Harmonic Analysis Techniques of Power System-A Review

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Abstract - *with the increasing use of nonlinear loads in power systems, the harmonic pollution becomes more and more serious. Controlling and reducing such harmonics have been a major concern. The power system harmonic analysis is the process of calculating the magnitudes and phases of the fundamental and higher order harmonics of system signals. This paper provides a review on the main developments in the area of power system harmonic analysis. Commonly accepted methods for conducting harmonic studies have been summarized.*

***Keywords*—FACTS, Harmonics analysis, modeling, DHD**

1. INTRODUCTION

Power system harmonics comes from a variety of sources, the dominant ones within transmission networks being large power converters such as those used for HVDC links and large industrial processes. Flexible alternating current transmission system (FACTS) controllers play an important role in electrical power transmission systems by improving power quality and increasing power transmission capacity. These controllers are nonlinear and complex as compared to mechanical switches. The harmonics generated by these devices can be divided into three categories:

• Integer harmonics: - are integer multiples of the power frequency.

• Inter-harmonics:- period and integer multiples of some base frequency, they normally result from cross-modulation of the integer harmonics of two systems with different power frequencies.

• Non-integer harmonics:- are the frequencies that do not fit either of the above two categories. They are not integer multiples of a base frequency and may not even be periodic.

The last two categories usually come from back-to-back HVDC links (periodic), Cyclo-converters (periodic) and arc-furnaces (non-periodic). However with the large motor drives and asynchronous HVDC links becoming more prevalent it is becoming important to take into consideration the non-integer and inter-harmonic based frequencies. Non-periodic frequencies create a special problem as they cannot usually be analyzed by traditional Fourier means, some authors have proposed the use of wavelet theory to analyses these wave shapes.

The large power converters produce mainly characteristic harmonics which are present during operation under ideal conditions and most of the early work revolved around these harmonics. Classical equations have been derived to obtain average firing angles, commutation durations, dc side voltages and harmonic magnitudes. However few of the harmonic problems reported occur under ideal system operation, and so this form of analysis is very limited for harmonic purposes. The linearity of synchronous machines and power transformers is very dependent upon their power-flow operating point. Both of these devices can normally be approximated as passive harmonic impedances, but these harmonic impedances often change with the system operating point. Transmission asymmetries lead to a negative sequence fundamental component in the terminal busbar voltages and due to the frequency coupling behavior of converters, this will lead to the generation of non-characteristic harmonics. Thus the ac transmission system must be represented in three-phase so that these effects be fully represented. The need for shared ac-dc right-of-ways will increase. The mutual coupling between these lines will result in both non-characteristic harmonic generation and converter transformer saturation problems. There are various solutions that minimise these effects, but analysis programs are required to accurately represent the systems.

2. EXISTING HARMONIC ANALYSIS METHODS

Harmonic analysis methods can be fitted into three categories; time domain, direct frequency domain and iterative techniques.

2.1 Time domain methods

Time domain modeling consists of different differential equations of interconnected power system then solve by means of the numerical integration. Various methods are available for the creation of these differentials equations and their integration. Commonly used methods are state variable, nodal analysis and Norton equivalent representation of dynamic components. Time domain representation is the most extensively used method for power system modelling. Although its primary function is for dynamic analysis, it is often used for steady-state analysis. Harmonic's analysis with a time domain package involves simulation to the steady-state and then the use of the Fourier transform. Due to the combination of both long (inductances and capacitances) and short (device switching times), time constants within a system, small time steps and long simulation times are required for accurate steady-states. Due to this computational expense, methods for accelerating convergence to steady-state using boundary problem analysis have been developed. A significant problem is the time domain modelling of the frequency dependency of transmission lines, but a variety of methods have been developed which provide a reasonably accurate representation. Other methods use RLC branches calculated by numerical analysis to provide simple equivalents of large networks.

2.2 Direct frequency domain method

Most commercial harmonic analysis packages use a direct frequency domain analysis using either single or three phase representation. The analysis consists of performing a load-flow to determine the system operating conditions and then calculating harmonic injections using simplified non-linear models. Then using the following nodal equation the system harmonic voltages are solved directly.

