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Optimization Algorithms for Solving Microgrid and Smart Grid Integration Problems

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Abstract

Smart Grid does not have a universally accepted definition, it can be described both in simple terms and in more complex forms. The evolution of conventional grids to Smart grids and the integration of distributed generation and microgrids have challenges such as generation forecasts, intelligent network management, determining the location, size and quantity of non-conventional sources of energy. This paper presents the optimization algorithms such as the Colony of Ants, Genetic Algorithm, Particle Swarm Optimization Algorithm, Bee Colony Algorithm and Tabu Search Algorithm, as the best solution to the presented challenges. To achieve the above, an application research was carried out in the fields of energy efficiency, network topology and distributed energy resources based on these algorithms. Given that the results have been satisfactory, it is proposed to continue with this line of research so that these technologies are more accessible to all users.

Keywords: Algorithms, integration, microgrid, optimization, smart grid

INTRODUCTION

Currently, electric power systems have similar characteristics all over the world, such as a centralized generation at a distance of several kilometers from the consumption centers, an infrastructure that has been used from 30 to 40 years, a growing energy demand and a constant concern for the environment [1].

There is a worldwide energy dependency on oil, carbon and natural gas related to a geographical distribution which has prompted nations to diversify their national energy basket and seek renewable energy sources for an environment-friendly generation that reduces greenhouse effect emissions and mitigates climate change [2]. Non-conventional renewable energy sources include wind energy, photovoltaic solar energy, biomass energy, geothermic energy, tidal energy, among others. They can generate electricity, heating and fuel as end products.

Nowadays, conventional electric systems are facing a wide range of problems such as overcharged transmission lines, high generation costs and variety in nodal voltages. In response, Distributed Generation (DG) has been successfully implemented and its resources, named Distributed Energy Resources (DER), can solve or minimize some of the aforementioned problems [3]. For instance, the installation of small generation centers close to the consumption spots enables the discharge of the transmission lines. However, some aspects still need to be improved like the continuity of the service which is interrupted in the case of solar energy since radiation is not present during all 24 hours of the day and the speed of the wind is discontinuous regarding wind energy. Microgrids (MG) are hence implemented which are electrical systems that can operate in island mode, being totally independent from the electric network or work in parallel to serve as backup units [4].

Microgrids are constituted by these elements: generation units, distributed storage units, a power converter and a control system [5].

Distributed resources are highly sought after due to their versatility and are installed in distribution systems to reduce the greenhouse effect. Their main disadvantage lies in the discontinuity of their generation which is why a large-scale power generation system is proposed to transform these technologies into technically competitive strategies. As the demand for electric systems keeps growing, it is necessary to investigate on the integration of DER in order to guarantee a service with high quality, efficiency and continuity [6].

The smart grid (SG) does not have a universal definition and can be described both in simple and complex terms. The term ‘smart’ implies that its operation is automation-based while the concept ‘grid’ is related to a network of electric conductors that provide electricity for certain points. That said, an idea can be conceived on what a smart grid is. It used to be dream or an idea but nowadays it is one of the most discussed topics in the modern electric sector. This modern network is capable of storing, communicating and making decisions. A SG transforms current networks into more cooperative and responding systems within a well-organized structure [7]. According to the strategic document of future electric networks in Europe, a SG is an electric network that can intelligently integrate the actions from all users (generators, consumers and mixed) connected to it to obtain electricity in an efficient, affordable and secure manner [5].

The National Institute of Standards and Technology (NIST) proposed to divide the smart grid into seven domains which include actors and applications. On one hand, the actors can be devices, systems or programs that make decisions and exchange necessary information to perform applications. They can be smart measuring devices, solar generators and control systems. On the other hand, the corresponding applications can be domotics, solar energy generation, energy storage and energy management [8]. Figure 1 shows the SG model presented by NIST.

Additionally, an energy management system is required for residential, industrial and commercial users that adjust to the needs of incorporating DG, DER, MG and SG. This management unit is called Distribution Management System (DMS) and comes from the need to implement technological support that makes decisions and enables an effective and efficient integration [9].

The goals of the DMS are to control, optimize, analyze and plan the network's operation as well as design the supply chain.

