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Design of distributed energy system through Electric System Cascade Analysis (ESCA)

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HIGHLIGHTS

- ▶ Development of a new cascading analysis method for distributed generation system optimization.
- ▶ Optimal sizing of non-intermittent power generator.
- ▶ Optimal sizing of energy storage.

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ABSTRACT

This paper presents a new numerical method called the Electricity System Cascading Analysis (ESCA). ESCA is developed based on pinch analysis principles and useful for designing and optimizing non-intermittent power generator (biomass, biogas, natural gas, diesel, etc.) and energy storage for Distributed Energy Generation (DEG) system. DEG system configuration for this case study comprise of solar Photovoltaic (PV), biomass power generator and Sodium Sulfur (NaS) battery system. Application of the technique on isolated community consisting of 100 houses and daily energy demand of 845 kW h reveals that the power capacity of the biomass power generator is 39.76 kW, NaS battery is 75.8 kW, and the energy capacity of NaS battery is 157.01 kW h.

1. Introduction

In the 21st Century, energy is expected to be among the most pressing global issues. The main challenge in the energy industry is the rapid growth of fuel demand which requires significant energy imports to meet future energy demand. This trend has led to significant interest in the implementation of energy systems which is efficient and renewable such as Distributed Energy Generation (DEG) system based on Renewable Energy (RE). According to the International Council on Large Electric System (CIGRE) working group [1], DEG is defined as generation that is not centrally planned, not centrally dispatched, usually connected to the distribution network, and less than 100 MW in size. DEG system is commonly applied in parts of the world with no power source. Currently, DEG is also considered for grid-connected community to reduce dependency on the centralized energy system [2].

According to the International Energy Agency (IEA) (2002), there are five major factors that direct the world's interest towards DEG system. These factors are (i) the advances of DEG technologies, (ii) constraints on the construction of new transmission lines, (iii) increased customer demand for highly reliable electricity, (iv) electricity market liberalization and (v) mitigation of global warming [3]. In addition, the technical and economic benefits of DEG system further captivate the world's attention. These benefits are classified into three categories: (i) composite of technical and economic benefits, (ii) technical benefits, and (iii) economic benefits [4].

i. Composite technical and economic benefits [4]:
   - Standby capacity or peak use capacity; this leads to lower operating costs due to peak shaving for on grid DEG system. Furthermore, reserve requirements and the associated costs may be reduced. To serve loads in the

Abbreviations: DEG, Distributed Energy Generation; RE, Renewable Energy; IEA, International Energy Agency; GA, Genetic Algorithm; LPSP, Loss of Power Supply Probability; HOMER, Hybrid Optimization Model for Electric Renewable; ESCA, Electricity System Cascading Analysis; PV, Photovoltaic; AC, Alternating Current; DC, Direct Current; NaS, Sodium Sulfur.

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event of sudden or unexpected failure of operating generating units, utilities must maintain some generation capacity as spinning reserve (power plant operating in standby mode, energy generated during standby is not utilized and thus dumped). A correct amount of spinning reserve has an equivalent effect to load shedding in controlling sudden frequency drops [5]. In this context, load shedding refers to an intentional power outage by the power provider to prevent total blackout of the power system.
- Reliability, security and power quality; in areas where voltage support is difficult, DEG has significant contribution because connecting DEG generally leads to a rise in voltage in the network. DEG enhances the security of electric power supply.

ii. Technical benefits:
- Climate, environmental, and health concerns; DEG reduces health care costs due to the improved environment and reduction of fuel costs due to the overall increment in efficiency [6].
- Grid support for grid-connect DEG; stabilize a dropping frequency due to a sudden under capacity or excess demand.

iii. Economic benefits:
- Developments in DEG technologies; some DEG technologies reduce the operation and maintenance costs of the generation units.
- Avoidance of electricity transmission costs and reduces exposure to electricity price volatility [7].

