYS 14, which is a finite-element method based software package for heat transfer problems.

2. Generator

The air cooled synchronous generator consists of [3]:

A. Stator that consists of: *1)* stator core: it is stacked with insulated electrical sheet-steel laminations (0.65 mm) having high silicon content, *2)* stator winding: It is a fractional-pitch duplex lap type copper conductor consisting of individual bars are located in slots of rectangular cross section which is uniformly distributed on circumference of the stator core. Bars are insulated with braided glass fiber insulation.

B. The rotor that consists of : *1)* Shaft; it is forged from vacuum cast steel ingot; *2)* rotor winding: ,silver–alloyed copper are insulated with of glass fiber layers.

C. Air cooler system; The cooling air is circulated in the generator interior in a closed circuit by the two fans and re-cooled in a single cooler sections arranged on the side of the generator.

D. Housing frame, the structure of the generator is

shown in Fig. 1.

Because of the complication of the theoretical thermal model of Siemens air cooled synchronous generator that developed here, the following propositions are taken into considerations:
- The three-dimensional problem is reduced to a two-dimensional, with acceptable accuracy. The upper half of the synchronous generator will be considered during this study due to the reflective symmetry, to reduce the calculation time, as illustrated in Fig. 2.
- The cooling air distribution inside the generator is uniform.
- The velocity of air gas inside the generator is circulated at constant speed.
- The winding insulation is taken into account, The rate of heat generated per unit volume of the iron core is uniformly distributed in it.
- The rate of heat generated per unit volume of the copper coils is uniformly distributed in it.
Measured values of ambient temperature are considered.
- The thermo-physical properties of air, generator components material are temperature dependent and found in [5].
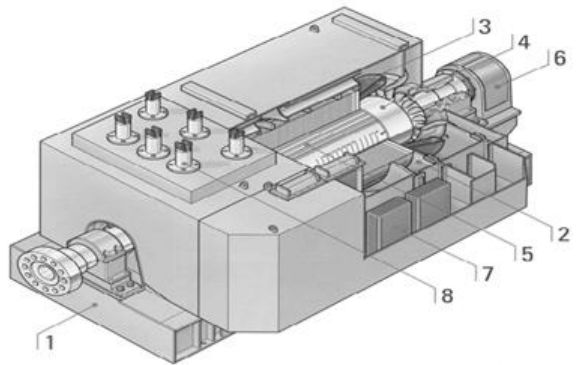
1-Base Frame, 2-Stator Core, 3-Stator Winding, 4-Rotor Shaft, 5-Rotor Winding, 6-Exciter, 7-Air Cooler, 8-Connections

Fig. 1. The structure of Three-dimensional Siemens synchronous generator.

Siemens air cooled synchronous generator machine data and properties are summarized in Table 1.

3. Heat Flow

The differential equation governing the heat conduction for heat transfer of two-dimensional model is:

$$\frac{d}{dx}\left(K\frac{dT}{dX}\right) + \frac{d}{dy}\left(K\frac{dT}{dY}\right) + q^o = \rho C \frac{dT}{dT} \qquad (1)$$

Where T is temperature in (K), x and y are locative variables in (m), K is the thermal conductivity in (W/m.K). q^o is the losses per volume in (W/m^3). C is the specific heat in (J/kg.K), and t is the time in (s) [6], [7].

Table 1. Generator Data

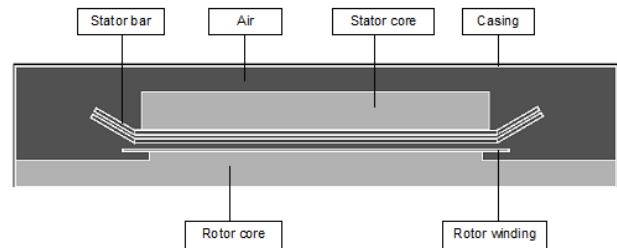| SIEMENS		
Generator	M11152	2006
TLR1 115/52	50s⁻¹	right
3 ~ YY	U$_1$V$_1$W$_1$	
16500V ± 5%	10952A	S1
313000kVA	cos φ = 0.85	
Static exciter	417V	1356A
Thermal class : F	IM7325	IP54
Air cooling	Cold air temp. : 32°C	
Stator transport weight : 240 Mg	IEC 34 /	
Rotor transport weight : 58.7 Mg	VDE 0530	

Fig. 2. The upper half-symmetrical (2-D) of air-cooled synchronous generator.

