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Small signal stability analysis of dish-Stirling solar thermal based autonomous hybrid energy system

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ABSTRACT

Present work presents small signal stability analysis of an autonomous hybrid energy system with dish-Stirling solar thermal systems (DSTS) in integration with diesel engine generators (DEG), fuel cells (FC), battery energy storage system (BESS), and aqua electrolyzer (AE). The performance of Genetic algorithm (GA) optimized integral (I), proportional plus integral (PI), and proportional-integral-derivative (PID) controllers in containing the frequency deviation in the proposed system has been investigated. The dynamic performance of all three controllers, so optimized, is compared with manually tuned I controller. Simulation results revealed that the performance of the GA optimized PID controller is found to be the best amongst all three controllers. Further, sensitivity analysis is carried out to access the robustness of the controllers.

Introduction

Anticipating the energy crisis due to continued depletion of the world's most valuable fossil energy resources and environmental hazards to be faced in the coming decades, concentrating solar thermal technology has been recognized as a promising candidate to provide critical solutions to global energy problems within a relatively short time frame without or with minimum carbon emission. Among all the renewable technologies that exist for large-scale power production today and for the next few decades, solar thermal technology is perhaps the best option to make significant contributions of clean energy because of its use of relatively conventional technology and ease of scale-up [1]. To date, major solar thermal technologies include solar power tower, solar parabolic trough, solar dish-engine, linear fresnel systems and zero to low concentration low temperature solar thermal systems. Out of these solar thermal technologies dish-Stirling solar thermal system is the most suitable one for stand-alone applications, because of modular design and the highest record for solar-to electric energy conversion efficiency among all solar thermal technologies. However, the detail study on the dynamic performance of controllers of an autonomous hybrid energy system with dish-Stirling solar thermal system is not yet reported.

Actually dish Stirling solar thermal technology is one of the oldest solar technologies. There are number of past and current demonstration projects, mostly in Europe, Japan, Australia and in USA [2,3]. All dish Stirling system deployments are reported in [4,5]. During last 20 years, eight different dish-Stirling systems ranging from 2 to 50 kW have been constructed by companies in the United States, Germany, Japan and Russia [6]. A plant with installed capacity 1.5 MW is in operation in Peoria, AZ, and plats with rated capacity of several hundred megawatts are in the planning stages [7]. In August 2005, Southern California Edison entered into an agreement with Stirling Engine Systems (SES) for purchasing power for 20-years using parabolic dish units of capacity between 500 and 850 MW (producing 1182–2010 GW h per year). Same year in September, SES publicized a contract with San Diego Gas & Electric to provide between 300 and 900 MW of solar power using the dish technology. Among operational solar dish systems around the world, 3 kW plant by Infinia Corp. and 10 kW by Schlaigh–Bergermann und Partner up to 150 kW by Stirling Energy Systems or Wizard Power Pty [4] are worth mentioning.

There are few more large projects currently under planning and construction that are worth highlighting because of their significant power size. These projects use Stirling Energy Systems technology and are located in the USA with an installed capacity of 750 and 850 MW and in India using Infinia Corp. Technology with a capacity of 9–10 MW [8]. Other than these, two dish Stirling systems, which are developed and expected to be in operation in commercial scale in 2010: the Euro Dish from Schlaich–Bergermann at Eskom in South Africa and Partner (SBP) and the

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Nomenclature

Δf	system frequency deviation.
K_{sys}	frequency characteristic constant of hybrid power system.
$G_{SYS(s)}$	transfer function of hybrid power system.
P_{DEG}	output power of diesel generators.
$G_{DEG(S)}$	transfer function of diesel generator.
K_{DEG}	gain of diesel generator.
T_{DEG}	time constant of diesel generator.
P_{FC}	output power of fuel-cell generators.
K_{FC}	gain of fuel cell.
T_{FC}	time constant of fuel cell.
$G_{FC(S)}$	transfer function of fuel-cell generators.
P_{DSTS}	output power of dish-Stirling solar thermal system.
$G_{DSTS(S)}$	transfer function of dish-Stirling solar thermal system.
T_{DSTS}	time constant of dish-Stirling solar thermal system.
K_{DSTS}	gain of the dish-Stirling solar thermal system.
P_{BESS}	power of battery energy storage system.
$G_{BESS(S)}$	transfer function of battery energy storage system.
K_{BESS}	gain of battery energy storage system.
T_{BESS}	time constant of battery energy storage system.
$G_{AE(S)}$	transfer function of aqua electrolyzers.
P_{AE}	Aqua electrolyzers power.
K_{AE}	gain of the aqua electrolyzer.
T_{AE}	time constant of the aqua elctrolyzer.
P_S	total power generation to the system.
P_L	average power absorbed by loads.
ΔPe	error in power supply and demand.
M	inertia constant of the hybrid power system.
D	damping constant of the hybrid power system.

