POWER SYSTEM STABILITY IMPROVEMENT WITH GEOTHERMAL AS MAJOR SOURCE OF POWER IN KENYA

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ABSTRACT

In recent years, predictions of increasing global climate change have sparked interest in the use of geothermal energy in countries where the resource is abundant. In Kenya, 766.6 MW (46.2%) of installed power generation in 2013 is hydropower and the geothermal energy is 250.2 MW (14.2%). Kenya’s installed generation capacity is projected to increase to about 14,676 MW by 2030 basing on the reference scenario. The intention is to diversify the base-load from hydro to other sources of energy mainly geothermal. The expected power supply from various sources by 2030 is projected to be: geothermal 5,450.00 (37.13) hydro 3,000MW (20.44%), diesel 500 MW (3.40 %), natural gas 1,500 MW (10.22%), and other sources will account for 12.32%. Thus, geothermal energy will be a major source of electrical energy in Kenya. In this regard, the country plans to develop her geothermal resources and subsequently build numerous geothermal plants in coming years thus increasing the proportion of geothermal energy of the total generated capacity. This paper aimed at carrying out analysis of the effects on power system stability due to increased integration of geothermal power in the Kenya by looking at the inertia of geothermal power plants with other main plants mainly hydro. The analysis is motivated by the large number of GPPs to be integrated to the system, geothermal resources being in volcanic area and uncontrolled load connectivity. As large numbers of geothermal power plants are connected into the Kenyan power system, the impact and effects on system stability/reliability need to be interrogated.

1. INTRODUCTION

Geothermal energy resources are abundant in Kenya. They are located within the Rift Valley with an estimated potential of between 7,000 MWe to 10,000 MWe spread over 14 prospective sites. When an increasing number of geothermal power plants are connected to the Kenyan power system, their effect on the power system is put to perspective as critical issues come up for transmission operators and power system engineers to deal with. Key among these issues is transient stability. The study of interconnection of several synchronous generators for GPPs and other power plants is important because of the power system stability, load demand variations and economic reasons.

1.1 Geothermal Power Plants

1.1.1 Direct Dry Steam

Steam plants use hydrothermal fluids that are primarily steam. The steam goes directly to a turbine, which drives a generator that produces electricity. The steam eliminates the need to burn fossil fuels to run the turbine. This is the oldest type of geothermal power plant. It was first used at Larderello in Italy in 1904. Steam technology is used today at The Geysers in northern California, the world's largest single source of geothermal electricity. These plants emit only excess steam and very minor amounts of gases. Flashed steam/dry steam condensing system; resource temperature range from about 320°C to some 230°C (Mwangi, 2006; Tripple, et al., 2012).

1.1.2 Flash and Double Flash Cycle

Hydrothermal fluids above 360°F (182°C) can be used in flash plants to make electricity. Fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or "flash." The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank (double flash) to extract even more energy. Flashed steam back pressure system; resource temperature range from about 320°C to some 200°C.For instance in Olkaria GPP, the plant works on single flash plant cycle with a steam consumption of 7.5 t/h/MW. The turbines are single flow six stages condensing with direct contact spray jet condenser1, (Mwangi, 2006; Tripple, et al., 2012).

1.1.3 Binary Cycle

Most geothermal areas contain moderate-temperature water (below 400°F). Energy is extracted from these fluids in binary-cycle power plants. The Hot geothermal fluid and a secondary (hence, "binary") fluid with a much lower boiling point than water pass through a heat exchanger for steam generate steam . Heat from the geothermal fluid causes the secondary fluid to flash to vapor, which then drives the turbines. Because this is a closed-loop system, virtually nothing is emitted to the atmosphere. Moderate-temperature water is by far the more common geothermal resource, and most geothermal power plants in the future will be binary-cycle-plants.(Mwangi, 2006; Tripple, et al.2012).

2.0 REVIEW ON OTHER RELATED STABILITY STUDIES

Stability studies on geothermal power plants are gaining momentum amongst countries with this resource. Past research tends to be more focused on geothermal heat and its applications, fluid thermodynamics and environmental factors rather than on electrical properties of a geothermal system. There are few stability studies published comparing the stability performance of geothermal power plants with other generation technologies, Ólöf Helgadóttir (2008).