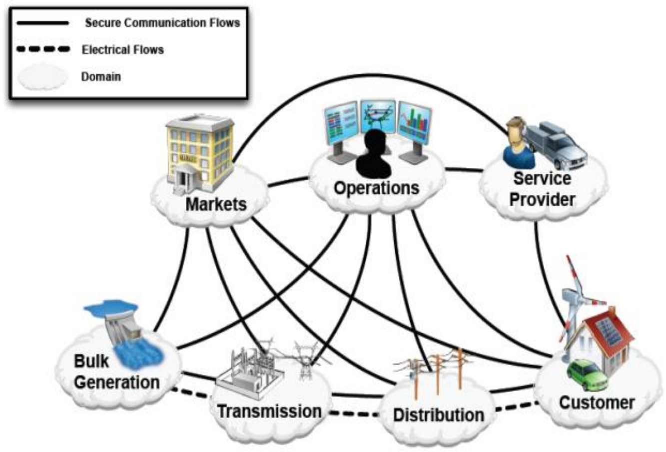

Figure 1. Interaction between actors in different domains of the Smart Grid through Secure Communication Flows and Electric Flows. Source [8]

PROBLEMS FOR SMART GRID AND MICROGRID INTEGRATION INTO THE CONVENTIONAL ELETRIC NETWORK

This section discusses the challenges of determining the location, size and configuration of a renewable power plant, the generation forecasts and the management and control in the integration of SG and MG into the conventional electric network. Said challenges are now described.

Location, size and configuration of a renewable power plant

To determine the location, size and configuration of renewable power plants, algorithms are required to optimize the available area since one of the characteristics of renewable power plants is that they take on a large extension of terrain in order to generate some megawatts (MW). Optimization algorithms can determine the location and size of a power plant in places where the weather information is scarce [10].

Generation forecast

The generation forecast becomes a challenge due to the variability of the resource used to generate. For instance, the periods of time when the wind flow is continuous cannot be predicted for wind energy systems or when solar radiation is optimal for photovoltaic solar systems [11]. This uncertainty in the prediction process turns systems into inefficient because there would not be a continuous and reliable service. Therefore, the Distributed Hybrid Energy System (DHES) offers to integrate DER and distributed energy storage technologies (such as battery systems) that can store enough energy and can be used in scarcity periods [12].

Management of Smart Grids

The management of the network is analyzed from four points of view: generation, transmission, distribution, management and control of the electric network. The challenges found in each aspect show some barriers that are arise in the migration from traditional electric networks to smart grids.

Generation

When microgrids (MG) are integrated into the electrical system, the offered energy must be planned from the dispatch centers whether it is produced from microgrids or large stations. In the case of Colombia, in [2] a modification of the offering mechanisms is proposed along with the creation of an intradaily market. The purpose is to plan paths of action oriented towards creating adequate and favorable conditions for the participation of MG and harness DER. This offer will be made based on the hourly generation forecasts.

Additionally, MG that cannot generate energy over periods of time shall receive support from power systems. These changes in the state of MG shall be made automatically in order to guarantee an electricity service of quality for the users [13].

Transmission

The different nodes of the electric system shall include interconnected DG systems that shall produce technical issues for the transportation and distribution networks. Such issues shall be related with difficulties in voltage control, reactive power management, reduction of the efficacy in electric protection strategies plus the negative impact in energy quality. Perhaps the biggest challenge that limits the proliferation of DG lies in the control of the voltage levels in the nodes [14][15]. This implies that an adequate operation is necessary to remotely control the voltage of nodes in order to maintain the balance of the electric system and assure that the power parameters are within the limits set by different standards.

Distribution

Distribution networks were designed for unidirectional energy flows and not to ease the penetration of DG. As a result, the distribution units that are stationed in inappropriate places, where generation does not meet the demand or surpasses the network's capacity, can have negative effects such as reverse power flows, increases in voltage, degradation of the quality of the voltage waveform, injection of harmonic components in the network or destabilization of the network [16][17].

The installation of bidirectional Smart measuring devices allows the identification of what has been consumed and what has been generated, in the different periods of time for the corresponding billing. Therefore, network operators can properly charge for the real consumption of each participant of the system.

The distribution of energy involves the term 'prosumer' which is the figure used to name the small system which is both producer and consumer of energy and that is connected to the electric network.