Although with such prevailing benefits, the implementation of DEG faces many technical challenges and is currently under research. Over the past years, researches had been conducted to improve DEG system covering many different aspects, however focusing mainly on self-relying power systems. Among the notable recent studies was by Zangeneh et al. [8] who developed a theoretical and practical approach based on multi-objective expansion planning of DEG technologies subject to technical, economical, and environmental constraints. Katsigiannis and Georgilakis [9] on the other hand, presented a method to determine the optimal size of small isolated power system that contains renewable and conventional energy technologies with the objective function to minimize the system's energy cost. Elnashar et al. [10] presented an exhaustive search algorithm to find the optimal location and size of a single DEG unit in a meshed system, taking into consideration the distribution system losses and short circuit level. Singh and Goswami [11] has developed a technique using Genetic Algorithm (GA) to determine the optimum size and location of multiple DEG units to minimize distribution system losses and power supply from main grid, taking into account the limits of the voltage at each node of the system. Yang et al. [12] presented a model for designing hybrid solar–wind systems employing battery banks. The model was useful to determine the optimum configuration as well as minimizing the annualized cost of the systems while satisfying the custom required Loss of Power Supply Probability (LPSP).

Other than optimization models, feasibility studies on DEG systems had also been conducted. Getachew and Bjorn [13] presented a feasibility study for a stand-alone solar-wind-based hybrid energy system for a model community of 200 families using the Hybrid Optimization Model for Electric Renewables (HOMERs) software. Kalantar and Mousavi [14] on the other hand, investigated the dynamic behavior of a stand-alone hybrid power generation system of wind turbine, solar array and battery storage and simulated the case study using MATLAB Simulink™ 7.2. Throughout their research, several optimization techniques such as GA, space vector, and fuzzy logic were applied.

This work is therefore, performed to overcome the complexity encountered using modeling and simulation method. A new numerical technique proposed in this paper known as the Electric System Cascade Analysis (ESCA) is a simple and systematic technique for designing and optimizing isolated DEG systems.

2. Electric System Cascade Analysis (ESCA)

Pinch analysis is a technique to predict optimal performance of a process prior to actual synthesis and design. By setting targets before detailed designing stage, pinch analysis allows its user to have full control over the decision making processes. Due to this advantage, pinch analysis has evolved over the decade from a tool for energy conservation [15] into a powerful analytical tool for process integration and resource optimization. Among the notable applications of pinch analysis are in heat exchanging networks [15], utility systems [16,17], mass exchanging networks [18], water networks [19,20], and production planning [21,22].

In addition to these fields of work, recently Bandyopadhyay [23] had demonstrated a new analysis technique to design an isolated energy system comprising of solar Photovoltaic (PV) and battery system by combining the design space approach analysis and pinch analysis. Design space approach was applied for the sizing of power generators in the system; meanwhile pinch analysis was applied to determine the optimal size of the battery systems. Through his work, he extended pinch analysis technique for sizing of energy storage devices using the grand composite curve where energy represents the flow variable and time represents the directional quality [23,24]. The configuration of the solar PV battery system is shown in Fig. 1 [23,24].

Although energy storage can ensure the reliability of the system, however large capacity of energy storage is usually required to ensure system operability. This is especially true for solar based system. Another possible solution is to install non-intermittent back-up generator. These generators are usually thermal power generator utilizing fuel such as biomass, municipal solid waste, natural gas, and diesel.

ESCA is therefore developed as an extension to the previous technique by Bandyopadhyay and is capable to design both the back-up generator and the energy storage device (include battery capacity, power and its initial energy content) for solar based DEG systems. In addition, if the system comprises only of non-intermittent power generator, ESCA is then capable to design the non-intermittent (thermal) power generator and the energy storage device. ESCA also aims to design the system with minimal energy dump (energy generation mainly due to power plant constraints which is not fed to the grid) and the technique includes inverter efficiency (Alternating Current (AC) to Direct Current (DC) and vice versa) as well as the battery charging and discharging efficiency in the analysis. The configuration for a general DEG system is as shown in Fig. 2.

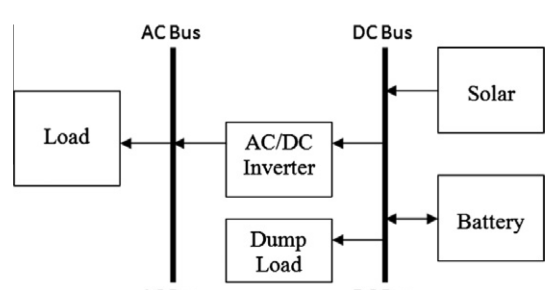

Fig. 1. Solar PV battery system [21,22].