2010

Introducing power system voltage droop as a new concept for harmonic current allocation

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Recommended Citation

Barr, Robert A. and Gosbell, V. J.: Introducing power system voltage droop as a new concept for harmonic current allocation 2010.

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Abstract

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Disciplines

Physical Sciences and Mathematics

Publication Details

Barr, R. A. & Gosbell, V. J. (2010). Introducing power system voltage droop as a new concept for harmonic current allocation. 14th International Conference on Harmonics and Quality of Power, ICHQP 2010 (pp. 1-5). Bergamo, Italy: IEEE.

Introducing Power System Voltage Droop as a New Concept for Harmonic Current Allocation

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Abstract—“Voltage Droop” is a new concept that has been developed primarily for use in the harmonic current allocation process. Voltage droop offers the opportunity to both vastly simplify the procedures required by the present IEC 61000.3.6 [1] guidelines for Stage 2 allocation and provide a solid theoretical base to this work. The voltage droop concept has also been found to provide a useful theoretical basis for the harmonic standard IEEE 519[2]. While this paper develops the voltage droop concept using diagrams and words, the companion paper “Harmonic Allocation Following IEC Guidelines Using the Voltage Droop Concept”[3] contains a full critical mathematical description including an example. The voltage droop concept can be applied to radial, meshed and SWER distribution systems where feeders are sufficiently short that line capacitance can be ignored and all capacitor banks are detuned to prevent resonances at harmonic frequencies. The concept has application in HV, MV and LV systems. Use of the voltage droop concept for flicker allocation and unbalance studies is also briefly discussed.

Index Terms-- distribution systems, harmonics, IEC standards, IEEE standards, harmonic allocation, voltage droop, voltage drop,

I. INTRODUCTION

Managing harmonic levels in power systems is an important and challenging responsibility for electricity distributors around the world. Unwanted harmonic voltages on power systems are caused primarily by the interaction of customer generated harmonic currents with network impedances.

Technical report IEC 61000-3-6 [1] “Limits – Assessment Limits for Disturbing Loads in MV and HV Systems” provides guidance on how limits should be set for network harmonic voltages. The overall responsibility for managing harmonics falls primarily on electricity distribution companies and in performing this role they need to set harmonic current limits for customers.

The application of 61000-3-6 is complex, often requiring many assumptions concerning not only existing harmonic loads but also allowances for future harmonic loads. In order to simplify the process for radial distribution networks, handbook HB264 [4,5,6] has been developed and is in use by most electricity distributors in Australia.

The purpose of this paper is to introduce and further

simplify the harmonic allocation process using a new methodology based on the concept of “voltage droop”. The new methodology is intended for widespread general use in distribution systems. The voltage droop concept:

- is based on the principals of IEC 61000-3-6.
- permits the harmonic allocation process to take place with very simple calculations.
- provides an effective theoretical base for the allocation process.
- requires minimal data and no assumptions.
- deals effectively with the provision of future harmonic loads.
- provides transparency - results can be readily reproduced by other engineers.
- can easily be explained to practicing distribution engineers and large customers.
- provides a basis for calculating expected maximum harmonic levels at any part of the network.

The success of the methodology depends on all shunt capacitors being detuned.

In addition, the results obtained from using the methodology have been shown in a companion paper [3] to be generally consistent with the IEEE 519 methodology and even provides a useful theoretical basis for this standard.

II. VOLTAGE DROP

Fig. 1 – Distribution Network Voltage Drop

All distributors are familiar with the concepts of voltage drop and voltage regulation shown in Fig. 1. Voltage drop is

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caused by the distributed load currents interacting with system impedances. In general terms, voltage drop needs to be restricted to no more than 6-10% between the last regulated MV busbar (11kV in the example shown in Fig. 1) and the LV customers at the end of the system. This is necessary to achieve LV steady state voltage performance like $230V \pm 6\%$ (i.e. a 12% range) or a similar range in a 110V system.

