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Energimyndighetens titel på projektet – engelska Planning and dimensioning of microgrid with up to a few thousand customers	
Universitet/högskola/företag Luleå tekniska universitet	Avdelning/institution Teknikvetenskap och matematik – Elkraftteknik
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Nyckelord: 5-7 st Mikronät, prognos, osäkerhet, planering, flexibilitet	

Förord

Projektet finansierades av Energimyndigheten och Skellefteå Kraft. Projektet utfördes av Luleå tekniska universitet. Referensgruppen till projektet hade representanter från, Skellefteå Kraft Elnät.

Innehållsförteckning

Sammanfattning

Projektet har fokuserat på att planera ett fristående förnybara energibaserade mikronät och på utnyttjandet av ett avbrytbar efterfrågestyrning program (ICDRP) i elkraftsystemet under osäkerhet.

Flexibilitetsresurser kanske inte finns tillgängliga för att klara av osäkerheterna i realtid driften av systemet. Källor till osäkerhet måste förutsägas i planeringsfasen. En stokastisk-probabilistisk metod baserad på Metropolis-kopplade Markovkedjan Monte Carlo simulering föreslås att förutsäga stokastiska

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beteende hos sådana osäkerhetskällor. En metod för klassificering av nya data föreslås för att härleda lämpliga sannolikhetsfördelningsfunktioner som baseras på långsiktiga historiska data. De målfunktioner som används vid mikronätsplanering är totalkostnaden och den totala energiförlusten (TEL). Den Epsilon-constraint-metoden används för att lösa ett multi-objektiv optimeringsproblem.

Slutligen verifierar resultaten att den föreslagna stokastiska modelleringen positivt påverkar planeringen och driften av ett fristående RES-baserat mikronät. Resultaten visar dessutom att det utformade mikronätet är berett att hantera scenarier med olika sannolikheter- och effekter.

När det gäller ICDRP påverkar osäkerheten i kundernas deltagande och lyhördhet i grunden elkraftsystemens drift i realtid. I den här rapporten undersöks risken i samband med utnyttjandet av osäkert ICDRP. Denna rapport syftar dessutom till att tillämpa riskhanteringskostnaden på prispolitiken för ICDRP. En riskobenägna optimeringsmetod baserad på informationsgap teori (IGDT) och Shapley-värdeberäkningen tillämpas för att utvärdera risken för osäkert ICDRP och ändra prispolitiken för det.

Den Shapley-värdeberäkningen används för att fastställa incitamenten som tillämpas på icke-lyhörda ICDRP-deltagare baserat på effekterna av ICDRP-deltagarnas kooperativa beteende på riskhanteringskostnaden. Resultaten visar att osäkerheten i ICDRP framförallt påverkar balansen mellan elproduktion och elförbrukning av elkraftsystemet. Dessutom, lutningsförmåga reserver och nätet topologi befanns spela en viktig roll i den tillhörande risken att utnyttja osäkra ICDRP i realtid drift av elkraftsystemet.

Summary

This report focuses on planning stand-alone renewable energy-based microgrids and the utilization of interruptible/curtailable demand response programs (ICDRPs) in the real-time operation of power systems, both studies considering uncertainties.

Flexibility resources may not be available to cope with the uncertainties in the real-time operation of the system. Sources of uncertainty need to be predicted accurately in the planning stage. A stochastic-probabilistic method based on Metropolis-coupled Markov chain Monte Carlo simulation is proposed to predict the stochastic behavior of such uncertainty sources. A novel data classification method is proposed for deriving appropriate probability distribution functions (PDFs) based on long-term historical data. The objective functions used in microgrid planning are the total cost and the total energy loss (TEL). The epsilon-constraint method is used to solve a multi-objective optimization problem.

Finally, the results verify that the proposed stochastic modeling positively impacts the planning and operation of a stand-alone RES-based microgrid. Moreover,

results show that the designed microgrid is prepared to cope with diverse probability and impact scenarios.

Regarding ICDRPs, the uncertainty in customers' participation and responsiveness profoundly affects the real-time operation of the power systems. In this report, the risk associated with the utilization of uncertain ICDRP is investigated. Moreover, this report aims to apply the risk management cost to the pricing policy of ICDRP. A risk-averse optimization method based on information gap decision theory (IGDT) and the Shapley value calculation is employed to evaluate the risk of uncertain ICDRP and modifying the pricing policy of ICDRP.