A study on the Dynamic Behaviour of Geothermal Power Plants Located at a Weak Point of Icelandic Transmission System, where a new 250 MW aluminium smelter in northern Iceland is planned and its power demand is met by both geothermal and hydro power plants, established that geothermal power plants to be installed have larger inertia than the power hydro plants they substitute. Therefore, the system is more likely to maintain stability under transient conditions when the new load is supplied from geothermal plants. Other interesting questions arise for system operators when an increasing number of geothermal power plants are connected to the power system. Next step in future work would be to address the issues appertaining to the role of geothermal power plants in taking part in regulation and operation of the system, in the same way as other power plants like hydro do in most countries including Kenya and the possibility to use this GPPs to start-up an energy intensive factory, like the aluminium smelters and other large power loads, with only geothermal electricity feeding it. This model developed was for single point in the system and was used to give the best source of power to the load considering the proximity of the both HEPs and GPPs to the smelter. To take care of variedly located GPPs, both from each other and load center, the model of a power system has to be expanded and modified to take of more GPPs enabling long-term stability studies including transient stability, Ólöf (2008).

Another research on integration of geothermal energy into the Australian transmission network focused mainly on voltage stability and outlines its effects on the system. Voltage stability studies on Australian South East 14 generators test system show that bipolar High Voltage Direct Current (HVDC) transmission lines are more stable compared to High Voltage Alternating Current (HVAC). Also in this study, it has been demonstrated that stability of the HVDC interconnection is not deteriorated when the length of the line increases. On the other hand, the stability margin of HVAC interconnection decreases proportionally when the length of the interconnection increases. Inter-area oscillations are caused by interactions among large groups of generators at two ends of an interconnection and improve the transient stability; the research is limited has it proposes supplementary control for current source converter HVDC; the integration does not provide the dynamic transient behaviour of the system as GPPs rise, Mehdi and Tapan (2011).

Further still, in the research on Impact of Widespread Penetrations of Renewable Generation on Distribution System Stability, these penetrations make transmission/distribution system more dynamic. The results show that with increasing penetration of solar energy, loadability improves, whereas it decreases with increased wind penetration. The increased penetration of wind power may limit the loadability due to Hopf bifurcation phenomenon. Grid loss has been found to increase after certain level of renewable penetration. Damping of low frequency oscillations improves as the wind and solar penetration increases. Also, transient stability improves with an increase penetration of renewable energy resources .Notably missing is the effect of penetration of geothermal power, also a renewable resource, hence there’s need to carry out its study, Tareq Aziz (2010). In the research on Modelling and Stability Analysis of Berlin Geothermal Power Plant (CGB) in El Salvador, This project present a local area model of the CGB and the surrounding grid, and it can be extended to add more units in the surroundings to make dynamics studies. The inter-area mode is not vividly explored in this study, Lopez and Alonso (2013).

Eigenvectors plots shows that the oscillation mode for this research study is local mode or Machine system mode, because all the units of CGB swing together with respect to the rest of the power system. By extending the model and having different locations of GPPs while including more of the surrounding grid and other power plants, there is an assumption that there will be additional oscillation modes or inter-area modes. The developed model is, however, very well suited for studying local phenomena. This research, thus recommended that the phenomenon be investigated, due its flexibility for systems with varied locations of GPPs (separated by large distances from each and the load centre) as this was limited to local area oscillations. There is need to extend the study to include inter-area mode of oscillations (Lopez and Alonso, 2013).

Because of difference in geothermal resource potential in other countries, unique physical location of Kenya’s resources, heavy/strenuous loading on the system and varying distance from between GPPs and load centre approach, the system dynamics differs from other countries endowed with the same. In this regard, Kenya intends to make it the leading source of electricity by 2030, thus will impact on Kenya’s stability positively.

3.0 REVIEW OF POWER SYSTEM STABILITY INVOLVING DIFFERENT SYNCHRONOUS MACHINES

3.1 Classification of Power System Stability

To achieve a better overview and structure of stability analyses of power systems, it is of great help to classify possible power system stability. The classification to be introduced here is based on the physical mechanism being the main driving force in the development of the associated instability. It could be either the active or the reactive power that is the important quantity (Kundur, et al. 2004).

A common characteristic of the instabilities to be discussed here is that they have their origin in too large an imbalance of active or reactive power in the system, locally or globally. This imbalance can then develop in different ways and cause unstable behavior depending on system characteristics. Power system stability is that property of a power system that enables it to remain in a state of equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. Figure 1 shows the classifications of power system stability (Kundur, et al. 2004).

