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論 文 内 容 の 要 旨

Improvement of smart grids and ICT (information and communication technology) has created new resources for the power systems. One of the availed new resources is demand response resources. Demand response (DR) can be defined as following;

"*Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*"

DR can be categorized mainly into reliability driven and economical driven types. Reliability driven DR resource are used when the power system reliability is under threat.

On the other hand, random failure of power system equipments, which is a threat to power system security, necessitates the introduction of spinning reserve resources as a way to secure the system and reduce the risk of blackouts and unplanned interruptions of power. Spinning reserve can be defined as "*the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power*". Optimal scheduling of spinning reserve is very important due to increasing urge for reliable electrical energy and integration of intermittent renewable energy resources such as wind generation.

Utilization of reliability driven DR resources in provision of spinning reserve provision is new. In most research on this topic, only the generation side has been considered in the reserve scheduling process and the demand side is mostly considered to be inactive or it is considered as a resource to cut the peak.

Reserve supplying demand response (RSDR) resources are demand response resources that have fast response and are utilized for spinning reserve provision. These resources are rather new in power system operation and will directly affect system reliability and reserve scheduling. However, since the optimal operation of the system will be affected by the spinning reserve provision considerably, they can affect economical aspect, generators scheduling and hence emitted pollution. Successful operation of power systems cannot be achieved if the effects of all new resources are not studied. Studying the effect of such demand response resources is in need of suitable frameworks, evaluation methods and analytical tools. The main goal of this dissertation is developing required methodology to incorporate fast response demand response resources, that are active in spinning reserve market, in optimal power system scheduling and analyze its different effects in system operation.

In this dissertation at chapter 2, first the RSDR resources are integrated in to a simultaneous system scheduling framework with social cost minimization point of view. Utilized scheduling framework considers the expected load-not-supplied cost, taking into account the load reliability requirements. Due to high computational burden of the adopted framework a mixed integer based optimization method was developed. In this method, first the binary variables of contingencies that are less than assumed threshold will be eliminated. This threshold will be adjusted in following iterations up to time to reach to optimal reserve schedule. Then in order to have a general understanding of RSDR resource effects, its effects are compared with contributions of peak clipping demand response (PCDR) resources. Numerical simulations show that RSDR resources are effective in increasing system reliability and reducing the social cost. However, this amount is influenced by factors such as the value customers attach to their reliability, offered DR price, load level and considered uncertainty level in generation side. This resource shows high capabilities for social cost reduction and reliability improvement when compared with PCDR resources. Also the numerical results show that the developed optimization method can reduce the computational burden while reaching to the optimal solution. At the end of this chapter, a model was developed for customer's decision making process from customer's point of view and how paid incentives for reserve and energy and other related parameters can influence the customer's decision in adopting a DR activity was studied.

The analysis in chapter 2 shows that the RSDR can affect different system aspects. Therefore, the study was extended to consider its effect on pollution emission reduction in chapter 3. In this chapter, in order to analyze the effect of RSDR resource on pollution emission reduction-operation cost tradeoff curve, the conventional combined environmental economic dispatch (CEED) was extended to consider the optimal reserve scheduling and RSDR resources. This is because the optimal system scheduling is affected by emission reduction and consecutively changes in the system scheduling, affects optimal reserve scheduling. Therefore, these aspects have mutual effects on each other and theoretically their mutual effect cannot be ignored specially in the new circumstances of power systems where intermittent renewable energies are integrated into power system. Considering this effect was not possible in conventional CEED frameworks. In this chapter, using the extended CEED, the effects of system optimal reserve scheduling and system pollution (SO_2, NO_x and CO_2) cost reduction were analyzed. The effects of relevant important parameters were also evaluated. The simulations carried out in this chapter show not only the amount of required reserve but also the type of units that provide reserve are changed by considering pollution emission. This chapter also showed that RSDR resources, which are not associated with actual reduction of the demand in the energy market, can be an effective tool for improvement of the environmental-economic cost characteristics. Although the system scheduling method and the system parameters can limit its effectiveness, its positive impact on reducing the pollution cost at the same operation cost level can be observed under a wide range of uncertainties considered for the parameters.

