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主　論　文　の　要　旨

論文題目　**Photovoltaic Power System Control to Increase the Flexibility of Frequency Control in Electric Power System**
(電力系統における周波数制御の柔軟性向上のための太陽光発電システムの制御)

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論　文　内　容　の　要　旨

In order to realize a carbon neutrality by 2050, Japanese government has set targets to achieve a substantial increase in renewable energy capacity, encouraging the development of renewable projects and the deployment of advanced technologies. As photovoltaic power generation (PV) systems will be most dominant renewable energy source, it is expected to provide ancillary services in the power system to support the grid frequency

PV systems currently undergo the maximum power point tracking (MPPT) control and its unstable power output property depending on irradiance fluctuation will increase the fluctuation of residual electricity load in overall power system. High penetration rate of intermittent PV power output becomes more prevalent and that will lead to various challenges for stable operation. Preserving the requirement of flexibility resources for maintaining grid frequency is one of the main challenges

Addressing the challenges associated with the increased penetration of PV system into the power system requires a combination of technological advancements. By adopting a holistic approach that considers grid flexibility, forecasting, and inverters' control upgrades, it is possible to ensure the stable operation of the power system while maximizing the benefits of PV systems.

Firstly, to implement PV-based frequency regulation effectively, it requires the integration of smart grid technologies and advanced control systems. These technologies allow for real-time monitoring and control of PV systems, enabling them to respond rapidly to grid frequency fluctuations. Additionally, appropriate market mechanisms and regulatory frameworks need to be in place to incentivize and facilitate the participation of PV systems in frequency regulation services. This approach not only optimizes the use of PV power but also contributes to the stability and reliability of the power system.

To perform a combination of different control schemes in a single PV-based control, PV system can accommodate two control schemes; firstly, to mitigate frequent fluctuations of load or generation disturbances and secondly, to suppress frequency deviations in contingencies. Most importantly, both control schemes should be applied simultaneously. Therefore, the first objective of this dissertation is to develop an autonomous active power control based on a dual active power–frequency (*p–f*) droop control is proposed which can respond to normal and sudden frequency fluctuations, and to demonstrate that it can work well without a negative dynamic conflict by using a numerical simulation.

In the proposed dual *p-f* droop control, the large frequency change of frequency can be detected immediately by the direct measurement (fast frequency measurement), while small frequency change of frequency within the regulation range is measured with low-pass filter for the stable measurement (slow frequency measurement). According to these measurements, in case of small fluctuations within regulation range, slow response control is activated, and PV system should respond properly, which should be addressed by LFC in power system. In case of detection of fluctuations exceeding the regulation range, fast response control becomes essential however, fast response control might cause higher fluctuations after the suppression of occasional violation of frequency threshold. Hence, slow frequency response will be required to operate simultaneously with fast response control to avoid these violations.

In this study, a combination of two different droop characteristics for slow-frequency and fast-frequency responses is proposed through three designs, e.g., Method-0 is a basic initial design proposal and Method-1 and Method-2 are the enhanced design proposals.

Two simulation models were conducted to highlight the importance of slow and fast responses of the enhanced methods. The first simulation test highlights the importance of slow-frequency response in mitigating the normal frequency fluctuations over a period of time. Whereas the second test shows the influence of fast response in both methods in the case of a dropout of one generator in the system.

The results revealed that the slow and fast frequency controls can work in coherence. As for Method-1, the fast frequency control enabled the mitigation of the frequency deviations that violated the frequency threshold in a quick manner. However, during the recovery of frequency, this method was effective in leading a smooth recovery due to the introduction of the transition signal and the switching of the thresholds. Whereas, Method-2 of dual *p-f* droop control that was anticipated to have a delay of reaction to the frequency violation, proved that that delay was insignificant in the simulation tests. It also provided smoother transitions than Method-1 from slow to fast controls in the recovery phase. That proves that Method-2 outperforms Method-1 in its simplicity as the main purpose of this study is creating the simplest version of dual *p-f* droop control.

Secondly, to utilize PV power for frequency regulation, another potential solution is to minimize PV power output curtailment and optimize the use of PV system. Frequency regulation is a critical aspect of grid stability, ensuring that the supply and demand of electricity remain balanced. Traditionally, this role has been fulfilled by conventional power plants, but with the increasing adoption of PV systems, PV systems can also contribute to frequency regulation.

The current PV power output curtailment scheme in Japan is that the power system operators forecast the PV power output and plan PV power output curtailment in a day-ahead UC scheduling. They communicate the curtailment plans to PV plant operators to ensure coordinated curtailment. Particularly, the power system operator will randomly communicate with PV plants to be disconnected based on the curtailment plan.

Consequently, the aggregated PV power output will be reduced meanwhile, the aggregated PV fluctuations characteristics will still exist. However, in the future, the curtailment scheme will be changed to determine the upper limit of PV smart inverters power output. This will reduce the aggregated PV power output as well as the aggregated PV fluctuations. Hence, reduced aggregated PV fluctuations will reduce the required flexibility capacity.

Therefore, it is essential to determine the curtailment level (CL) of each PV power output so that the fluctuations in the aggregated PV power output are further minimized as it is a major cause of frequency fluctuations. When the required flexibility capacity is reduced, the requirement of curtailment can be reduced, hence mitigating the waste of PV power output.

Therefore, the second objective is to propose PV power curtailment scheme so that CL in each region is optimally allocated to minimize the fluctuation of aggregated PV power output without precisely forecasting the time-series of PV power output. In this proposal, a simple straightforward approach should be adopted assuming that the fluctuation characteristics can be predicted in the short-term forecasting and be expressed in several typical patterns. Thus, instead of using huge accurate forecasted time-series PV power output for each region, each region will be given a typical prepared pattern that reflects its level of fluctuations based on the short-term forecasting.

The proposed method employs two functions, i.e. the relationship between CL and maximum fluctuations (MF), and between CL and average power output (Avg) prepared for typical fluctuation modes based on statistical data of past PV irradiance observations. Accordingly, the optimal CL is allocated to minimize the fluctuations in aggregated PV power output by merely identifying the region's MF and average modes instead of precisely observing the short-term time-series PV power output.

The proposed methods were tested using the time-series of PV power output at 61 observation points in the central region of Japan for one year. The results of the proposed methods were found to be almost as effective as the method using perfect short-term forecasting of PV power output.

The proposed methods becomes functional when there are regions with different modes of power output ranging from fluctuating to non-fluctuating, and high average to low average regions meaning that different modes of MF-CL and Avg-CL are utilized for optimizing the CL allocation. However, for days with similar modes among different regions, for instance in summer days with high and uniform power output, the same CL application can be sufficient.

In summary, the deployment of smart inverters with droop control brings practical benefits such as grid stability and enhanced grid resilience. On the business side, it creates opportunities for revenue generation through ancillary services and participation in grid services markets, while also driving changes in business models and necessitating regulatory adjustments. Overall, these advancements contribute to a more reliable, flexible, and sustainable energy system in both the practical and business realms.

It is also important to note that while curtailment reduces the immediate utilization of PV power, it can still be a valuable strategy for grid management and long-term sustainability. Striking the right balance between PV power curtailment and maximizing renewable energy utilization is a key consideration for the successful integration of PV power into the energy landscape.