The Shapley value calculation is used to determine the penalties applied to non-responsive ICDRP participants based on the impact of the cooperative behavior of ICDRP participants on the risk management cost. The results show that the uncertainty of the ICDRP notably affects the balance between generation and load consumption in real-time operation of the power system. Also, the ramping capability of reserves and the network topology was found to play a significant role in the associated risk of utilizing uncertain ICDRP in the real-time operation of power systems.

Inledning/Bakgrund

Nowadays, renewable energy sources (RESs) are being used widely to supply electricity, especially in remote areas [1]. Combining different energy sources can improve the planning and operation of energy systems from economic and technical viewpoints. Moreover, considering a hybrid RES-based system enhances the flexibility of an energy system.

According to the U.S. Department of Energy, a microgrid is a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes [2]. Microgrids are a popular alternative to integrate RESs, which are becoming prevalent [3]. Nevertheless, the uncertainty of RESs is a challenge not only in designing a RES-based microgrid but also in its operation [4]. This challenge is becoming more prominent, especially when it comes to planning a stand-alone RES-based microgrid [5], [6].

Load consumption is another critical source of uncertainty. The adequacy of reserves, keeping the energy balance in the long-term planning and real-time operation, reliability, and the capital and operation costs are essential issues in microgrids planning [7]–[9]. The operator of a microgrid uses smart grid technologies, such as energy storage, demand-side management, vehicle-to-grid, etc. to deal with these uncertainties. As the flexibility alternatives in the operation stage can be limited, carefully considering these uncertainty resources in the planning level will further help the system operator to keep the power balance in real-time.

Interruptible/curtailable demand response program (ICDRP) is part of dispatchable loads used at peak hours or emergencies [10], [11]. It comes along with customer incentives that provide a rate discount or bill credit for accepting to curtail load consumption. Participants who do not adjust their consumptions typically are obligated to pay penalties. The terms of the ICDRP contracts are negotiated by policy-makers, network operators, and load-serving entities. The final response to the contract depends on the participants' conditions (i.e., social behavior, revenue, incentives, and penalties). In practice, since participants often do not respond to the contract, ICDRP utilization imposes a significant burden of risk upon system operation [12]–[15]. This uncertainty affects the transparency of the pricing policy of ICDRP and the advantages of using ICDRP as an ancillary service.

There are several stochastic and deterministic methods to model the behavior of uncertainty sources in the planning process of microgrids. Forecasting methods have been used in several articles to design a grid-connected microgrid [16]. These methods can model time series, seasonality, and long-term trend of uncertainty sources for a specific time duration in the future. Nonetheless, there are some problems associated with using well-known autoregressive forecasting methods (i.e., ARMA, ARIMA, and SARIMA) to design a stand-alone RES-based microgrid. These methods generate scenarios with high probability based on conditional density by taking into account trends and seasonality. Nevertheless, these methods cannot generate scenarios with a low probability but high impact on the operation of stand-alone renewable energy-based microgrids (e.g., one week with stormy weather every year) [17].

This research work deals with the stochastic optimal planning of a stand-alone renewable energy-based microgrid with up two thousand customers. Besides, it evaluates the risk-averse optimal utilization of demand response programs as a flexibility source in power systems' operation. The main objective is to design a microgrid considering all notable uncertainties, modeling their stochastic behavior, and utilizing different flexibility sources within a stochastic planning approach.

Genomförande

The project started on June 1st 2018 and was finished on December 31st 2020. The project was developed at Luleå University of Technology, with Math Bollen as project leader. Involvement from Skellefteå Kraft R&D group allowed to build a case study for a community with about 2000 customers within the municipality.

People involved in the project:

- Math Bollen, LTU, Project Leader
- Jin Zhong, HKU, Hamed Bakhtiari main supervisor
- Manuel Alvarez, Hamed Bakhtiari co-supervisor

Technical implementation

The project was developed in two main parts. The first part was about planning a standalone RES-based microgrid. The second part was about evaluating the associated risk of utilizing uncertain ICDRP.