Abbreviations or subscripts

GA	genetic algorithm
AE	aqua-electrolyzer
DEG	diesel-engine generator
FC	fuel cells
BESS	battery energy storage system
PS	power system
DSTS	dish-Stirling solar thermal system

"SunCatcher Dish Stirling system" developed by Stirling Energy Systems (SES) in Spain [2].

Significant development in this technology is the construction of large scale solar dish Stirling systems within the framework of Solar One and Solar Two projects of company Stirling Energy System (SES), which was launched on 2005 [2]. The two projects, overall, will include 64,000 dishes, generating 1750 MW, which will provide electricity for approximately1,100,000 homes.

Increasing penetration of dish-Stirling solar thermal power into the utility grid demands for simulation studies to assess the dish-Stirling system's impact on steady state and transient behavior of the utility grid, a topic that has not attracted much attention of the researchers till date. Because of its unpredictable nature and dependency on weather and climatic changes, the variations of solar thermal energy may not match with the time distribution of load demand. Fortunately, the problems caused by the variable nature of this resource can be partially or wholly overcome by hybridization with fossil fuel based backup systems. A fossil based backup system allows the compensation of solar input fluctuations and permits night-time operation. And the integration of energy storage systems into the solar plant allows an increase in annual solar operating hours as well as compensates short time fluctuations in the solar energy input [9,10]. In this paper, a dish-Stirling solar thermal diesel autonomous hybrid energy system has been proposed. Diesel provides a cushion against variation in dish-Stirling solar thermal power in an isolated hybrid energy system, thereby increasing the reliability of the system.

Like wind energy, dish Stirling electric power is also characterized by intermittent nature and use of a non-conventional, asynchronous generator [7]. Because of the intermittency of solar energy in dish Stirling systems, both voltage and frequency of utility grid fluctuates. Present work considers frequency control of dish-Stirling solar thermal based autonomous hybrid energy system.

Studies on wind-diesel-energy storage based hybrid energy systems have been carried out in the past. Lee and Wang [11] are the first to propose and discuss the basic concept of effective utilization of renewable energy sources in an isolated hybrid system. Their proposed autonomous hybrid system consists of wind turbine generators, photo voltaic system, fuel cells, diesel engine generator and energy storage system in different combination. However, they have not investigated thoroughly into different control schemes and their performance including effective coordination among various subsystems. In time-domain analysis of case 1, they have considered that during $0\ \text{s} < t < 50\ \text{s}$ aqua electrolyzer would absorb a fraction of energy generated by wind generators even when total power generated by three wind turbine generators is less than .3 p.u. and diesel generator would supply 0.9 p.u. to mitigate the difference in generation and load. While electrolyzer absorbs a fraction of wind energy during low wind penetration and supplies the hydrogen so produced to fuel cell, diesel generator is used to supply rest of the load demand to mitigate power mismatch. The power control and management concept is unwise from economical point of view. Further, their simulation results revealed that the dynamics of hydrogen generation by absorption of energy, and supply of hydrogen to the fuel cell occurred simultaneously.

Another study on autonomous hybrid system comprising of wind turbine generators, diesel generators, fuel cells, and aqua electrolyzer, conducted by Senjyu et al. [12]. Prime objective is to mitigate effect of wind power fluctuations by using electrolyzer, and control of system frequency by altering the output power generation of subsystems by employing controllers. Aqua electrolyzers absorb the rapidly fluctuating output power from wind turbine generators and generate hydrogen. Generated hydrogen by an aqua electrolyzer is used as fuel for fuel-cell generators. The proportional plus integral (PI) controllers were employed to regulate the output powers from distributed generation system to achieve power balance condition due to sudden variations in generation and load. The proposed system improves the efficiency of the system. However, the gain values of PI controller are chosen by trial and error method which does not ensure the optimal performance of the controller.

There are several tuning methods in literature e.g., Ziegler–Nichols Ultimate-cycle tuning, Cohen–Coon's, Astrom and Hagglund and many other traditional techniques. Although new methods are proposed for tuning the controllers, their usage is limited due to complexities arising at the time of implementation [13]. The method described in Ziegler and Nichols is conventional one. The controller gains once tuned for a given operating point are only suitable for limited operating point changes. Therefore, the use of the conventional PI controller does not meet the requirements of the robust performance [14]. Moreover, when the number of parameters to be optimized is large, conventional technique