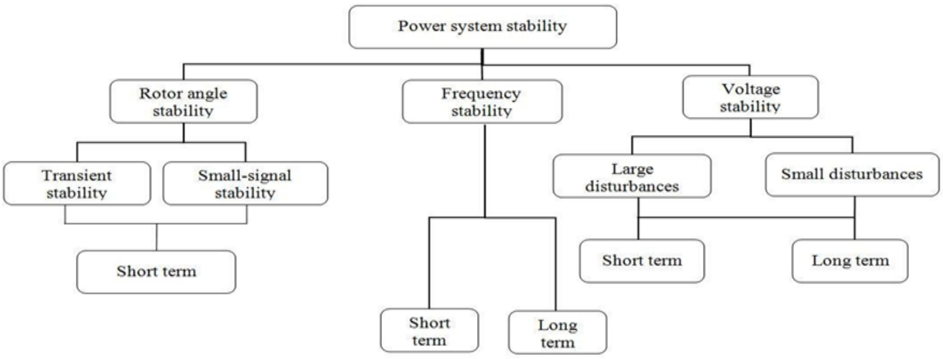

Figure 1: Classification of power system stability. Kundur, Paserba, Ajjarapu, and Andersson (2004)

3.2 Synchronous Machines Parameters Operating Principle

In the synchronous machines, a magnetized rotor creates a rotating magnetic field in the air gap. If the rotor field is ideally sinusoidal and if the rotor rotates at constant speed, this will induce ideally sinusoidal voltages in the stator windings. If the machine terminals are connected, the currents flowing in the stator windings create a second rotating magnetic field which causes a torque on the rotor. In a synchronous motor, this torque drives a mechanical load; in a synchronous generator, the magnetic torque opposes the mechanical driving torque of the prime mover (e.g. a turbine). Under balanced, a steady-state condition the magnetic torque is equals the mechanical torque, and so the rotor continues to rotate at constant speed. These machines use either round rotor or salient pole rotors (Sridhara, et al., 2013).

Round rotors are used with high-speed turbines such as steam or gas turbines; also called turbo generators. Salient pole rotors are used with low-speed hydro turbines. In order to obtain the appropriate frequency in spite of the low rotor speed, salient pole rotors typically have multiple pole pairs. For run-of-river power stations the numbers of poles can be as high as p = 200.Such rotors have very large diameters and short lengths (Sridhara, et al., 2013).

3.3 Stationary Operation of Synchronous Machines

With the losses neglected, the total impedance of the generator as seen from the stator is modeled with a single lumped inductance X_d. This is strictly only valid for the turbo generator with its homogeneous air gap. In the salient pole generator, the same effects that give rise to the reluctance torque which causes the active part of the stator current see a smaller reactance Xq than the reactive part, for which the reactance X_d is effective[8, 21]. Typical values for X_d and Xq are listed in Table 1.

Table1: Typical values of synchronous machine reactances.

	Round Rotor	Salient Pole Rotor
X_d (p.u.)	1.0 – 2.3	0.6 – 1.5
X_q (p.u.)	1.0 – 2.3	0.4 – 1.0

3.4 Dynamic Operation of Synchronous Machines

During network transients, the reactance of the synchronous generator is not constant. For symmetrical transients, on short circuits of synchronous machines, the machine reactance itself undergoes transient changes as the machine passes through the sub-transient, transient, and steady-state stages. The rotor of a synchronous machine rotates with synchronous speed in steady state. An important parameter in the analysis of rotor oscillations is the total moment of inertia of the synchronous machine J. This is the sum of all moments of inertia of all rotating parts of the synchronous machine, i.e. the sum of the moments of inertia of the rotor, turbines, shafts and other devices on the shaft system, e.g. generator feeding the field winding. As for electrical quantities it is practical to express J in a suitable p.u. Hence the base inertia constant of the synchronous machine H is defined as:

$$H= 0.5J\ddot{\omega}^2_{mo}/S \qquad (1)$$

Where S is MVA rating of the machine and $\ddot{\omega}$ is rotor angular velocity. The numerator is an expression for the total kinetic energy stored in the synchronous machine in steady state and the unit for H is thus seconds. The inertia constant states how much time it would take to bring the machine from synchronous speed to standstill if rated power is extracted from it while no mechanical power is fed into it. The value of the inertia constant will vary within a much smaller range than the value of J for different machines. Table 2 shows typical values of H for different types of synchronous machines (Sridhara et al., 2013).