The best candidates for the RSDR resource, such as air conditioning load, have payback effect. The probabilistic payback effect can put a reliability threat on power system if ignored in power system scheduling. Therefore, the scheduling horizon was extended to 24 hours and a new model was proposed for integration of probabilistic payback effect of RSDR resources in chapter 4. In order to do this, the extra interruption cost imposed by probabilistic payback of RSDR resources was formulated and integrated in the objective function. Simulation results show that when probabilistic payback is taken into account, in higher load reliability requirement less of the RSDR bid will be accepted in comparison to the case of lower load reliability requirement. At the same time, the ability of an RSDR resource to reduce the total system cost will drop. However, even with payback characteristics, the RSDR assists the system in reducing the total system cost and improving the reliability of the system. As the numerical simulation of this chapter suggests, when the RSDR resources have payback that is ignored in the scheduling process, the final schedule will be more costly and the expected interruption cost will rise compared to the case in which this effect is not ignored but rather integrated into the market scheduling, as is done in this chapter.

論文審査の結果の要旨

本論文では，電力システムの運用計画において供給コストと停電コストの和で表される社会コストに基づき，これを最小化する瞬動予備力を決定する方法を提案している。従来の電源運用計画を拡張し，需給逼迫時の需要調整手段として新たにデマンドレスポンスの導入を提案し，経済性や環境性からみた導入効果を，シミュレーションにより検証している。その主要な成果は，以下の通りである。

(1)予備力供給型デマンドレスポンスについて，入札価格等をパラメータとした，単一時間断面における適正予備力や社会コストに与える影響を分析している。さらに，提案する予備力供給型デマンドレスポンスを従来のピークカット型デマンドレスポンスと比較することにより，電力システムの系統運用コストや需要家停電コストに与える影響および，系統運用者からみた導入効果の違いを明らかにした。一方，需要家における経済性の視点から，ピークカット型と予備力供給型の各インセンティブの設定が需要家意志決定に与える影響を評価し，シミュレーションにより提案法の妥当性を確認した。

(2)経済性のみを考慮した従来の電源運用計画に対し，本論文では予備力とデマンドレスポンスを考慮するとともに，環境指標として SOx, NOx, CO_2 を考慮した電源運用計画を提案・評価している。デマンドレスポンスの導入により，オフピーク時間帯では経済性の改善よりも環境負荷の低減効果の方が大きく，逆にピーク負荷時には環境性より経済性の改善に効果的であることを明らかにしている。すなわち，デマンドレスポンスが瞬動予備力を供給することにより，電力システムの経済性だけでなく環境負荷についても削減できることを示した。

(3)本論文では，予備力供給型デマンドレスポンスにおけるペイバック現象が，発電機の起動停止計画におよぼす影響を評価した。ペイバック現象による，適正予備力や社会コスト，発電機の起動停止計画に与える影響を評価した結果，デマンドレスポンスにより削減した負荷の 70%がペイバックとして次の時間帯に生じた場合，社会コスト削減量が減少するため，ペイバックの存在を陽に考慮した運用計画の必要性を示している。なお，予備力供給型デマンドレスポンスにおいて，ペイバック現象を考慮することで最適化計算における組み合わせ数が膨大となるが，提案する起動停止計画では想定事故を選択する際のパラメータを適切に更新することにより，実用的な時間内で最適解が得られることを示している。

以上のように，本論文では電力系統の最適運用におけるデマンドレスポンス導入の提案と，その導入効果分析において重要な知見を得ており，電力系統技術の進展に貢献する成果を挙げている。よって，本論文は博士論文として価値あるものとして認める。