The used approaches are presented as follows:

- A retrospective model is used to represent the stochastic behavior of uncertainty sources in a deterministic way. Monte Carlo simulation, Markov chain Monte Carlo, and Metropolis Coupled Markov chain Monte Carlo simulation are applied to model the behavior of uncertainty sources in a stochastic way.
- A novel data classification method is proposed to model the time-dependency in generated values (Papers A and B). Moreover, a novel curve fitting approach is examined to improve modeling accuracy of Markov chain states and the long-term probability of uncertainty sources (Paper A).
- A multi-objective optimization problem has been solved using the particle swarm optimization (PSO) method. The epsilon-constraint method is used to build the Pareto frontier (Paper B).
- The optimal risk-averse utilization of the demand response program is determined using information gap decision theory (IGDT). This method helps system operators to be prepared to cope with the unknown uncertainties of customers' responses (Paper C).
- Shapley values have been used to find the best nodes for implementing demand response programs. It is also used to determine the penalty for participants who are not responding to their contracts (Paper C).

Resultat

The results of this project are organized according to the contributions on the papers A, B and C.

Paper A

- A modified MC^3 simulation model has been presented to improve the process of predicting stochastic behavior of wind speed, solar radiation, water flow, load consumption, and electricity price in planning a RES-based microgrid.
- A novel data classification method has been proposed by considering the concept of adjacency and periodic correlation.
- A new curve fitting method has been proposed to determine the representative PDFs for uncertainty sources with multimodal distribution function.

- The modified MC^3 has been benchmarked against the MCS and retrospective model from different viewpoints.
- With regards to the simulation models to represent the stochastic behavior of uncertainty sources, neither a retrospective model nor the Monte Carlo simulation (MCS) model is competitive in terms of accuracy when compared to the Metropolis-coupled Markov chain Monte Carlo MC^3 simulation model.
- The worst year data, out of long-term historical data, has been considered the input data in a retrospective model. In the retrospective model, the occurrence probability of selected values is too low, and the Pearson correlation coefficient (PCC) between the histograms of the selected values and the long-term historical data is low. Consequently, the planning process is likely to end up with an oversized microgrid.
- Although the MCS model generates samples in a stochastic process with an accurate probability distribution function (PDF), it cannot represent the time-dependency, the continuity of predicted values, and the steady-state probability of uncertainty sources accurately.
- The modified MC^3 simulation shows a high correlation between the histograms of the 8760 predicted values and the long-term historical data. The results confirm that the time dependency and continuity of predicted samples have been appropriately modeled. Moreover, the high correlation between the steady-state probabilities of the predicted values and the long-term historical data represents that the modified MC^3 can model the long-term stochastic behavior of uncertainty sources.

Paper B

- The MC^3 simulation model has been used to predict uncertain variables' stochastic behavior in planning a stand-alone RES-based microgrid comprising wind turbines, PV panels, and hydro turbines, hydrogen storage system, and battery.
- The total cost of the system planning and the total energy loss have been taken into account as objective functions in planning process.
- Two additional models, the retrospective and simple MCS models, have been considered to verify the designed microgrid using the proposed method.
- The operations of three designed microgrids have been evaluated using the historical data of the last three years.
- Using the retrospective model for the data, has resulted in an oversized microgrid. Using the MCS model has resulted in oversized power capacity and undersized energy capacity.

- The results show that using the MC^3 simulation model has improved the planning process of a stand-alone RES-based microgrid from the economy and reliability viewpoints. The model has decreased the total cost of planning by enhancing the representation of uncertain variables.
- The real impact and advantages of PV panels and hydrogen storage systems have been demonstrated in a city in the northern part of Sweden. Furthermore, it shows that the designed microgrid can cope with all possible worse scenarios like windy, rainy, and snowy days. In other words, the planning process of a stand-alone RES-based microgrid has been improved from both energy and power capacity viewpoints.