Table 2: Typical values of H for different types of synchronous machines (Sridhara et al., 2013).

Type of Synchronous Machine	Inertia Constant H (s)
Thermal Power • Steam Turbine • Gas Turbine	 4 – 9 7 – 10
Hydro Power • Slow (< 200 min−1) • Fast (≥ 200 min−1)	 2 – 3 2 – 4
Synchronous Compensators	1 – 1.5
Synchronous Motors	≈ 2

It can be observed that the H value is higher for thermal units as compared with hydro units. In line with this, electrical power system is more stable when geothermal plants are used to meet the power demand of the load. This is so because the inertia of geothermal power plants is higher than for hydro plants. A smaller inertia decreases the critical clearing time. The reason is that the smaller the H constant the smaller P_{max}. A smaller P_{max} constrains a machine to swing through a smaller angle from its original position before it reaches the critical clearing angle. Therefore, smaller H constant decreases the critical clearing time and lowers the probability of the system to maintain stability. Thirty to sixty per cent of the total inertia of a steam turbo-generator unit is that of the prime mover, whereas only 4-15% of the inertia of a hydroelectric generating unit is that of the waterwheel, including water.

4.0 KENYA'S POWER SYSTEM

4.1 Technical Parameter of Power plants in Kenya

Table 3: Technical data of Kenya's power system

GENERATOR	T'do	$T''d_o$	$T'q_o$	$T''q_o$	H	D	Xd	Xq	X'd	X'q	X''d =X''q
AELOUS_WIND							1	0.9	0.35	0.6	0.3
AGGREKO1 45MVA	3.16	0.05	1	0.198	1.6	0	2.49	1.85	0.25	0.46	0.23
AGGREKO1 8.1MVA	3.16	0.05	1	0.198	1.6	0	2.49	1.85	0.25	0.46	0.23
AGGREKO2 15MVA	3.16	0.05	1	0.198	1.6	0	2.49	1.85	0.25	0.46	0.23
AGGREKO2 22.5MVA	3.16	0.05	1	0.198	1.6	0	2.49	1.85	0.25	0.46	0.23
AGGREKO2 25MVA	3.16	0.05	1	0.198	1.6	0	2.49	1.85	0.25	0.46	0.23
BUJAGALI	6.85	0.138	0.34	0.041	2.835	0	1.932	1.9	0.312	0.34	0.198
EMBAKASI GT1	4.75	0.05	1	0.198	3.2	0	1.4	1.372	0.231	0.236	0.16
EMBAKASI GT2	4.75	0.05	1	0.198	3.2	0	1.4	1.372	0.231	0.236	0.16
GITARU G1	9.2	0.06	0	0.06	3	0	1.1	0.7	0.203	0.7	0.15
GITARU G2	5	0.05	0	0.05	4	0	1.1	0.7	0.203	0.7	0.15
GITARU G3	9.2	0.06	0	0.06	3	0	1.1	0.7	0.203	0.7	0.15
GULF_POWER	4.8	0.041	1	0.105	1.5	0	1.98	1.04	0.362	0.5612	0.2806
IBERAFRICA 2 G1-7	4	0.041	1	0.199	1.3	0	1.75	0.88	0.288	0.368	0.184
IBERAFRICA G1	3	0.041	1	0.041	1.3	0	1.58	0.79	0.26	0.414	0.207
KAMBURU G1	5	0.06	0	0.06	2.76	0	0.968	0.571	0.3	0.571	0.205
KAMBURU G2,3	5	0.05	0	0.05	3.6	0	0.968	0.571	0.3	0.571	0.205
KIAMBERE G1	6.6	0.13	0	0.13	2.96	0	0.72	0.51	0.27	0.51	0.21
KIAMBERE G2	5	0.05	0	0.05	3.8	0	0.72	0.51	0.27	0.51	0.21
KINDARUMA G1	6	0.06	0	0.06	3	0	0.905	0.56	0.29	0.56	0.23
KINDARUMA G2	5	0.05	0	0.05	3.5	0	0.905	0.56	0.29	0.56	0.23
KINDARUMA G3	5	0.05	0	0.05	3	0	0.9	0.56	0.29	0.56	0.23
KIPETO/PRUNUS_WIND							1	0.9	0.35	0.6	0.3
KIPEVU I	4.7	0.041	1	0.134	1.5	0	1.28	0.7	0.287	0.4393	0.2197
KIPEVU II	4.8	0.041	1	0.105	1.5	0	1.98	1.04	0.362	0.5612	0.2806
KIPEVU III	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
KWALE_SUGAR	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
MASINGA G1	4.1	0.06	0	0.06	3	0	0.903	0.56	0.306	0.56	0.1936
MASINGA G2	5	0.05	0	0.05	3	0	0.903	0.56	0.306	0.56	0.1936
MUHORONI G1	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
MUHORONI G2	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
MUMIAS G1,2	3	0.041	1	0.041	1.3	0	1.58	0.79	0.26	0.414	0.207
MUMIAS G3	4	0.041	1	0.199	1.3	0	1.75	0.88	0.288	0.368	0.184
MUMIAS G4	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
NAIROBI SOUTH	3	0.041	1	0.041	1.3	0	1.58	0.79	0.26	0.414	0.207
NGONG WIND							1	0.9	0.35	0.6	0.3
NGONG_WIND							1	0.9	0.35	0.6	0.3
OLKARIA I 90MVA	6.39	0.06	0.9	0.12	3.8	0	2.213	2.1	0.286	0.4	0.199
OLKARIA I G1	6	0.05	1	0.05	3.1	0	2	1.9	0.21	0.6	0.12