[Inode]=[Ysys] [Vnode] (1)

This form of analysis is well suited to audio-frequency ripple control studies, where the injected frequencies are non-integer and of low magnitude. However, it does not permit the incorporation of the effect of harmonic voltages on the non-linear devices or the transfer of harmonics across HV dc links. To maintain simplicity a variety of linearised converter models have been developed for analysing harmonic interaction with control systems and for the transfer of harmonics across dc links. However, the accuracy of these methods is limited by the approximations made within the device linearization's and the use of fixed operating points.

The harmonic produced by nonlinear component should be specified or calculated for base operating condition obtained from a load flow solution. These harmonics are fixed throughout solution means that non-linear component is represented as constant harmonic current injection.

2.3 Iterative Harmonic Analysis

When a non-linear device injects a harmonic current into a non-infinite linear ac system bus-bar, a harmonic voltage of that same frequency is produced. If the non-linear device is sensitive to harmonic voltages, the injected harmonic current will change. This then requires an iterative solution to solve the system for accurate harmonic information.

The following techniques have been used for Iterative Harmonic Analysis (IHA).

1: Basic iterative techniques

Two basic iterative methods are used in power system IHA; Fixed Point Iteration (Gauss-Seidel) and the Newton method. The simplest and previously most predominant iterative technique has been the Fixed Point Iteration. The current injections of a non-linear device (Inl,) are calculated from the system nodal voltages (Vnodei)' Then using these currents and the system admittance matrix (Ysys), new nodal voltages (Vnodei+l) are calculated which are then used to re-calculate the non-linear device current injections. This iterative method is shown as follows:

Inli=f(Vnodei) (2)

Vnodei+1= [Ysys]-1Inli (3)

This method has been reported to have poor convergence for highly distorted or resonant systems. Better convergence has been obtained by using the Newton method for adjusting the solution variables. A mismatch function is calculated which compares the non-linear device harmonic currents (Inli) with the nodal currents (Inodei) calculated from the nodal voltages (Vnodei). This mismatch function is then used in conjunction with the system Jacobian (a matrix of partial derivatives) to calculate adjustments to the nodal voltages (ΔVnodei) As the solution progresses, the mismatch function (Mi) is driven to zero by the Jacobian (Ji) and convergence is obtained. This is as follows:

Inli=f(Vnodei) (4)

Inodei=YsysVnodei (5)

Mi=JiΔVnodei (6)

Vnodei+1=Vnodei-ΔVnodei (7)

2. Harmonic solution format

A problem with the representation of non-linear devices is the phase dependency inherent within their linearisation. The linearisation of this phase dependency using complex numbers requires the complex conjugate notation of Equation 8 which uses positive and negative frequency phasors.

$$\begin{bmatrix} \Delta I + \\ \Delta I - \end{bmatrix} = \begin{bmatrix} Y1 & Y2 \\ Y1* & Y2* \end{bmatrix} \begin{bmatrix} \Delta V + \\ \Delta V - \end{bmatrix} \quad (8)$$

where If = I-f for a real valued waveform. This can also be represented by using real-valued positive frequency phasors.

$$\Delta I+=Y1\Delta V++Y2\Delta V^*+ \quad (9)$$

Decomposing this into real and imaginary positive frequency components in Matrix form is

$$\begin{bmatrix} I_r \\ I_l \end{bmatrix} = \begin{bmatrix} Y1_r & -Y1_i \\ Y1_i & Y1_r \end{bmatrix} + \begin{bmatrix} Y2_r & Y2_i \\ Y2_i & -Y2_r \end{bmatrix} \begin{bmatrix} V_r \\ V_i \end{bmatrix} \quad (10)$$

Approximately the same amount of storage and computation is required for the linearised admittance of the non-linear devices, though the complex conjugate method requires twice as much computation for the linear systems.

The complex conjugate notation creates difficulties when incorporating real valued variables. the linearization of a loadflow becomes approximate and significantly more difficult in complex form. The inclusion of the DC term of ac systems can also cause numerical problems.

It should be considered though that the complex conjugate method was used for the representation of magnitude dependent magnetic non-linearities described by the function:

$$Y=f(x) \quad (11)$$

3. THE DYNAMIC HARMONIC DOMAIN (DHD) TECHNIQUE

The DHD technique, which is an extension of the HD method, allows for the determination of the harmonic content of distorted waveforms, not only in the steady state, but also during transients.