When different parts of a rigid body are at different temperatures, heat flows from the hotter parts to the cooler ones. There are three distinct methods by which this transference of heat takes place: conduction, in which heat passes through the substance of the body itself; convection, which heat is transferred by relative motion of portions of the heated body, and radiation, when heat is transferred directly between distant portions of the body by electromagnetic radiation [8], [9].

All mechanical and electrical losses occurring are converted into heat thus transferred to the surrounding air. Heat transfer begins from the inner of the core and the windings and spread to their external surfaces by conduction, subsequently the transfer of heat from the surface of the windings and the core to the gas by forced convection. A thermal radiation between the windings surface, the core surface and the inner surface of the housing is taken place. Then the heat is dissipated by convection from the gas to the water heat exchanger and from the gas to the inner generator's housing. The transmission of heat energy through the thickness of the generator housing is by conduction. Consequently, the dissipation of heat from the external generator housing to the surrounding air

occurs by convection and heat radiation. Fig. 3 represents the heat flow in the air cooled synchronous generator.
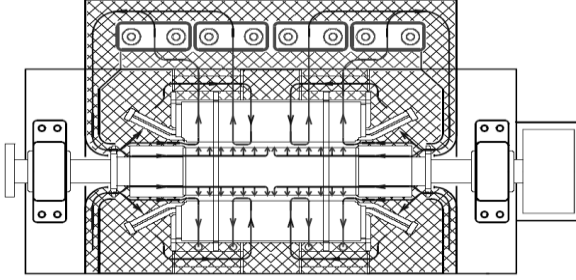

Fig. 3. Heat flow in the air-cooled synchronous generator.

4. Losses

The output of a generator is always less than the input because some of the energy supplied is lost as heat. These losses raise the temperatures of machine parts. The losses of the air cooled synchronous generator are classified as electrical and mechanical losses. The electrical losses consist of the winding losses (which include the stator copper losses and field losses), and the iron core losses. The mechanical losses consist of the windage and bearing friction losses [10].

The rate of heat generated per unit volume of each component of the generator is:

$$q° = \frac{q\ (W)}{Volume\ of\ each\ component\ (m^3)} \qquad (2)$$

Where q is the loss of each component in (W) and $q°$ is the heat transfer rate per unit volume in (W/m³).

The losses components of the air cooled synchronous generator could be concise as:

4.1 Winding Losses

It is the energy loss in the windings when the synchronous generator is loaded. It contains stator copper losses (short circuit losses) and field losses (excitation losses).

4.1.1 Stator Copper Losses in (W)

The copper losses are not constant, but vary as the square of the load current [3].

$$q = 3\ (R_S)_{dc}.K_R.I_1^2 \qquad (3)$$

Where:
R_s: Stator winding resistance, (Ω).
I: Stator winding current, (A).
K_R: Skin effect coefficient, dimensionless.

4.1.2 Field Losses

The excitation losses in (W) have Field winding DC losses [3]:

$$q = 1.294R_f.I_f^2 \qquad (4)$$

Where:
R_f: Field winding resistance, (Ω).
I_f: Field winding current, (A).

4.2 Core Losses

The core loss is obtained from the hysteresis and eddy current losses. The core loss is the difference in power input required to drive the alternator at synchronous speed with the rotor excited at no-load (open circuit test) with the rotor excited [3].

4.3 Mechanical Losses

These losses are proportional to speed, and since an alternator operates at synchronous speed, these losses are constant and got from the no-load test by measuring the input power required to drive the alternator with the rotor field unexcited [3].

All the losses of the synchronous generator are converted into heat rises the temperature of the insulation and machine parts. If this converted heat is not removed, then the machine gets overheated and insulation is damaged. In order to keep the temperature rise of the various parts of the generator and winding insulation from exceeding the respective maximum permissible value, every generator requires continuous cooling during its operation.

5. Termination of Coefficient of Heat Transfer

Boundary conditions can play an important function in the heat transfer process. In the present investigation, the convective and radiative heat transfers are completely involved.

5.1 Convective Heat Transfer

Convection is the dominant form of heat transfer in liquids and gases from a solid or the reverse. Movement of a fluid could be forced by means other than bouncy forces.