Management and control of the electric network

In every point of the system, the information from electric variables is being registered in real time. Therefore, it must be recollected in order to establish the users' behaviors and the profiles of the electric network so to optimize the network management. This involves an evolution of the network management based on centralized systems (SCADA) into decentralized or distributed control systems to assure optimal levels of efficiency, security and reliability [18]. The amount of information is so large that it needs to be handled by technologies such as Big Data.

In tandem with the electric network, information transmission networks must exist that are generated by remotely controlled units so that they can operate in case of failure or maintenance to the infrastructure.

OPERATIONAL RESEARCH

Operational Research is an interdisciplinary modern science that adopts theory and special techniques to seek the optimal solution of complex problems related to the management, organization and control of the systems existing in nature and those created by mankind (organized systems, physical systems, economic, ecological, educational, social, etc.) for optimal decision-making [19].

Informally, optimizing means that something more than improving. However, in the scientific context, optimization is the process of trying to find the best possible solution to a specific problem. In an optimization problem, there are different solutions and often the criterion to set them apart consists on determining the best one [20].

OPTIMIZATION ALGORITHM

Next, the most relevant optimization algorithms in current literature are analyzed.

Ant Colony Optimization (ACO)

In general, ants tend to leave pheromones in the environment when looking for food. When they manage to find food, they deploy even more pheromones on their way back to the nest with the purpose of guiding the other ants. The next ants will then optimize the path since they will take the path that requires the lowest effort. The pheromones gradually disappear and the most recent cells remain. Figure 3 describes the optimization process with the ant colony method.

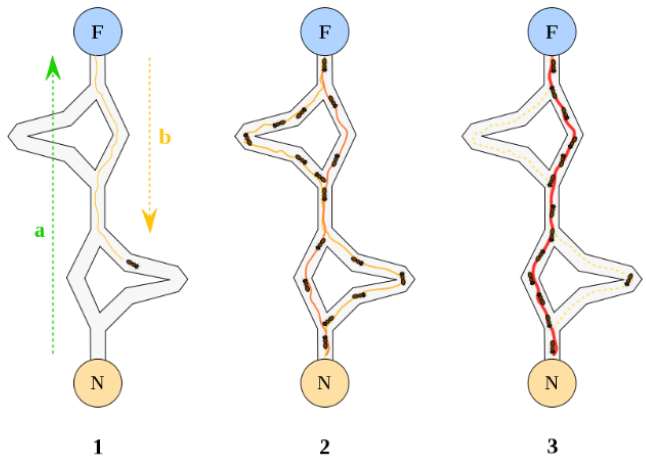

Figure 2. Ant colony optimization. Source [21]

This algorithm was developed by Marco Dorigo in 1992 [22], and is based in the natural behavior of ants while they are looking for food and seek an optimal path. ACO had the initial purpose of solving the travelling salesman problem (TSP) which consists on visiting several cities in the shortest possible time by passing only once per city, except for the origin and the final destination that can be visited twice. Although the results were good, ACO did not show a better performance than other algorithms used to solve the TSP [22]. However, it performs well in sequential orders, balance in the assembly line and in fabrication and logistics problems involving programming [23].

The k^{th} ant moves from state x to y with the probability described in equation (1)

$$p_{xy}^{k} = \frac{(\tau_{xy}^{\alpha})(\eta_{xy}^{\beta})}{\sum(\tau_{xy}^{\alpha})(\eta_{xy}^{\beta})} \quad (1)$$

Where τ_{xy} is the number of pheromones deposited in the transition to state x to y, $\alpha \geq 0$ is a parameter used to control the influence of τ_{xy}, η_{xy} is the convenience of state xy (an a priori knowledge, typically $1/dx$ with d as the distance) and $\beta \geq 1$ is a parameter to control the influence of η_{xy}.

When all ants have completed the solution, the traces are updated according to equation (2).

$$\tau_{xy} \leftarrow (1 - \mathrm{p})\tau_{xy} + \sum_{k} \Delta\tau_{xy}^{k} \quad (2)$$

Where, τ_{xy} is the number of pheromones deposited for a transition state xy, p is the pheromone coefficient and $\Delta\tau_{xy}^{k}$ is the number of pheromones deposited by the k^{th} ant, often given by the Travelling Salesman Problem.

