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論　文　名	「Harmonic Analysis in Electric Power Systems with Independent Component Analysis （独立成分分析手法を用いた高調波解析に関する研究）」
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論文要旨

The Alternate Current (AC) electric power systems are designed to operate with sinusoidal voltage and currents. However, nonlinear and electronically switching loads will distort steady state AC voltage and current waveform which is called harmonics. Harmonics are component of a distorted periodic waveform whose frequencies are integer multiples of the fundamental frequency. When the waveform is identical, it can be shown as a sum of pure sine waves where the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. The impact of harmonics in electrical power systems has been increasing during the last decades.

For the increasing of harmonic distortion on power systems, the harmonic mitigation methods are necessary. The harmonic filters are designed for this purpose, which include passive filter and active filter. The reliable design of a passive filter requires a correct knowledge of the system harmonic impedance and its variations throughout the day to avoid creating a resonance condition, which could destabilize a power system. Active filters also require a good knowledge of the system harmonic impedance to ensure stable controller operation and also can be used in the generation of the filter reference currents. For harmonic analysis and mitigations, the identification and measurement of harmonic impedance has become an important issue in electric power systems.

Identification of harmonic sources in power systems also has been a challenging task for many years. Many techniques have been applied to determine customer and systems responsibility for harmonic distortion. As the method with synchronized measurements in multiple points in the network is a rather difficult and expensive task, more practical approaches are based on measurement data at the Point of Common Coupling (PCC) between the customer and the systems. Although there are a few indices dealing with harmonic contribution determination at PCC, none are widely used in practice.

The main objective of this thesis is to estimate the system harmonic impedance and the

harmonic current contribution of industry load at PCC. The both methods are based on the complex value Fast Fixed Point Independent Component Analysis (Fast-ICA) algorithm, which is the most powerful algorithm in ICA algorithms. The main advantage of these methods is that only harmonic voltage and current have to be measured for estimation without knowing the systems information and disrupting the operation of any devices. This thesis is organized in 7 chapters, described as follows:

In Chapter 1, as introduction of the thesis, the background and motivation of these researches are described. A common philosophy of harmonic analysis in power system is to conduct a deterministic study based on the worst case in order to provide a safety margin in system design and operation. However, this often leads to overdesign and excessive costs. Field measurement data clearly indicates that voltage and current harmonics are time-variant due to continual changes in load conditions. Consequently, statistical techniques for harmonic analysis are more suitable, similar to other conventional studies like probabilistic load flow and fault studies.

In Chapter 2, as the basic of our study, fundamentals of harmonic, harmonic sources, effect of harmonic distortion, limits of harmonic distortion and mitigation techniques of harmonics are presented. The wide spread utilization of power electronic devices has significantly increased the number of harmonic generating apparatus in the power systems. The harmonics distortions of the voltage and current have adverse effects on electrical equipment such as increase losses of devices, equipment heating and loss of life. To eliminate the harmonic current and voltage distortion, the harmonic analysis becomes an important and necessary task for engineers in power systems.

In Chapter 3, the ICA algorithm, known as one of Blind Source Separation (BSS) techniques, is introduced. BSS techniques have received attention in applications where there is little or no information available on the underlying physical environment and the sources. BSS algorithms estimate the source signals from observed mixtures. The word 'blind' emphasizes that the source signals and the way the sources are mixed, i.e. the mixing model parameters, are unknown. ICA transforms the observed signals into mutually, statistically independent signals. It thus exploits the statistical independence between the sources. Statistical properties of signals are a key factor in estimation by ICA, since there is almost no other information available.

In Chapter 4, the characterizations of the waveform distortion from grid-connected Photovoltaic (PV) plants under different installing capacity are described. The stochastic aggregate harmonic load model is introduced to represent the harmonic current of loads and used the inverter model that is modeled by measurement data to represent the harmonic current of PV. The numerical simulation is consist two parts: Mega-PV and residential type PV. As a result, with the increasing of installed PV, the harmonic current and harmonic voltage at the connected point also increased. When the installed capacity of PV is up to 30%, the harmonic current distortion at the connected point will exceed the standard limit of Japan. The simulation shows that increasing of PV will make a serious power quality problem where it is connected.