Paper C

- To study ICDRP, a three level optimization problem has been formulated aid by an optimal power flow (AC-OPF), the calculation of Shapley values, and information gap decision theory. Through the OPF the effect of the network is considered.
- Three objective functions are evaluated namely, maximizing the purchasing price of ICDRP, minimizing the penalties to the participants, minimizing the risk for the system operator should be able to cope with 100% of uncertainty regarding the response of the participants.
- The difference between the locational marginal prices (LMPs) with and without DR has been used as a reference to define the purchasing price of demand response.
- The impact of the variation of the purchasing price of ICDRP over the locational marginal price, and consequently in system operation costs, is studied using a sensitivity analysis.
- To consider the ramping capabilities of the system, the transition between the penultimate hour towards the peak-hour have been considered in the AC-OPF.
- The ramping capability of reserves should be considered as a criterion in the risk-averse utilization of ICDRP. The frequency regulation requires that load and generation are balanced in the required time window, and for the system operator this requirement translates into ramping capability.
- Penalizing the non-responsive participants, applying the cost of coping with associated risks of utilizing uncertain ICDRP, to the pricing policy of ICDRP, helps the system operator cope with the uncertainty coming from the participants response. The higher the penalty and the purchasing price,

the higher the uncertainty ratio the system operator will be able to deal with.

- Further studies are needed to investigate the impact of reserve capacities on the utilization of uncertain ICDRP for a duration bigger than one hour.

Diskussion

Paper A

The simulation method allows to compress long-term historical data into a representative year that does not look like any year in the raw database, but has an equivalent impact from the operation point of view, and regarding scenarios and their frequency of occurrence. The fitting procedure proposed for multimodal probability density functions allows to capture infrequent scenarios that might have a big impact in the system.

Paper B

The developed optimization model to design the microgrid does not focus on a particular investor. According to unbundling regulation, the system operator cannot own the resources within the grid but could be partially involved in the operation of the system. The pursuit of the system operator is an improvement in the availability of the service, and a reduction of the electricity cost to the final customers. For the required reliability level of the electrical service in Sweden, an standalone microgrid seems to be a far too expensive alternative for the consumers, or a non-profitable option for investors. A grid connected microgrid will be investigated in future research endeavors.

Paper C

Customer participation in DSM is limited. Despite being registered in DSM programs, electricity users do not necessarily engage actively in real time when requested. The DSM program could potentially reduce the electricity bill for the customers, and the revenue gap for the system operators. The DSM program studied in this project is mainly intended for congestion management.

The study considers industrial customers. These customers respond to a price signal. The contract form is assumed to be a moving price agreement. The mechanism by which the consumers are informed about the price in real time, i.e. technology, smart metering, local energy management system, and the relationship with the industry type, and their particular operational restrictions will be investigated in future research endeavors.

Publikationslista

Paper A: H. Bakhtiari, J. Zhong, M. Alvarez, "Predicting the stochastic behavior of uncertainty sources in planning a stand-alone renewable energy-based microgrid using Metropolis coupled Markov chain Monte Carlo simulation" submitted to Applied Energy, 2020.

Paper B: H. Bakhtiari, J. Zhong, M. Alvarez, "Planning and evaluation of a stand-alone renewable energy-based microgrid using Metropolis-coupled Markov chain Monte Carlo simulation" submitted to International Journal of Electrical Power & Energy Systems, 2020.

Paper C: H. Bakhtiari, J. Zhong, M. Alvarez, "Investigating the Impact of Ramping Capability of Reserves on Risk-Averse Utilization of DR Programs: A Shapley Value-Based IGDT Approach" to be submitted to IEEE Transactions on Power Systems, 2020.

Paper D: Bakhtiari, H., Zhong, J., & Alvarez, M. (2021). The Utilization of demand Response Programs in Renewable-Based Microgrids: Benefits and Challenges. Under writing - to be presented in CIRED 2021.

Paper E: Bakhtiari, H., Kazi Ahmed, M. U., Zhong, J., & Bollen, M. (2021). A stochastic modelling of electrical vehicle load and its impacts on the Swedish distribution network. Under writing - to be presented in CIRED 2021.

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Bilagor

- Administrativ Bilaga
- Half-way report (KÄNSLIG INFORMATION)
- Vetenskaplig artikel A (KÄNSLIG INFORMATION)
- Vetenskaplig artikel B (KÄNSLIG INFORMATION)
- Vetenskaplig artikel C (KÄNSLIG INFORMATION)