In the present air cooled synchronous generator model, heat is transferred by forced convection inside the synchronous generator because the cooling air is circulated in the generator interior in a closed circuit by the two fans and re-cooled in single cooler sections [3]. However, it is by bouncy from the external surfaces of the synchronous generator housing to the surrounding air by natural convection. The term convection refers to heat transfer that will occur between a surface and a moving fluid when they are at different temperatures. The mathematical formulation of this convection boundary condition is achieved by considering an energy balance at the surface stated as [6]:

$$-\left(K\frac{dT}{dX}\right) - (K\frac{dT}{dy}) = h(T - T_B) \qquad (5)$$

Where h is the convective heat transfer coefficient in (W/m^2.K), and it can be determined by classical Nusselt number correlation's as [11], [12].

$$h = \frac{K}{L}N_u \qquad (6)$$

Where K is the thermal conductivity, L is the characteristic length in (m), Nu is Nusslet number (dimensionless).

5.1.1 Forced Convection
Heat transfer by forced connection is considered when an external mean imposed the fluid motion. The following relation for evaluation Nusslet number for forced convection is [8], [9]:

$$Nu = 0.0296Re^{4/5}.Pr^{1/3} \qquad (7)$$

The dimensionless parameters of forced and natural convection as Reynolds number, Prandtl number, and Grasshof number are presented in [8], [12]. All physical properties are evaluated according to [8].

Reynolds number (Re), is the ratio of the inertia to viscous forces, and is used to characterize boundary layer flows.

$$Re = \frac{\rho UL}{\gamma} \qquad (8)$$

Where ρ is the density in (kg/m^3), U is the fluid velocity, L is the characteristic length in (m), and ν is the dynamic viscosity in (kg/m.s) .

Prandl number: Pr, is a transport property of the fluid and provides a measure of the relative effectiveness of momentum and energy transport in the hydrodynamic and thermal boundary layers, respectively [8], [11].

$$Pr = \frac{C\gamma}{K} \qquad (9)$$

Where C is the specific heat (J/kg.K), ν is the dynamic viscosity in (kg/m.s), and K is the thermal conductivity in (W/m/K).

5.1.2 Natural Convection
The fluid motion sets up as a result of the bouncy force. A suitable choice should be consistent with the physical reality. The recommended empirical correlation of free convection for laminar and turbulent flow is [8], [9]:

$$Nu = 0.14 \, (Gr.Pr)^{1/3} \qquad (10)$$

The dimensionless parameter of Grasshof number is [8]:

$$Gr = \frac{g\beta\rho^2(T-T_B)L^3}{\gamma^2} \qquad (11)$$

Where g is the gravity acceleration, β is the coefficient of thermal expansion (K^{-1}), and T_B is the bulk temperature (K).

5.2 Radiation Boundary Convection
Radiation is the transmission of the energy by the electromagnetic wave. The radiation effect generally appears in the heat transfer analysis only through the boundary conditions. In this model of the air cooled synchronous generator, two types of enclosure surfaces are concerned in the radiation process. An open type enclosure surface radiates heat between the outer surfaces of the synchronous generator housing and the surrounding air with predetermined ambient temperature. In addition, a closed type enclosure inside the synchronous generator is taken into account, which is a thermal radiation between the windings surface, the core surface and the inner surface of the generator housing. Each radiating surface is described by an emissivity value and a direction of radiation assigned to it.

The mathematical formulation of this radiation boundary condition is obtained by considering an energy balance at the surface[8], [11].

$$-K\frac{dT}{dX} - K\frac{dT}{dY} = \epsilon\sigma F_{1-2}(T_1^4 - T_2^4) \qquad (12)$$

Where σ is Stefan-Boltzman constant. ϵ is the infrared emissivity. The view factor F_{1-2} is defined as the proportion of the radiation which leaves surface A_1 that strikes surface A_2. The view factor is presented in [8], [11].

6. The Calculated Results and Analysis
The thermal model was verified using ANSYS 14; finite-element analysis program and results (nodal temperatures) are obtained from the thermal analysis. The accuracy of numerical results was verified by comparing the computed results with the measured values that recorded in power plant (kureimat station in Egypt), and with Siemens test report [3]. This mentioned the slot temperatures are measured with resistance temperature detectors, which are embedded directly in the stator slots between the bottom and top bars at points where the highest temperatures are expected.