Voltage drops further up in the MV and HV systems also need to be restricted to keep within the tapping range of On Load Tap Changing (OLTC) transformers. Typically, voltage drop in these parts of the system need to be restricted to about 10-20% at each voltage level under (N-1) conditions and hence less under normal conditions.

III. VOLTAGE DROOP

Fig. 2 – Distribution Network Voltage Droop

Voltage droop is the summation of all the individual voltage drops in the distribution network between the transmission system represented by the Thevenin voltage source and a network point being considered. Total voltage droop in a network is the sum of voltage drops between the transmission system and the end LV customer at the extremities of the network.

Voltage droop represents the complex interaction between distributed loads interacting with a configuration of network impedances. The concept applies to a range of configuration types including combinations of radial, mesh and SWER networks.

Where Fig. 2 shows the distribution network extending with many tee offs right through to the end of the low voltage system, there are in fact usually thousands of low voltage networks and thousands of paths to these points. The most critical point in the low voltage network having the highest voltage droop will often change as new loads are added to the network and the network is augmented/reconfigured. Knowing exactly where the worst LV point on the network is not critical, what is important is knowing that there is a critical LV point on the network and having harmonic management procedures in place to control harmonics at this point. Controlling harmonic voltage levels within specified limits at the weakest point on the network ensures that other network locations will have better performance than the minimum requirements of the standards.

The usefulness of the voltage droop concept comes from the fact that it can be readily defined mathematically and is a quantity that is naturally capped in all distribution networks. Knowing typical values of voltage droop at the extremities of the distribution networks is a critical requirement of the new methodology. Most distribution systems have one or two regulating OLTC transformers between the transmission system and the LV system. Typically at each voltage level there are OLTC transformers that need a boost capacity above the nominal tap of approximately 10-20% under emergency (N-1) conditions. Under normal (N) conditions with all lines and transformers in service, 10% boost is considered typical. Hence with two OLTC transformations of 10% and another 10% voltage drop between the last regulated MV busbar and the extremities of the LV network, 30% voltage droop is considered to be a reasonable value. More work involving measurement and modeling of real distribution networks is needed to make more informed assessments of voltage droop under normal and abnormal conditions.

If new customer connections to a network caused voltage droop to reach levels much greater than 30%, customers would experience very large steady state voltage variations and network losses would tend to be excessive. This is indicative of the network lacking capacity to supply the connected loads. If a distribution network had voltage droop levels much less than 30%, it would be a sign that the network has over capacity and has been over capitalised. This is a situation that is unlikely to occur in the development of networks under normal economic constraints. In other words, engineers normally only provide network capacity when new and growing loads justify the capital expenditure.

Growing power systems have new and increasing customer loads dispersed throughout their length on a regular basis. They also have continuing network additions and reinforcement to cater for this growth. The process of new loads and network augmentation is a natural process of power system development that occurs all around the world.

In mathematical terms, the process of network augmentations chasing customer load growth is simply a process of keeping voltage droop down to manageable levels. When a distributor augments a transformer from 20 MVA to 40 MVA to cater for load growth, the network voltage droop at the extremities of the network is reduced. With the addition of the new load that triggered the augmentation, voltage droop will tend to return to its original level. This process takes place on a continuous basis in all networks. This ongoing process makes voltage droop one of those constants of distribution network development.

Voltage droop is a fundamental frequency (50/60Hz) measure/characteristic that can be assessed at any part of the network. Voltage droop is in fact a scarce resource that needs to be allocated carefully and sparingly to customers. While voltage droop is of interest throughout the distribution network, the level of voltage droop at the extremities of the LV network is critical and is of most interest. At the extremities of the LV network, every load connected to the entire network is contributing to voltage droop. Nearby loads

make a large contribution whereas distant LV loads and loads in the HV and MV systems make only a small contribution.