Dynamic Harmonic Domain (DHD) analysis, can been used successfully to analyze the transient and steady state responses of electrical networks that contain nonlinearities and embedded power electronics. The method makes use of an orthogonal basis (the complex Fourier series), complex differential operators, and approximations of these operators. The DHD method is an extension of the HD method, and it expands the scope of the usage of power quality indices from measuring the performance of steady state applications to the transient range. An important feature of the DHD method is that it reduces a linear time-periodic (LTP) system to a linear time-invariant (LTI) system, which improves the available tools and techniques that are used to solve LTP systems.

A. Basic Theory

In this section, we describe the conversion of an ODE in TD to the DHD [19], [20]. The basis for the line modelling which involves ODEs.

Without loss of generality, consider the linear time periodic (LTP) system for the scalar case

$$\dot{x} = a_p x + b_p u \quad (12)$$

$$y = c_p x + d_p u \quad (13)$$

where subscript p stands for time-periodic, for instance, a_p defined as

$$a_p = a_{-h} e^{-jhw_o t} + \cdots . + a_0 + \cdots + a_h e^{jhw_o t} \quad (14)$$

with h representing the highest harmonic ω0 and the fundamental frequency. By expressing all the variables from (12), (13) by their Fourier series and by removing all the exponential factors, the state representation (12), (13) in the DHD becomes

$$\dot{X} = (A - S)\mathrm{X} + B\mathrm{u} \quad (15)$$

$$\mathrm{y} = C\mathrm{X} + Du \quad (16)$$

where the variables are now complex vectors with time-varying coefficients, e.g.,

$$X = [x_{-h}(t) \ldots . x_0(t) \ldots\ x_h(t)]\mathrm{T} \quad (17)$$

where T denotes the transpose. S is called the operational matrix of differentiation defined by [21]

$$S = diag\{-jh\omega_0, \ldots ., -j\omega_0, 0, j\omega_0, \ldots ., jh\omega_0\} \quad (18)$$

and A matrix has the Toeplitz structure.

$$A = \begin{bmatrix} a_0 & a_{-1} & \cdots & a_{-h} & . \\ a_1 & a_0 & \ddots & . & a_{-h} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_h & . & \ddots & a_0 & a_{-1} \\ . & a_h & \cdots & a_1 & a_0 \end{bmatrix} \quad (19)$$

Note that, in the DHD, we obtained a system of ODEs of dimension 2h+1for the general case. The system becomes diagonal when dealing only with linear elements and can further be reduced to order h/2 when considering half-wave symmetry.

Note also that if a_p from (12) is a real coefficient then (19) becomes a diagonal matrix.

By comparing (12),(13),(15) and (16) the LTP system has been transformed into a linear time invariant (LTI) system through the DHD. The steady state of the system is easily obtained by setting derivatives to zero in the (15),(16) thus yielding

$$X = (S - A)^{-1} Bu \quad (20)$$

$$y = CX + Du \quad (21)$$

Hence, the evolution of the harmonic content, i.e., with respect to time, can be obtained from (12),(13) and the corresponding instantaneous values are calculated by assembling a Fourier series as in (14).

4. CONCLUSIONS

In this paper, we have reviewed some methods of power system harmonic analysis. Commonly accepted methods for harmonic studies have been presented here. The paper discusses the frequency domain solution method in the power system harmonic analysis. The frequency domain solution method is one of the major mathematical approaches for harmonic analysis.

REFERENCES

[1] Wilsun Xu , Senior Member, IEEE," Status and Future Directions of Power System Harmonic Analysis.

[2] C. D. Collins, G. N. Bathurst, N. R. Waston, and A. R. Wood, " Harmonic domain approach to STATCOM modeling," IEE Proceedings on Generation, Transmission, Distribution, Vol. 152, No. 2, March 2005, pp. 194–200.

[3] C.D. Collins, N.R. Waston, and A. R. Wood, "Unbalanced SSSC modeling in the harmonic domain," Proceedings of the 7 th International Power Engineering Conference, Vol. 2 , Nov. 2005, pp. 705–710.