6.1 Steady State Performance
When the boundary conditions and body loads do not vary with time and there are no specified initial conditions, steady-state solutions are obtained by calculating the effects of steady thermal loads on a system. The accuracy of the developed mathematical

thermal model of the synchronous generator [Siemens type (TLRI 115/52), three phase, 313 MVA, 16.5 KV, 50 Hz, and air Cooling)], is tested by comparing the computed results with the measured values that recorded in power plant (kureimat station in Egypt) at loads; 75% load (235 MVA), 54% load (170 MVA), and with Siemens test report [3]. Systematic studies were carried out to investigate the influence of varying the fluid insulation types.

6.1.1 Analysis Study at 75% of Full Load

The presented model is verified for the air cooled synchronous generator of Siemens type at (235 MVA) 75% of the continuous rating, at ambient temperature 36 °C, and ambient air pressure 0.1 MPa. Fig. 4. Shows the contour plot for nodal temperature distribution of the air-cooled synchronous generator under previous mentioned conditions. It can be noticed that the hottest spot temperature, located at the bottom center of the generator stator bar is 98.71 °C. That is due to the fact of the rate of heat generated per unit volume of the stator core is concentrated in this inner region. The measured value of the highest stator bar temperature is 97.56 °C, which highlights a satisfactory agreement between the calculated and the measured values, and with Siemens test report. It mentions that the slot temperatures are measured with resistance temperature detectors, which are embedded directly in the stator slots between the bottom and top bars at points where the highest temperatures are expected [3].

The predicted results of the stator core temperatures, the stator bar temperatures, the average gas temperature (air between the stator core and the generator casing), the rotor winding temperatures, the rotor core temperatures, and the casing temperatures versus the width cross section which passes through the center of each component of the synchronous generator components, are shown in Fig. 5. It can be seen that the average difference between the evaluated stator core temperatures is less than the average stator bar temperatures with 0.7 °C. The maximum temperature of the rotor winding is 84.57 °C and more than the max rotor core temperature by 0.5 °C. Generally, the temperature values of stator core and rotor core are maximum near to stator bar and rotor bar respectively, and it has lower temperature values near the casing.

Fig. 6 illustrates the temperature distributions of the synchronous generator components versus the height (longitude cross-section) which passes the center of the generator where the hot spot temperature is located too. It can be found that the air insulation temperatures are high around the core and low near to the generator casing, because there is higher heat dissipation from the upper surface of the stator core through the air insulation and the

generator surface to the surrounding air. The maximum temperatures of the stator bar is 98.71 °C , the stator core is 98 °C, the rotor winding is 84.57 °C, and the rotor core is 84.1 °C.
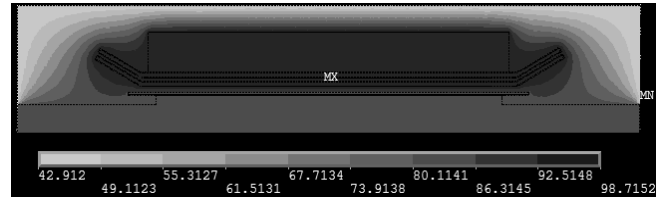

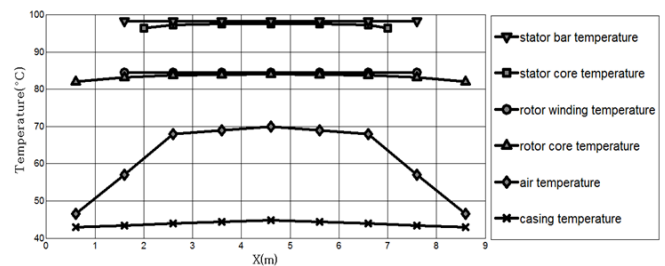Fig. 4. Predicted temperature distribution at 235 MVA (75% of full load).

Fig. 5. Variation of predicted temperatures at 235 MVA versus the width cross section (through the center of each component) of the generator components.
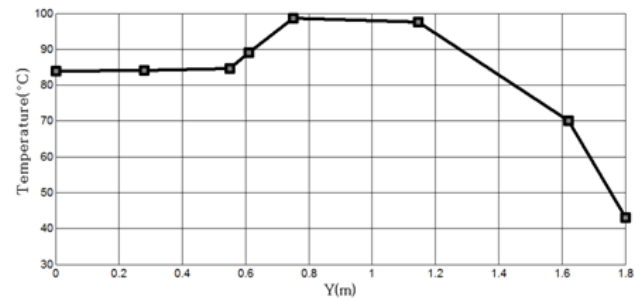

Fig. 6. Variation of predicted temperatures at 235 MVA versus the height (longitude cross-section), passing the center of the generator.

