A NEW PROCEDURE FOR ALLOCATING VOLTAGE FLUCTUATION LIMITS IN POWER SYSTEMS

by

Maria Jose Arechavaleta Castagno

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
December 10, 2016

Power quality, voltage fluctuations, flicker, electromagnetic compatibility

Approved by

Mark Nelms, Department Chair, Professor of Electrical and
Computer Engineering
Mark Halpin, Alabama Power Company Distinguished Professor of Electrical and
Computer Engineering
Charles Gross, Professor Emeritus of Electrical and Computer Engineering

ABSTRACT

Procedures for determining the requirements for the connection of fluctuating installations in MV, HV, and EHV power systems are provided in IEC Technical Report 61000-3-7. The objective is to provide guidance to system owners/operators in order to help in the provision of adequate service for all connected customers. The approach is based on the allocation of the capacity of the system to absorb disturbances. The guidelines provided in the Technical Report can be difficult to apply in practice and are based on simplifying assumptions. A new approach is proposed in this thesis based on the concept of system voltage droop. It is based on the IEC Technical Report 61000-3-7 requirements and provides an effective theoretical foundation for the allocation process. In this procedure, the allocation of the system capacity to absorb disturbances depends on the users' contribution to the system voltage droop. It is analytically proven that the method gives realistic emission limits to individual users without requiring unsupportable assumptions. Demonstrations of the proposed procedures are given utilizing a modified version of the IEEE 13-node distribution system and compared to results obtained using IEC Technical Report 61000-3-7. Furthermore, the proposed procedure is applied to a real MV rural network provided by Electricite de France and the results are compared to those obtained using the existing procedure in IEC Technical Report 61000-3-7.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

CHAPTER 1: INTRODUCTION

Power supply systems and electrical equipment are designed to operate at a certain voltage with particular characteristics for successful operation. Power supply systems are designed to operate continually with sinusoidal steady-state voltage having a fundamental frequency of 50/60 Hz and equipment is dependent on its normal operating voltage range for successful operation.

The supply system has only control of the voltage; it has no control over the currents that different loads might draw. Thus, the power supply system attempts to maintain the voltage at the service point within a certain voltage range for the successful operation of customer equipment. This has been recognized since the beginning of the electric utility industry, and in the United States, the American National Standards Institute (ANSI) has defined and standardized the input voltage range of a power system as "the range of input voltage over which the system can operate properly" [1]. Permissible variations for low voltage (LV) system voltages which have to be met at the service and utilization points, for normal and abnormal ranges, are shown in Table 1.

Table 1: Standard Voltage Profile for Low-Voltage Regulated Power Distribution Systems [1]

	Range A (V)	Range B (V)
Maximum allowable voltage	126	127
Voltage drop allowance for primary distribution line	9	13
Minumum primary service voltage	117	114
Voltage drop allowance for distribution transformer	3	4
Minimum secondary service voltage	114	110
Voltage drop allowance for plant wiring	6	6
Minumum utilization voltage	108	104

Likewise, loads need to maintain a pure sinusoidal current at the fundamental frequency (50 or 60 Hz). Otherwise they could distort the steady-state voltage when interacting with network impedances and affect other equipment in the network. Unfortunately, power supply systems and equipment are very likely to be subjected to electromagnetic phenomena such as lighting strikes, system faults, harmonics, and flicker, among others, which can lead to malfunction and/or end of life of equipment.

Poor voltage characteristics may have a negative financial impact on utilities, customers, and manufacturers. Furthermore, additional expense may be incurred due to efforts to improve voltage characteristics. Because of these potentially significant financial impacts, there is great interest in voltage characteristics. The field of study that deals with electromagnetic phenomena which affect the voltage characteristics is called power quality (PQ). The Institute of Electrical and Electronics Engineers (IEEE) has defined PQ as “the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment” [2]. The International Electrotechnical Commission (IEC) defines PQ as “characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters” [3]. Another way PQ can be viewed is “good power quality is whatever electrical supply necessary for end-use equipment to perform its intended function(s) in its operating environment” [4].

The concept of PQ is difficult to measure, quantify, and assess whether it is harmful or not because there are various types of electromagnetic phenomena and different equipment sensitiveness; the ultimate criteria to determine if there is a problem or not is the performance and productivity of the end-user equipment. The recognition of these problems has led to the development of voluntary and mandatory standards as well as technical reports in order to provide good engineering practices to maintain PQ at both at the system and equipment level. The two major standards organizations in the world which develop PQ standards and technical reports are the IEEE and the IEC, the latter being the main organization in the international community, and both containing a consensus of knowledge and experience of voluntary members. The documents produced provide guidelines and requirements for controlling electromagnetic disturbances in the form of recommendations and methods. These help understand, quantify, and assess the problem, hopefully achieving overall quality in the entire system.