OLKARIA I G2	6	0.05	1	0.05	5	0	1.9	1.8	0.27	0.3	0.12
OLKARIA I G3	6	0.05	1	0.05	4.5	0	1.9	1.8	0.27	0.3	0.12
OLKARIA II	7.8	0.041	1	0.1	4.6	0	1.89	1.83	0.28	0.36	0.18
OLKARIA III	7.8	0.041	1	0.1	5.1	0	1.89	1.83	0.28	0.36	0.18
OLKARIA IV 25 MVA	6	0.05	1	0.05	4.2	0	2	1.9	0.21	0.6	0.12
OLKARIA IV 90 MVA	6.39	0.06	0.9	0.12	3.5	0	2.213	2.1	0.286	0.4	0.199
OWEN FALLS	5	0.05	0	0.05	2	0	1	0.7	0.26	0.7	0.14
RABAI G1-5	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
RABAI G6	4.8	0.041	1	0.105	1.2	0	1.98	1.04	0.362	0.5612	0.184
SANGORO G1	6	0.06	0	0.06	3	0	0.9	0.56	0.29	0.56	0.23
SANGORO G2	5	0.05	0	0.05	2.9	0	0.9	0.56	0.29	0.56	0.23
SINGIDA_PHASE_2	6.3	0.042	0.26	0.077	2.646	0	2.41	2.308	0.373	0.56	0.243
SONDU MIRIU	6	0.06	0	0.06	3	0	0.91	0.59	0.204	0.59	0.17
SUSWA_COMPENSATOR							1	0.9	0.35	0.6	0.3
TANA G1,2	5	0.13	0	0.13	3	0	0.9	0.56	0.29	0.56	0.23
TANA G3,4	5	0.13	0	0.13	3	0	0.9	0.56	0.29	0.56	0.23
THIKA_POWER_20MVA	9.128	0.041	1	0.1272	2	0	1.977	0.992	0.338	0.4646	0.2323
THIKA_POWER_8.75MVA	4.8	0.041	1	0.105	1.5	0	1.98	1.04	0.362	0.5612	0.2806
TRIUMPH	4.8	0.041	1	0.105	1.5	0	1.98	1.04	0.362	0.5612	0.2806
TURKANA_WIND							1	0.9	0.35	0.6	0.3
TURKWEL	7.6	0.13	0	0.13	2.5	0	0.94	0.57	0.27	0.57	0.21
WOLYATA	6.3	0.042	0.26	0.077	2.646	0	2.41	2.308	0.373	0.56	0.243