6.1.2 Analysis Study at 54% of Full Load

In order to check the accuracy of the computed results, they are compared with the measured results reported in the manufacturer manual for the air cooled synchronous generator loading at (170 MVA) 54% of the continuous rating, at ambient temperature 22 °C, and ambient air pressure 0.1 MPa. The recorded value of the highest stator bar temperature is 75.96 °C. The calculated hottest spot temperature, located at the bottom center of the generator stator bar is 77 °C as presented in the numerical solution of nodal temperature distribution of Fig. 7. A good agreement has been occurred between the recorded and predicted values. The max temperature of the stator bar is 77 °C, the stator core maximum temperature is 76.35 °C, the rotor winding

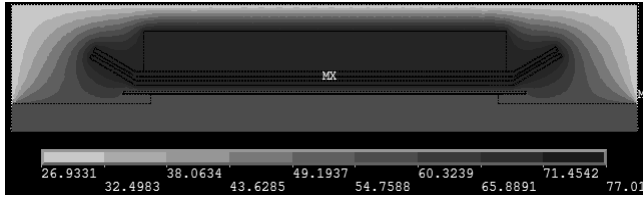maximum temperature is 58.93 °C, and maximum temperature of the rotor core is 58.4 °C.

Fig. 7. Predicted temperature distribution at 170 MVA (54% of full load).

Fig. 8 represents a comparison between the two previous cases of 75% of full load, and 54% of its rating load of the temperature distributions of the synchronous generator components versus the height (longitude cross-section), which passes the center of the hot spot temperature is located.
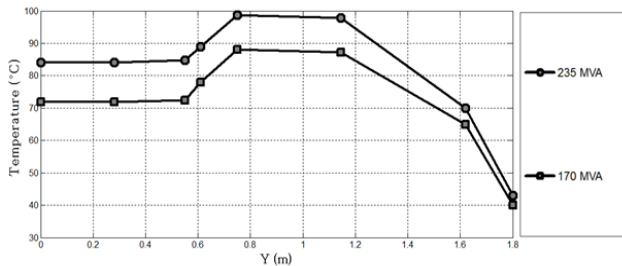

Fig. 8. Comparison between variation of predicted temperatures at 235 MVA and 170 MVA versus the height (longitude cross-section).

It can be seen that, the decrease of load and ambient temperature causes a decrease of temperatures distributed inside the synchronous generator. An appreciable decrease in all components temperatures except the lower part of the upper half-symmetrical of the synchronous generator was recognized. That is due to the generator surface is closely linked to the ambient temperature, and the most heated part is concentrated in the center of the generator too.

6.1.3 Different Cooling Fluid

To retain the temperature rise of the different parts of the generator from overtaking the maximum allowable amount, every generator requires continuous cooling during its operation. The efficiency of cooling depends up on the cooling medium type that has different physical properties. The developed thermal model was carried out to investigate the influence of varying cooling medium such as hydrogen, air and Carbon dioxide to predict the temperature distribution of the synchronous generator, for loading at 235 MVA (75% of continuous rating) at 36°C ambient temperature.
Fig. 9 presents the temperature distributions of the

synchronous generator components versus the height (longitude cross-section) which passes the center of the hot spot temperature is located, for hydrogen, air and Carbon dioxide. It could be observed that hydrogen achieves the best temperature distribution inside the generator than air and carbon dioxide. Although, Air is used in cooling large synchronous generator because air is available but hydrogen needs generation unit to get it. In addition to this, air cooled synchronous generator has simple construction than that using hydrogen, and using air as cooling medium is safety than using hydrogen [2].
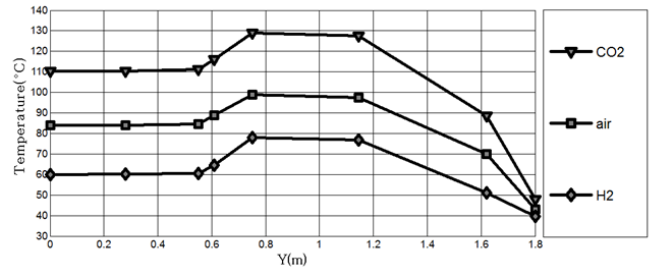

Fig. 9. Variation of predicted temperatures at different cooling fluid versus the height (longitude cross-section).