Fig. 3 – Voltage Droop Components

Voltage droop in phasor terms is illustrated in Fig. 3. While the current I is shown as a simple vector, it is fact a representation of thousands of loads distributed throughout the network. The importance of Fig. 3 is that it illustrates that at the extremities of the network, voltage droop has both resistive and reactive components. In using the proposed methodology, the “IR Droop” component is generally small and can be ignored. At harmonic frequencies, the “IR Droop” component becomes even less important as the “IX Droop” component increases in proportion to frequency. Where voltage droop is referred to later in this paper, it is only the “IX Droop” component that is being considered.

Whereas the difference in magnitude of the sending and receiving end voltages (apparent voltage droop) varies significantly with power factor, the “IX Droop” component is dependent only on the network impedance and the magnitude of the loads.

IV. CUSTOMER CONTRIBUTION TO VOLTAGE DROOP

Fig. 4 – Customer Load Contribution to Voltage Droop

Fig. 4 illustrates a single customer’s contribution toward the total voltage droop. Under the proposed methodology, a load’s contribution to voltage droop is used to make an assessment of the customer’s use of the available network capacity and its harmonic allocation.

Assessing a customer’s contribution to voltage droop is quite simple. A load’s voltage droop contribution to the

network can be assessed by dividing the MVA maximum demand by the Fault Level at the point of network connection. It is this simplicity that makes the proposed methodology attractive.

Where the network impedance has a significant resistive component, only the reactive part of impedance should be used in assessing the fault level.

Because voltage droop is capped by natural network development, customer harmonic current injection becomes limited only by the magnitude of the customer’s load and fault level at the point of connection.

V. HARMONIC ALLOCATION METHODOLOGY

Voltage droop is a fundamental frequency voltage that has many of the characteristics of higher order harmonic voltages. Both voltage droop and harmonic voltages are generated by customer loads interacting with network impedances. Like harmonic voltages, voltage droop needs to be managed and contained down to manageable levels. The main difference between voltage droop and higher order harmonics are:

- voltage droop can be “cancelled out” by voltage regulators or OLTC transformers.
- higher order harmonic voltage diversify more than fundamental droop voltages.

Fig. 5 – Linking Harmonic Voltage to Voltage Droop

Fig. 5 shows the voltage droop contribution and the corresponding 5th harmonic contribution for an 11kV load. In this case the 11kV customer load is considered to be the only load connected to the network. Note how both the voltage droop and the 5th harmonic voltage build up from the source as the reference point moves toward the load. At the point where the load is connected, both the voltage droop and the harmonic voltage then remain constant and appear at the extremity of the LV network.

The fundamental principal of IEC 61000.3.6 is to limit harmonic voltage at the extremities of the network to predetermined planning levels. The new methodology limits customer harmonic currents to a level governed by their individual contribution to voltage droop. The full mathematical analysis is detailed in the companion paper “Harmonic Allocation Following IEC Guidelines Using the Voltage Droop Concept” [3]. This paper illustrates that by using the voltage droop concept, a customer’s harmonic

current limits can be determined effectively from the customer's maximum demand and the fault level at the point of network connection. The analysis in this paper shows how this can be achieved either with or without considering diversity.

A. No Diversity

The new methodology makes an assessment of harmonic levels at the end of the LV network by considering in aggregate the harmonic contributions from all distributed loads. If diversity is ignored, customer harmonic currents can have an allocation limit set in proportion to their fundamental current. The allocation limit can be selected such that when the aggregated impact of all customers are considered, the LV harmonic voltage planning levels are reached when the voltage droop reaches its natural limit. For example, a 5th harmonic current allocation constant can be set such that the 5th harmonic 5.5% planning level is reached at the extremities of the LV system when the voltage droop reaches 30%. Details of the "no diversity" allocation process are provided in mathematical terms in [3].

B. With Diversity

Complications occur when diversity is considered. The diversity law [1] reflects the fact that higher order harmonics have more diversity than fundamental frequency droop voltages. Diversity has been introduced into the methodology by using the diversity law in conjunction with the network fault level at the customer connection point. The mathematical treatment of diversity into the harmonic allocation process is provided in [3].