In Chapter 5, the technique that estimates system harmonic impedance at PCC is described. Harmonic impedances of a supply system characterize the frequency response characteristics of the system at specific buses. It is very desirable in many applications to directly measure the system harmonic impedances. This method uses the complex value Fast-ICA algorithm to estimate the system harmonic impedance. The method introduced the Norton equivalent circuits to set up the linear mixing ICA model to estimate the system harmonic impedance in condition that customer side harmonic impedance changing. The method just needs one point measurement data at PCC which is not necessary the extra device. Furthermore, the method does not require the any knowledge of system parameters. The method used the Fast-ICA twice to avoid the effect of orthogonalization which is necessary in Fast-ICA algorithm. As a result, the method can estimate the system harmonic impedance correctly. However, when changed the kurtosis of harmonic current source represent equation from -0.8 to -0.3, the MAE of estimated system impedance is also increased

In Chapter 6, the estimation of harmonic contribution of industry load at PCC is described. The industry load can be departed to three part easily, which before the working, under the working and after the working. And in each part, the loads are swing in the same level. Thus, it can be assumed that the customer side harmonic impedance of each part is changing small in mixing process. As a result, the artificial data simulation proved that the method is suitable to evaluate the harmonic contribution at PCC. The measurement data simulation shows that the customer side is mainly responsible for the harmonic current distortion. However, the customer is not full responsible for harmonic current at PCC. The system side also have responsible for harmonic current distortion.

In Chapter 7, concludes the thesis with a summary, review of main contribution points.

審査結果の要旨

本論文は、エネルギー問題の解決のため太陽光発電が電力システムへ大量導入されることで顕在化すると予想される高調波障害を低減するために、電圧・電流の高調波を高精度、高効率に推定する新たな手法について研究したものであり、以下の成果を得ている。

（１）太陽光発電の大量導入により、電力システムの電流・電圧ひずみが増加し、導入率 30%を超えると高調波電流の流出量が、連系ガイドラインの上限値を超える可能性が高いことを数値シミュレーションにより明らかにした。

（２）システムモデルの情報を必要とせず、一地点での観測データだけで状態推定が可能である独立成分分析を新たに電力分野に適用し、上位系統高調波インピーダンスの推定を行った。実測値を参照して設定したデータによる数値シミュレーションにより、高調波フィルタ設計に重要となる上位系統高調波インピーダンスが精度よく推定できることを明らかにした。

（３）逐次的直交化の影響による推定誤差を低減するため、独立成分分析の推定結果を用いて再度試行する推定手法を提案し、数値シミュレーションによりその有効性を検証した。その結果、元信号である上位系統高調波電流と負荷高調波電流がガウス分布に近づくほど、上位系統高調波インピーダンスの推定誤差が大きくなることを確認し、推定精度を向上させ

るための提案手法の適用指針を明らかにした。

（４）高調波発生源の推定として独立成分分析を応用した新たな高調波方向別分離手法を提案した。数値シミュレーション結果より、提案手法は負荷の高調波電流を方向別に精度よく分離できることを明らかにした。

（５）太陽光発電が設置された工場負荷の実測値を用いて提案手法の有効性を検証した。その結果、高調波電流は主として工場負荷側で発生されており、電流歪の主原因は工場側にあるが、高調波電流の一部は上位系統側からも発生していることを明らかにし、提案手法の実システムへの応用についての知見を得た。

以上の諸成果は、高調波の発生源とインピーダンスの推定を、電力システムに擾乱を起こすことなく、かつ、一地点での観測データのみを用いて高精度に実現するもので、実用面からも有効であり、高調波フィルタ設計への応用等による高調波障害の低減によりシステムの信頼性向上に貢献するところ大である。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。