6.2 Transient Performance

In order to determine the transient performance of a synchronous generator, a procedure to evaluate temperature changes with time of the various synchronous generator components is required. The transient temperature values under variable loading may be obtained by dividing the loading curve into a sufficient number of time intervals. The finite element thermal model described earlier [3] is applied to determine the response of a generator to a change in current loading. This response depends on the combination of heat sources or sinks within the generator and the heat stored during the transient by the constituent parts of the generator itself and its surroundings. A steady-state solution at all nodes inside the generator is needed in order to set the initial conditions.

The precision of the thermal model is validated by comparing the computed temperatures of the air-cooled synchronous generator with the measured temperatures that recorded at kureimat station in Egypt. The synchronous generator under consideration is subjected to a daily load diagram illustrated in Fig. 10. The ambient temperature changes as presented in Fig. 11, over a period of twenty-four hour period, which actually recorded in power plant (kureimat power station in Egypt). The thermal model developed is capable of estimating the synchronous generator component temperatures at any specified location within it.

For this purpose, a vertical line is drawn passing through the center of the stator slots between the bottom and top bars at points where the highest

temperatures are expected, as mentioned in Siemens test report [3], and it is passing through the other synchronous generator components too, as shown in Fig. 12.
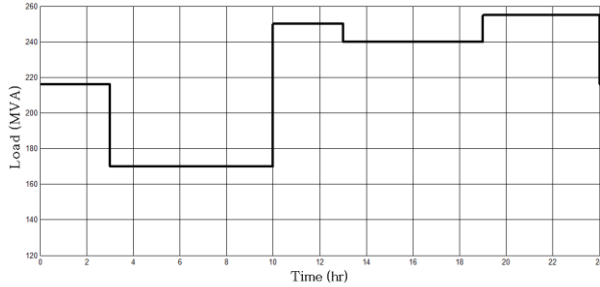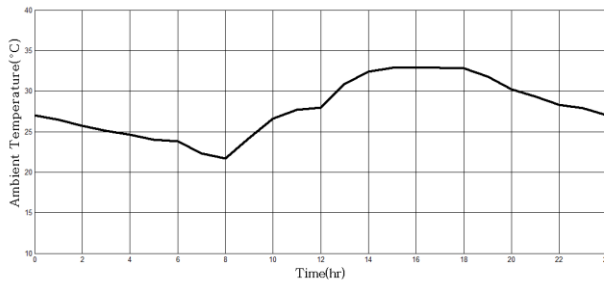

Fig. 10. Load allocation over 24 hours.

Fig. 11. Time change of ambient temperatures.

The accuracy of the thermal model is reinforced by evaluating the hottest stator slot temperature (between top and bottom stator bar) over 24 hour period. Fig . 13 illustrates a comparison between the estimated and measured values of the hottest stator slot temperature. It can be seen that there is a good agreement between the estimated and measured values using the evolved model.

During the first three hours, the generator load is (216MVA, 69% of full load), an appreciable decrease of the stator temperature was recognized because the temperature decreases at this period. The maximum difference in temperatures is (5°C) between the actual temperature (84°C) and the calculated temperature (79°C).

Through the following seven hours, the load was reduced to (170 MVA) and the ambient temperatures decreases until 8 am then increases, the stator temperatures are affected with the varying in ambient temperatures. And the maximum difference between the evaluated (93.8°C) and the measured (88°C) slot temperature is (5.8°C).

The load over the rest of the investigated 24 hour period was increased and changed between 250 MVA and 240 MVA. Consequently, the hottest stator slot temperature is increased due to the increasing of rate of heat generated per unit volume of the stator copper.

It is shown that from fig. 14, the temperature distribution of stator and rotor winding, stator core, rotor core, air temperature, and casing temperature are responding to the change of the generator load and the ambient temperatures. An appreciable increase in all generator components temperature was recognized when the load and the ambient temperature increases and vise versa. That may be attributed to the thermal properties of the generator, which are affected by the environmental conditions. When the load increases, the increase in temperature values, are occurred due to the increase in the heat generated per unit volume per unit time of both the core and the windings.
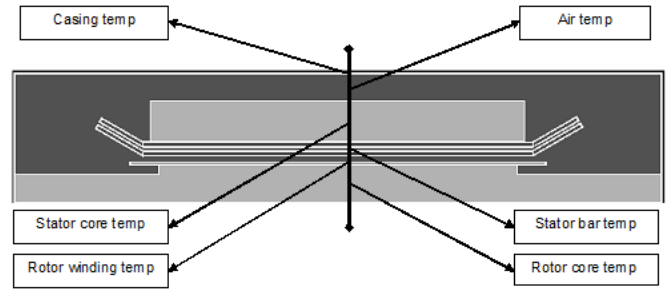