[4] C. D. Collins, "FACTS device modeling in the harmonic domain," Ph.D. Dissertation, Univ. Canterbury, New Zealand, 2006.

[5] C. D. Collins, N. R. Waston, and A. R. Wood, "UPFC modeling in the harmonic domain," IEEE Transactions on Power Delivery, Vol. 21, No. 2, April 2006, pp. 933–938.

[6] J. Jesus Rico, M. Madrigal, and E. Acha, "Dynamic Harmonic Evolution Using the Extended Harmonic Domain," IEEE Transactions on Power Delivery, Vol. 18, No. 2, April 2003, pp. 587–594.

[7] B. Vyakaranam, M. Madrigal, F. E. Villaseca, and R. Rarick, "Dynamic Harmonic Evolution in FACTS via the Extended Harmonic Domain Method," Power and Energy Conference at the University of Illinois, Urbana-Champaign, IL, February 2010.

[8] H. García, M. Madrigal, B. Vyakaranam, R. Rarick, and F. E. Villaseca, "Dynamic Companion Harmonic Circuit Models for Analysis of Power Systems with Embedded Power Electronics Devices," Electric Power Systems Research Journal (Elsevier), October 2010, pp. 340–346.

[9] J. Arrillaga, B.C. Smith, N.R. Watson, A.R. Wood, Power System Harmonic Analysis, John Wiley & Sons, Chichester, 1997.

[10] Semlyen , E. Acha, J. Arrillaga, "Newton-type algorithms for the harmonic phasor analysis of nonlinear power circuits in periodical steady-state with special reference to magnetic nonlinearities," IEEE Transactions on Power Delivery, Vol. 3, No. 3, July 1988, pp. 1090–1098.

[11] G.N. Bathurst, B.C. Smith, and N.R. Watson. Newton solution of a generic minimum gamma controlled HV dc inverter in the harmonic domain. Proceedings of the third New Zealand conference of postgraduate students in Engineering and Technology, volume 1, pp. 52-57, July 1996.

[12] G.N. Bathurst, B.C. Smith, N.R. Watson, and J. Arrillaga. Analysis of the HVdc inverter in the harmonic domain. Proceedings of the 7-th EPE Conference, volume 1, pp. 1.260-1.265, 1997.

[13] G.N. Bathurst, B.C. Smith, N.R. Watson, and J. Arrillaga. A modular approach to the solution of the three-phase harmonic power-flow. Proceedings of the 8th ICHQP conference, volume 1, pp. 407-411, October 995.

[14] G.N. Bathurst, B.C. Smith, N.R. Watson, and J. Arrillaga. Harmonic domain modelling of high pulse converters. lEE Proceedings (accepted for publication), 1995.

[15] C.D. Callaghan and J. Arrillaga. Double-iterative algorithm for the analysis of power and harmonic flows at ACjDC converter terminals. lEE Proceedings Part C, volume 136(6), pp. 319-324: November 19S9,

[16] C.D. Callaghan. Three phase integrated load and harmonic flows. PhD thesis, Department of Electrical and Electronic Engineering, University of Canterbury, Christchurch, New Zealand, August 19S9.

[17] J. Arrilaga, A. Medina, M.L.V. Lisboa, M.A. Cavia, P. Sanchez, "The harmonic domain. A frame of reference for power system harmonic analysis," IEEE Transactions on Power System, Vol. 10, No.1, February 1995, pp. 433–440.

[18] M. Madrigal and E. Acha. Modelling of custom power equipment using harmonic domain techniques. Proceedings of the 9th ICHQP, 1:264-269, 2000.

[19] J. J. Rico, M. Madrigal, and E. Acha, "Dynamic harmonic evolution using the extended harmonic domain," IEEE Trans. Power Del., vol.18, no. 4, pp. 587–594, Apr. 2003.

[20] A. Ramirez, A. Semlyen, and R. Iravani, "Harmonic domain characterization of the resonant interaction between generator and transmission line," IEEE Trans. Power Del., vol. 20, no. 4, pp. 1753–1762, Apr. 2005.

[21] E. Acha and M. Madrigal, Power Systems Harmonics. London, U.K.: Wiley, 2001.