Genetic Algorithm (GA)

Genetic algorithms are optimization, search and learning algorithms inspired in the processes of natural evolution and genetic evolution. From an initial population, the most capable individuals are chosen to reproduce and mutate, and finally obtain the following generation of individuals that is more adapted to survive than the previous generation [24].

The genes in GA are the design variables and the chromosome represents a potential solution. Possible solutions are saved after each iteration. When calculating the value of the physical aptitude (that is determined through an assessment of the individuals of a population), two individuals are chosen to be modified with genetic operators, including crossing and mutation, to create a new generation [25].

Figure 3 shows the operation of a basic genetic algorithm.

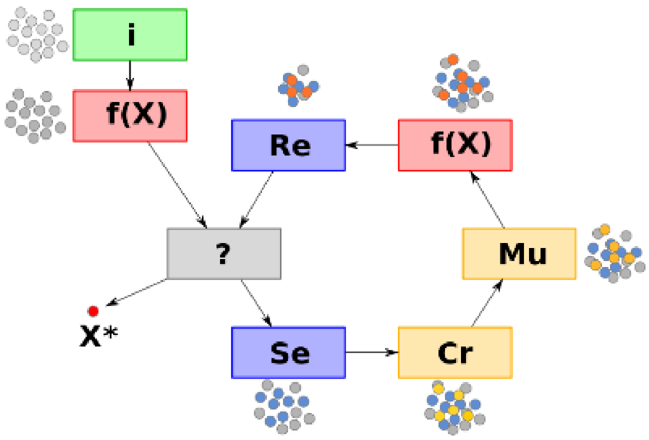

Figure 3. Genetic algorithm i: Initialization, f(X): Assessment, ?: End condition, Se: Selection, Cr: Crossing, Mu: Mutation, Re: Replacement, X*: Best solution. Source [26]

Particle Swarm Optimization (PSO)

The optimization with particle swarm, better known in scientific literature with the PSO acronym is a stochastic method of evolutional computation inspired in the social behavior of organisms such as flocks of birds or school of fishes [26].

Particles represent possible solutions. PSO are based on swarms and uses a set of particles to seek the best solutions. Then, the best experience of particles and swarms is followed in which the algorithm recollects the best location and speed of each particle. The movement of the particles is followed as the particles move until the end criterion is met, which is an optimal acceptable solution or a given number of iterations [27].

Bee Colony Algorithm (BCA)

The algorithm of artificial bee colonies was proposed by Dervis Karaboga in 2005 and is based on the foraging behavior of bees and originally designed for numerical optimization problems with no restrictions, although it can be used to solve combinatory problems [28].

There are three classifications for bees: worker, spectator and explorer. First, the worker bees seek food and when they find it, they return to the hive. Then, the spectator bees can trace high quality sources of food. When the recollection ends, the worker bee joins the explorer bees that constantly seek food. The spectator and worker bees are modelled with the exploitation method while the explorer bees are modelled with the exploration technique. The catch in the BCA method is that it is good for exploration yet it lacks the exploitation factor [25].

Taboo Search (TS)

The taboo search (TS) introduced by Glover in 1986 is a meta-heuristic approach that tackles combinatory optimization problems. More precisely, TS is an extension of local search classic methods that can be interpreted as the combination of local search with short term memories. Two basic elements of TS are the definition of its search space and its neighborhood structure. The search space is defined as the space containing all possible solutions that can be visited during the search process. Regarding the neighborhood structure in each iteration of the algorithm, the local transformation that can be applied to the current solution defines a set of neighboring solutions in the search space, i.e. the neighbor of the current solution. In fact, the environment of the current solution is a subset of the search space of all possible solutions obtained by adopting a unique local transformation for the present solution [25].

Meta-heuristic hybrid method

The implementation of two or more optimization algorithms carries superior advantages in comparison to the individual implementation. Therefore, the hybrid implementation has had a growing trend in its use. However, hybrid algorithms can be a hybrid of two or more meta-heuristics or a hybrid of meta-heuristics and traditional optimization approaches [29].

