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A novel frequency-domain approach for distributed harmonic analysis of multi-area interconnected power systems

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ABSTRACT

This paper presents a novel frequency-domain approach for distributed harmonic analysis (DHA) of a multi-area interconnected electric power system within restructured environment. The proposed approach is based on a decentralized structure in which harmonic analysis of an area is independently conducted, even with limited available data, via local computing resources. The large-change sensitivity (LCS) concept is then applied in a secure platform to account for the effects of whole network to each single area of the interconnected power system. Frequency-dependent models of system elements accompanied by any existent harmonic assessment method can be utilized for harmonic penetration calculation. The proposed DHA approach is capable of finding exact values as those of the interconnected system using TCP/IP communication facility. Moreover, it allows operator of a utility to independently conduct DHA within a restructured power network. The developed method is implemented in an existing software package and applied to several networks including the IEEE 118-bus test system.

1. Introduction

During the last decade, electric power systems have experienced several changes raised by increasing privatization and newly deregulation polices. The prevalent vertically integrated structure has been substituted by a competitive arrangement which has affected both operation and planning aspects [1]. Power systems engineers believe that some issues such as system reliability, control, security, and power quality, require further scrutiny and research in the new environment [2]. To achieve such objectives, application of some centralized control frameworks accompanied by multi-agent approaches have been proposed in the specialized literature [3,4].

From the power quality perspective, deregulation increases deployment of inverter-based generation units and FACTS controllers in the transmission stage [5]. Besides, increasing proliferation of switching devices at the customer side aggravates poor power quality scenarios. On the other side, identification of harmonics contributors and localization of distributed harmonic sources have to be addressed in the restructured environment [6,7]. Hence, harmonic analysis methods, which represent important tools for power quality assessment, should to be adapted to the new structure, especially for cases where information sharing is restricted and variable [8,9].

Harmonic assessment has become an important topic in power system operation due to the widespread penetration of nonlinear loads and switched devices connected to the electrical grid. During the last decade, researchers have proposed device models and implemented several simulation tools for harmonic studies. At present, harmonic analysis is widely used for power system planning, resonance identification, reliable network operation, equipment design, among other applications [10,11].

Due to the technological advances of digital computers, computer-based simulation has become the preferred tool for power system harmonic modeling and analysis [12]. Several methods including time-domain (TD), frequency-domain (FD), and hybrid TD–FD algorithms have been addressed for harmonic studies [13–15]. In Refs. [16,17], different techniques for modeling nonlinear devices in harmonic domain are reported. Also, digital simulators are widely used for real-time harmonic analysis [18,19].

Despite the number of existent models and algorithms, harmonic analysis of real-life networks still faces some challenging issues [12]. Firstly, lack of adequate computing resources which foils to deal with large-scale network simulation, especially in under-developed countries. Secondly, in the deregulated environment the interconnected networks are composed of multiple areas, each of them is usually owned and operated by an independent

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utility. This scenario does not always permit to access network layout and detailed data of neighboring areas as they may belong to several privatized entities. Thirdly, the operator of each area may not have a complete set of network data, especially of large customers such as factories and small manufacturers, and the operator information is usually limited to a metering device located at the substation supplying those customers. The above mentioned issues become important as precise models of nonlinear devices accompanied by configuration of the neighboring networks have significant effects on harmonic analysis of each single area. Besides, it should be noted that harmonic analysis of real-life large-scale networks becomes more complex due to a non-stationary network topology and loads' values [6].

To address some of the aforementioned issues, the following, briefly described, research has been conducted in recent years. In Ref. [20], a diakoptics-based method is proposed for 3-phase harmonic power flow studies of large-scale systems. In Ref. [20], the network devices are modeled as multi-port components and the system admittance matrix is assumed as frequency-dependent with block diagonal form. This study does not address DHA, but the employed diakoptic technique helps to reduce the system complexity. In case of DHA, a parallel distributed computing approach is reported in Ref. [21] for harmonic analysis of multi-bus systems. A time-domain method is developed in Ref. [22] by taking advantages of parallel processing into account. The developed algorithm of Ref. [22] employs parallelism via a limit cycle technique based on Newton methods and the Poincaré map. In Ref. [23], an efficient computation method is proposed for parallel multi-processing analysis of networks that include nonlinear elements. The method proposed in Ref. [23] adopts a Newton-type technique for fast time-domain periodic steady-state computations accompanied by parallel virtual machine plan. Other harmonic analysis algorithms which employ parallel processing platforms can be found in Refs. [24,25].