As part of the documents, indices were developed in order to characterize performance and to assess levels and determine limits for common electromagnetic phenomena. They also provide measurement and monitoring procedures so that electromagnetic phenomena can be assessed in a consistent way. They provide requirements at the supply system level and at the electrical equipment level.

Electromagnetic disturbances may be mitigated at the utility supply point, at the end-user equipment point, or anywhere in between. Sometimes, however, it is complicated to determine who or what produces the disturbance and this has a direct impact on the responsibility for the mitigation of the disturbance. There is a great interest in PQ because the mitigation of disturbances has a substantial economic impact on utilities, customers, and equipment manufacturers. System operators and/or customers may be penalized for creating disturbances because of a contractual relationship or because of national regulatory rules. Economic expense is a real incentive for having well defined and recognized electromagnetic phenomena, measurements, and indices.

It is clear that there is a need for common PQ indices in order for different system operators to measure and report quality in a consistent and harmonized manner. Therefore, documents are developed to coordinate voltage quality between the electric supply system and the end-use equipment to avoid PQ disturbances, equipment failures, and penalties.

With the increasing changes in equipment electronics, distributed generation, and the smart grid, the sources of electromagnetic disturbances continually vary and increase. Not only do these new sources produce more disturbances, but also they are more susceptible to the very disturbances to which they contribute. It is necessary to continue to revise the contemporary standards and try to adapt them to the new and different types of electrical sources, loads, and environments. Therefore, it is of great importance to understand the PQ problems and be able to determine how they affect the electric supply system and the end-use equipment. Likewise, understanding the standards and how to apply them correctly is important so that best engineering knowledge and practices are used.

One category of electromagnetic disturbances is referred to as voltage fluctuations which are intermittent variations in the voltage magnitude as low as 0.1% of nominal system voltage. These voltage fluctuations produce the visual effect of flicker in lights which has been associated with health effects such as headaches, eye strain, and fatigue. According to [5] the effects of flicker can range from decreased visual performance to non-specific malaise to the onset of some forms of epilepsy. Voltage fluctuations, which is the electromagnetic phenomenon causing the disturbance, may also affect very sensitive electronic equipment.

In the international community, there are both equipment and system level standards that attempt to manage voltage fluctuation disturbances. For example, the IEC 61000-3-3 and 61000-3-11 standards specify the limits for voltage fluctuations produced by equipment having a rated input current less than 16A and 75A, respectively, and intended to be connected to a public low-voltage (LV) distribution system.

For the power system as a whole, IEC Technical Report (TR) 61000-3-7 [6] (abbreviated in this document as “3-7”) was developed to provide procedures for determining the requirements for the connection of fluctuating installations in medium voltage (MV), high voltage (HV) and extra high voltage (EHV) power systems. Large fluctuating installations creating voltage changes can produce flicker, which propagates through the power system possibly creating problems at other locations. Control of disturbance levels is required to provide quality service for all installations connected to the power system. The TR provides guidance to system owners/operators in the provision of adequate service for all connected customers. The procedure is intended to amount to a process of equitable (economic) allocation. A new procedure for determining the requirements for the connection of fluctuating installations in radial power systems is the subject of the remainder of this thesis. The procedure results in a greater utilization of the system capability to absorb disturbances and offers an improved economic allocation.

CHAPTER 2: POWER QUALITY

Power quality is mainly concerned with the compatibility between the quality of the voltage delivered by the power supply system and the needs of the end-use equipment. It is a general term that is used to define the quality of the system voltage so that equipment can operate correctly. According to IEC, the electromagnetic phenomena which cause electromagnetic disturbances on the system voltage are classified in groups as shown in Table 2.

Table 2: Principal Phenomena Causing Electromagnetic Disturbances [7]

Group	Electromagnetic phenomena
Conducted low-frequency phenomena	Harmonics, interharmonics
	Signal systems (power line carrier)
	Voltage fluctuations
	Voltage dips and interruptions
	Voltage imbalance
	Power-frequency variations
	Induced low-frequency voltages
	DC in AC networks
Radiated low-frequency phenomena	Magnetic fields
	Electric fields
Conducted high-frequency phenomena	Induced continuous wave (CW) voltages or currents
	Unidirectional transients
	Oscillatory transients
Radiated high-frequency phenomena	Magnetic fields
	Electric fields
	Electromagnetic fields
	Continuous waves
	Transients
Electrostatic discharge phenomena (ESD)	
Nuclear electromagnetic pulse (NEMP)	

The electromagnetic phenomena listed in Table 2 can be divided into two broad categories: steady-state and non steady-state phenomena. Steady-state disturbances are used to define the requirements for the voltage supplied by the power supply system, and also the responsibilities of the supply system, end users, and equipment in maintaining the required quality of voltage. Voltage regulation, harmonic distortion, voltage fluctuations, and unbalance are the most common examples of steady-state phenomena. These phenomena can be further described by properties such as amplitude, frequency, spectrum, and modulation. Non steady-state phenomena, on the other hand, occur randomly, thus different properties are used to further describe them such as rate of rise, amplitude, duration, spectrum, frequency, rate of occurrence, energy potential, and source impedance [7]. Momentary interruptions, voltage sags, swells, and transients are examples of non steady-state phenomena.