APPLICATIONS

In [30], Roberto and Thiago present an algorithm based in ACO for the optimal allocation of distributed generation in medium power electric networks. The problem is solved with the purpose of minimizing the real power losses, considering the installation costs of the generators. The ant algorithm has been tested in a radial distribution system of 33 energized bars at 12.66 kV (see Figure 4) and nine options of distributed generation that can be used several times throughout all 32 bars (without including the bar linked to the substation). The results show the efficiency of the methodology presented by managing to reduce the losses in active energy by a 59.66%. Furthermore, its robustness is shown with a good quality solution, significantly reducing the losses and improving the voltage profile.

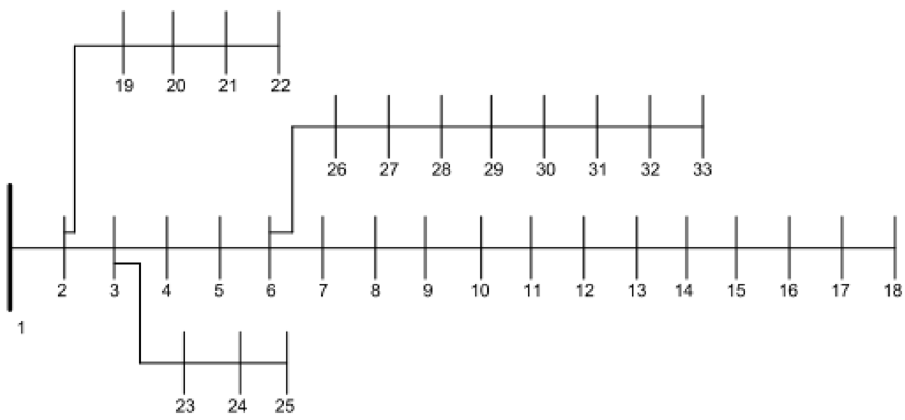

Figure 4. System of 33 bars. Source [30]

In [31], Wang Pu plans to reduce the energy consumption of a train line between the Yizhuang and Beijing stations, which are separated by 2682 meters and have an execution time of 185 seconds. An optimization method based in a golden ratio genetic algorithm is proposed. In first place, the train model is established. In second place, the optimal operation strategy of the subway train is analyzed with different tracks. Then, the golden ratio genetic algorithm (GR-GA) is proposed to solve the problem, seeking the optimal energy transfer position for the train. The results show that the algorithm has a better optimization result in comparison to the traditional genetic approach. It improves savings by 14.2%.

Furthermore, in [32], Elbaset defines the optimal and efficient design of a wind energy park in a determined territory interconnected to the electric network. This implies several complex optimization problems. Multi-target functions are shown, based on PSO techniques for an optimal distribution of the farm in a place near Zaafrana, in the Suez Golf. To begin with, the target function has to find an optimal number of wind turbines to produce a specific annual demand of energy. Then, the effect of the trail is minimized to achieve an optimal placement of the wind turbines based on binary PSO. Furthermore, the optimal number of suppliers is calculated in order to minimize the generated cost per kilowatt-hour. The trail loss model is represented by the model based on Jensen and the economic model is based on the concept of annual cost of the system. A complete numerical example is detailed within an industrial framework.

Moving on to another focus, the intermittent nature of photovoltaic (PV) solar sources' output generation due to transitory clouds leads to considerable fluctuations to be expected in the voltages of distribution systems with high penetrations of distributed generation using PV energy. Abdelfatah Ali in [33] proposes a method to mitigate voltage fluctuations caused by photovoltaic energy when simultaneously optimizing the reactive power from photovoltaic inverters and the charge/discharge of pluggable hybrid electric vehicles (PHEV). To effectively mitigate the voltage fluctuations, Abdelfatah presents a new target function that represents the average deviation in voltage. These new objective greatly reduces voltage fluctuations. The BCA algorithm is used to solve the optimization problem in real time, while the limitations of the distribution system, the photovoltaic inverters and the PHEV are considered. The simulation results in the distribution system with 33 bars prove the effectiveness of the proposed method in mitigating the voltage fluctuations for a PV generation profile with strong variations.

CONCLUSIONS

Optimization algorithms are an important tool in the search for technical solutions and financial improvements in different scenarios and integration processes of distributed generation into current electric networks and smart grids. Therefore, scientists are recommended to proceed with these developments in order to make these technologies more accessible for all users and promote the efficient use of energy.

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