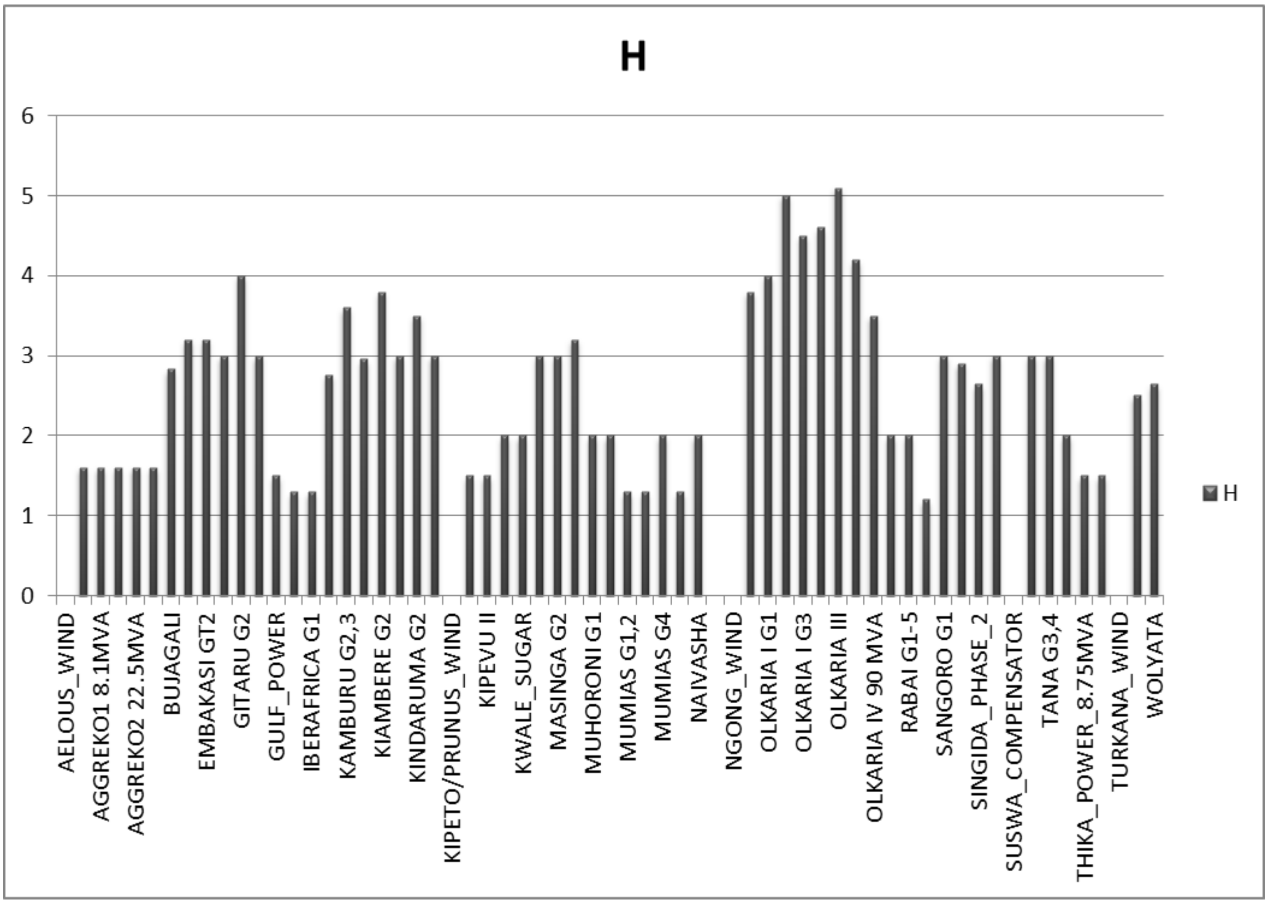

Figure 2: Inertia constants of Kenya's power plants (source: Kengen)

From the above, the inertia constant of power plants in Kenya range from 1.2 to 5.1. The power plants with largest inertias located mainly at hydro and geothermal power plants. Hydro plants inertia constants range from Turkwel's 2.5 to 3.6 in Kamburu. GPPS have an inertia constant of between 3.1 in Olkaria 1 to 5.1 in Olkaria 3. It is evident that that inertia constant of geothermal power plants are higher than those of hydro power plants for the plants already installed in Kenyan power system. The inertia constants of the other power plants are generally low.