Fig.12. locations of the calculated temperatures during transient.
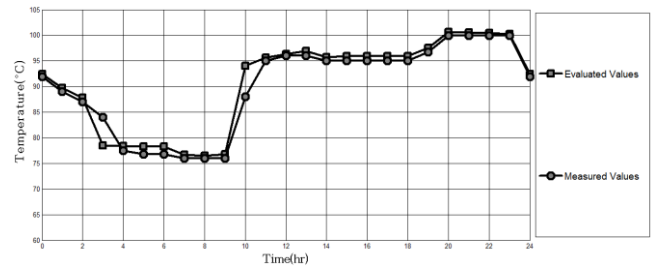

Fig.13. Comparison between evaluated and measured hottest stator slot temperature.
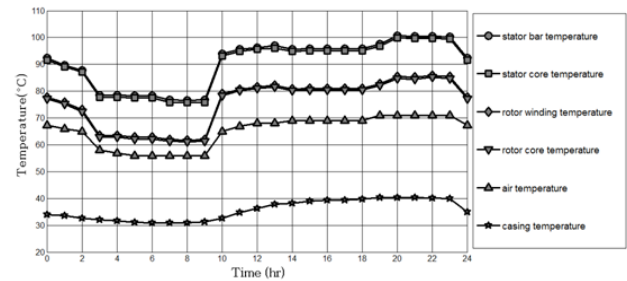

Fig. 14. Time change of evaluated generator temperatures.

7. Conclusion

Air-cooled synchronous generator is simulated in this paper, involving Finite element method. To determine its thermal performance at steady state and transient, include variations in boundary conditions. When comparing between the measured

and the calculated temperatures of the synchronous generator components using the developed thermal model, it could be noticed that there is a satisfactory coincidences between them. The methodology introduced in this paper, if implemented at the design stage, may provide great services.

References

[1] S.j.Chapman, Electric Machinery Fundamentals. 2nd ed. McGraw-Hill, New Yorrk,1991.

[2] Geoff Klempner, Isidor Kerszenbaum, Operation and Maintenance of Large Turbo-Generators. Canada: John Wiley & Sons, Inc., Hoboken, New Jersey, Hoboken, New Jersey, 2004.

[3] Manual manufacturer, Technical Documentation for Operating and Maintenance of Siemens Turbo Generator, July 2006.

[4] Erdogan Madenci,Ibrahim Guven, The Finite Element Method And Applications in Engineering Using ANSYS®. New York: Springer Science Business Media, LLC, 2006.

[5] John H. Lienhard IV, John H. Lienhard V, A heat transfer textbook. Third Edition. Cambridge, Massachusetts, U.S.A: Phlogiston Press, 2005.

[6] Magdy B. Eteiba, Mohamed Mamdouh Abdel Aziz, and Jehan Hassan Shazly, "*Heat Conduction Problems in SF_6 Gas Cooled-Insulated Power Transformers Solved by the Finite Element Method*", IEEE, Trans. On Power Delivery, Vol. 23, No. 28, pp. 1457-1463, July 2008.

[7] Li Junqing, and Baoding, "*A thermal model for the water-cooled stator bars of the synchronous generator*", IEEE, Xplore, on Power System Technology, 2002. Proceedings. PowerCon 2002, Vol.2, P. 756-760.

[8] Peter von Böckh, Thomas Wetzel, Heat Transfer (Basics and Practice). Berlin, Heidelberg, New York: Springer, 2012.

[9] Lihui Wang, Dynamic Thermal Analysis of Machines in Running State.London: Springer, 2014.

[10] Ion Boldea, The electrical generators hand book. Boca Raton: CRC Press, Taylor & Francis Group, 2007.

[11] M. N. Ozisik*, Heat Transfer a Basic Approach*. NewYOrk: McGraw- Hill, 1985.

[12] Hou Yunpeng, Li Weili, Zhou Feng, and Cheng Shukang, " *Analyais and calculation of stator windings end part temperature field for large synchronous generator*", IEEE Xplore, on Electrical Machines and Systems, 2001. ICEMS 2001, Vol.2, P. 1145-1148.