Based on existent research, one can note that although computational burden and accuracy issues have been greatly resolved by developing parallel computing-based methods, the lack of observability and load identification of nearby networks, especially in the restructured environment, still remain. Additionally, information sharing is limited within the competitive structure as it may affect independency of the utilities [8,9]. As a consequence, external system modeling approaches may not be effective, particularly in harmonic assessment in which not only injected harmonics/network topology vary with respect to time, but also the employed harmonic models severely affect the obtained results. Hence, it is desirable to conduct an exact harmonic analysis of real-life networks in a secure and decentralized structure which can be established based on local computational resources. The advantages of such approach have been so far demonstrated in solving basic power system problems such as load flow, fault analysis, and transient stability [26–29].

This paper presents a FD approach for distributed harmonic analysis (DHA) of interconnected power systems. A major feature of the proposed approach is the combination of the large-change sensitivity (LCS) concept with the current injection method for harmonic penetration calculation in FD; noting that other harmonic analysis methods can be readily incorporated into the proposed methodology. In the proposed approach, the system admittance matrix is assumed as frequency-dependent with block-diagonal form. A DHA algorithm is applied to each area of the interconnected system in a secure platform and the minimum volume of data from each individual area is sent to a wide area coordinator (WAC) through a TCP/IP communication facility. Two major features of the proposed methodology are: (1) it can readily simulate real-life large-scale networks for DHA with several distributed harmonic sources and (2) it can be used for harmonic assessment of multi-area interconnected power systems without requiring details of network layout and load's behavior, which can be non-sharable under utilities' security and independency policies. The proposed DHA method is developed within an existing software package and has been successfully tested on several networks, including the IEEE 118-bus test system.

Potential applications of the proposed technique are in power quality assessment and power system distributed analysis. Moreover, as it employs general routines of prevalent FD software modules, it may merit considerations from the power system software development in the harmonics arena. However, it should be noted that consideration of interharmonics and applying different harmonic analysis methods to DHA are beyond the scope of this work.

2. Modeling and analysis of power system harmonics in FD

An important part of the proposed methodology is harmonic power flow computation, which can be achieved with any efficient and reliable technique. As the goal of this paper is not to compare harmonic power flow methodologies, due to its simplicity and effectiveness, the current injection method is utilized in the proposed approach. Nevertheless, any other technique can be incorporated with ease.

2.1. Current injection method

There are several mature techniques for power system harmonic analysis reported in the specialized literature [12–17]. Among those techniques, FD-based methods are usually utilized in harmonic analysis of distribution and industrial networks [12]. FD techniques inherently are linear methodologies which can be extended to solve nonlinear problems by means of an iterative solution fashion. Typical FD-based methods for harmonic analysis include frequency scan analysis, current injection method, and harmonic power flow analysis [13].

Currently, the current injection method has gained interest in the power engineering community for performing harmonic propagation studies, particularly in industrial power system analysis software packages. It is a non-iterative technique which represents a nonlinear element by a current source at different harmonic frequencies. For completeness of the paper, the general solution procedure of the current injection method can be described as follows:

Step 1: Fundamental frequency power flow is conducted while the harmonic-producing loads are modeled as constant power loads;

Step 2: Harmonic current source models of nonlinear elements are defined at harmonic h, resulting in $\boldsymbol{I}_h$;

Step 3: System elements are modeled for harmonic h and included into the system admittance matrix, $\boldsymbol{Y}_h$;

Step 4: Harmonic voltages of order h, $\boldsymbol{V}_h$, are calculated via the following network nodal equation:

$$\boldsymbol{I}_h = \boldsymbol{Y}_h \boldsymbol{V}_h. \tag{1}$$

Step 5: Steps 2–4 are repeated until all harmonic orders are accounted for;

Step 6: Harmonic currents and, if desired, total harmonic distortion (THD) factors and telephone influence factors (TIFs) are calculated [12].

It should be noted that $\boldsymbol{Y}_h$ represents a large complex sparse symmetric matrix which has to be inverted by employing sparsity and factorization techniques. Also, some of the elements of $\boldsymbol{Y}_h$ may change due to interaction between the power frequency and the characteristic harmonics, or due to incorporation of harmonic cur-