VI. HARMONIC VOLTAGE PROFILES IN THE DISTRIBUTION NETWORK

The proposed harmonic allocation approach is based only on satisfying a planning level at the extremities of the LV system. This is unlike the full IEC approach which requires the determination of planning levels to be applied across the power system by voltage level. The new methodology provides for a more continuous variation in expected harmonic voltage levels across the network where the key parameter is fault level rather than voltage level.

Fig. 6 shows a modeled 5th harmonic voltage profile for a distribution network with a disbursed set of loads using the voltage droop concept and incorporating diversity. The harmonic profile shows the expected variation of 5th harmonic voltage from the 132kV connection point to the transmission system down to the extremities of the LV system. The profile shows the impedance effect of 132/33kV, 33/11kV and 11/0.415V transformers in addition to the effects of 132kV, 33kV, 11kV and 415V lines. Of interest is the slope of the profile curve for the transformers as the fault level changes from the primary side to the secondary side. While both lines and transformers have impedance, the difference in the profile slope between the lines and transformers is caused by the lines being modeled with distributed loads along their length. By comparison, transformers have a simple impedance with no

load connection possible between the primary and secondary terminals.

Fig. 6 – Modeled Harmonic Voltage Profile using the Voltage Droop Concept

Overlaid on top of the profile are typical planning levels from HB261 [6] located on the graph using indicative fault level ranges for each of the voltage levels.

Fig. 6 illustrates that the simple harmonic allocation methodology using voltage droop can produce results that are directly comparable to the much more complex planning level approach described in IEC/TR 61000-3-6 [1] and HB 265 [6].

Under the new methodology, planning levels other than at the extremities of the LV network are not required. However, harmonic profiles can be built based on fault levels that can be used by distributors to assess if measured harmonic voltages are considered to be high or low at any part of the network. More work is required in this area.

VII. SPECIAL ISSUES

A. Special Cases

The voltage droop methodology can be applied to most harmonic situations where the harmonic currents flow in the same path at the fundamental current. Triplen harmonic currents are a special case where this may not be the case depending on transformer vector groups and network connections. The methodology can and needs to be adapted to cover this and other special situations.

B. Voltage Droop Measurement

While 30% has been used as a benchmark for maximum network voltage droop, there are benefits to be gained by measuring typical values in a range of networks. Measurement of voltage droop is not a straightforward process and will involve measuring voltage and phase angles at the transmission source, monitoring the tap position of OLTC transformers (most likely via SCADA) and measuring voltage and phase angles at the weak extremities of the LV network. Simultaneous measures of phase angles between the HV source and remote LV supplies will be required using special

instruments designed for that purpose. Allowance will need to be made for the vector groups of all intermediate transformers.

C. Flicker Allocation and Unbalance

The allocation methodology readily lends itself to flicker allocation and unbalance studies. This will be the subject of further publications.

D. Transmission Systems

In its present form the harmonic allocation methodology is not suitable for use in transmission systems due to resonances at harmonic frequencies caused by shunt capacitances of transmission lines and non detuned capacitor banks. With further work, the possibility exists to extend the methodology into this environment.

Where transmission system harmonics voltages are significant compared to the harmonics generated in the distribution network, they need to be considered and added with diversity to the customer generated harmonics. More work is required in this area.

E. IEEE 519

Comparison of results with IEEE 519 [2] have been made and explained in the companion paper[3].

F. Embedded Generation

Any new harmonic allocation process needs to be able to incorporate embedded generation. While embedded generation has not been addressed directly in this paper, the voltage droop concept can easily be adapted. The most likely approach will be to increase the maximum voltage droop to cater for the effects of generation while treating the generation like any other customer load. More work is required in this area.

VIII. CONCLUSIONS

A new methodology for harmonic current allocations has been proposed using the concept of voltage droop. The new methodology offers the benefits of a sound theoretical base combined with simple calculation and minimal data requirements. The new approach can be applied at both the MV and LV customer level and at equipment level.

The methodology can be applied to both mesh and radial systems and allows allocations to be made without the need for harmonic load flows.

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X. BIOGRAPHIES

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