3.6 Installed Capacity

Table 4: Kenya's installed Capacity (2008-2013)

KENYA'S INSTALLED CAPACITY(2008-2013)						
	2008	2009	2010	2011	2012	2013
Hydro	736.9	748.4	757.9	763	788	816.1
Diesel	444.7	447.9	510.6	627.1	688.1	694.8
Geothermal	128	172	198	198	209	250.2
Wind	0.4	0.4	5.1	5.3	5.3	5.3
IPPs	145	180.3	346.5	347	351	391.2
Off-Grid	9	11.7	11.7	9.1	10.1	17.1
EPPs	150	150	60	60	120	120
TOTAL	1310	1368.7	1471.6	1593.4	1690.4	1766.4

Kenyan installed capacity was 1,765MW in June 2013 for an effective capacity of 1,652MW (94%). Hydro is the most widespread power generation mean with installed and effective capacity of 816MW and 767MW respectively, accounting for 46% of the country's total capacity. Then come thermal (258.9MW and 209.1MW) and geothermal (158MW and 153MW). Wind capacity remains marginal with only 5.3MW, as is off-Grid governmental capacity with 17MW. Overall IPPs' installed capacity amounts 391MW for an effective capacity of 387MW and Emergency Power Producers (EPP) operate 120MW. The growth of three power generation sources is indicated in Figure 3.

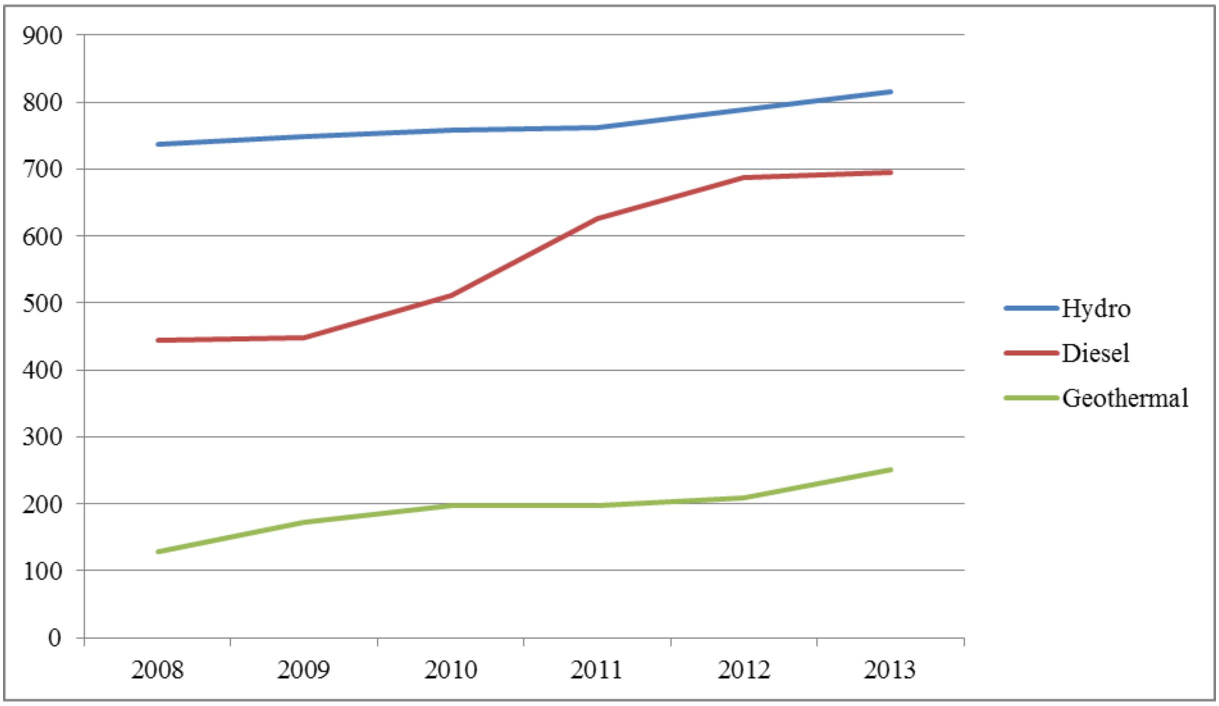

Figure 3: Growth of power sources (2008-2013)

3.7 Projected growth in power generation in Kenya

Kenya installed generation capacity is projected to increase to about 14,676 MW by 2030 basing on the reference scenario. The strategy is to diversify the base-load from hydro to other sources of energy mainly geothermal. The expected power supply from various sources will by 2030 be composed of: geothermal 5,450.00 (37.13) hydro 3,000MW (20.44%), diesel 500 MW (3.40 %), natural gas 1,500 MW (10.22%), and other sources will account for 12.32%. thus, geothermal energy will be a major source of electrical energy Kenya. The projections are indicated in the Table 3 and Figure Table 5 below:

Table 5: Power generation projections

KENYAS PROJECTED GENERATION (2018-2030)				
	2017	2022	2027	2030
Hydro	900	1500	2500	3000
Diesel	1000	1243	2000	2916
Geothermal	800	2000	4000	5450.5
Wind	500	900	1200	1500
Others (co-gen, Solar-PV etc)	92	405	1006	1810

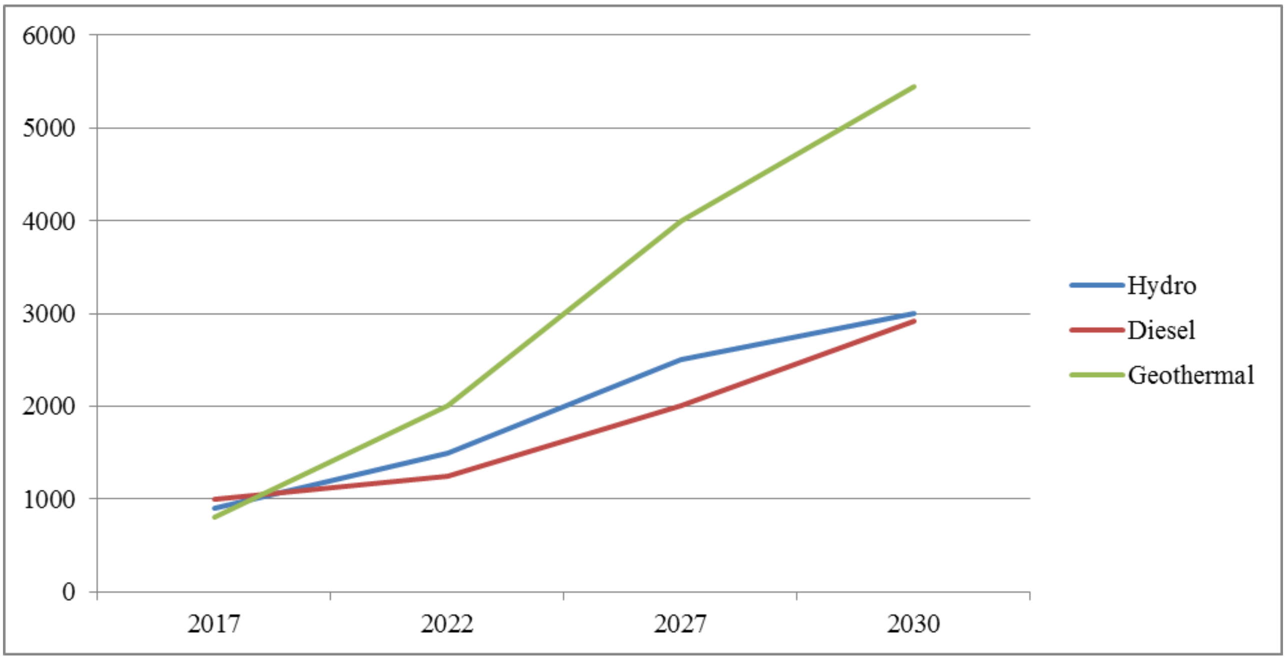

Figure 4: Projected increase of power generation in Kenya (2017-2033); Source: March 2013, LCPD (2013-2033)

CONCLUSIONS

It is apparent from the analysis of the existing power plants in Kenya that inertia constant of geothermal power plants are higher than those of hydro power plants. From the projections, geothermal power plants will constitute 37.13 % of total power generation compared to 20.44% from hydro power plants making geothermal the major source of electrical power after 2030. From power systems analysis, during disturbances or faults, the smaller the H constant of the machine is, the smaller the angular swing of the machine. Lower H constant increases transient reactance of the machine causing the critical clearing time to decrease and lessen the probability of maintaining stability under transient conditions.

Thus, that the impacts of integrating geothermal power on stability of the Kenyan power system are hugely positive by reducing machine swings and damping of oscillations after fault occurrences. Once it becomes a major source, analysis of the improved stability of the power system will be essential to understand the behavior of the GPPs under steady state and dynamic conditions especially for fault recovery conditions and system planning. The system dynamics and their characteristics under normal operation and under faults conditions will greatly be enhanced.

Further still, since the inertia constant (H) is higher for geothermal power plants as compared with hydro generating units, Kenya's electrical power system stability margins will continue to increase as more and more geothermal plants are interconnected to meet the increasing power demand of the system load as projected to 2030. This will also guarantee system reliability.

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