The recommended practice in the United States [8] classifies the electromagnetic phenomena into groups and categories in terms of magnitude, duration, and frequency range as shown in Table 3. The classification in Table 3 provides a way to clearly describe the nature of electromagnetic disturbances for analysis purposes. There are different requirements to monitor, measure, and mitigate electromagnetic disturbances depending on the particular nature of the phenomena. Therefore, it is very useful to know to which class a particular phenomenon belongs.

Table 3: Categories and Characteristics of Power System Electromagnetic Phenomena [8]

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive	5ns-0.1ms rise	50ns-1ms	
1.2 Oscillatory	<0.5kH-5MHz	0.3ms-5us	0-8pu
2.0 Short-duration root-mean-square (rms) variations			<0.1-1.8 pu
2.1 Sag		0.5 cycle-1min	0.1-0.9 pu
2.2 Swell		0.5 cycle-1min	1.1-1.8 pu
3.0 Long-duration rms variations			0-1.2 pu
3.1 Undervoltage		>1min	0.8-0.9 pu
3.2 Overvoltage		>1min	1.1-1.2 pu
4.0 Unbalance			
4.1 Voltage		steady-state	0.5-2%
4.2 Current		steady-state	1.0-30%
5.0 Waveform distortion			
5.1 DC offset		steady-state	0-0.1%
5.2 Harmonics	0-9kHz	steady-state	0-20%
5.3 Interharmonics	0-9kHz	steady-state	0-2%
5.4 Notching		steady-state	
5.5 Noise	broadband	steady-state	0-1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1-7%
			0.2-2 P_{st}
7.0 Power frequency variations		<10s	+/- 0.10 Hz

As well as knowing the different categories and characteristics of electromagnetic disturbances, knowing where the disturbance comes from is very important; there are several different sources of disturbances and therefore different mitigation solutions which have huge economic impacts. The fact that most of the time the economic factor has the biggest impact on the decision cannot be ignored, so an in depth and technical analysis of this issue is important.

One common way to describe where the disturbance comes from is whether it came from the "utility side" or the "user side." This interpretation serves to assess who is responsible for the mitigation of the disturbance. Another way to describe where the disturbance comes from, in a more technical way, is to determine the nature of the source, for example, lightning, load switching, power system fault, non-linear loads, or radiated electromagnetic interference. In Fig. 1, a representation of the different sources and natures of disturbances can be seen.

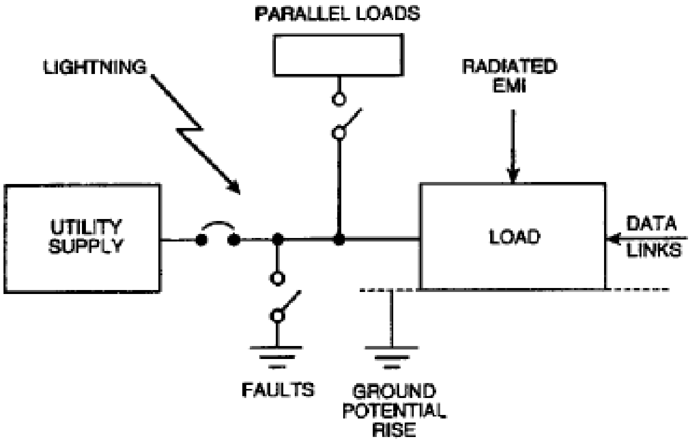


Fig. 1: Sources of Load Disturbances (Both Internal and External) [2]

According to [2] the most likely disturbances as far as the supply system is concerned are sags, transients, interruptions, and swells. On the other hand, experience suggests that the most likely power quality problems originating on the end-user side are improper wiring and grounding, harmonics and voltage fluctuations. The concerns and management of voltage fluctuations are the subject of this thesis.

2.1 VOLTAGE FLUCTUATIONS

One way voltage quality may be analyzed is with the concept of flicker, defined as “a variation of input voltage, either in magnitude or frequency, sufficient in duration to allow visual observation of a change in electric light source intensity” [2]. Another definition of flicker is “impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time" [6]. The degree of annoyance depends on the magnitude, frequency, and rate of occurrence and duration of the associated voltage changes. Flicker is just the visual effect from lamps, while the electromagnetic phenomenon causing the disturbance is referred to as voltage fluctuations. Voltage fluctuations are defined as "a series of voltage changes or a cyclical variation of the voltage envelope" [6]. The supply voltage may be viewed as a carrier wave being modulated by random voltage fluctuations. The voltage magnitude variations capable of creating problems may be as low as 0.1% of nominal system voltage.

Typical loads or operations that produce voltage changes causing flicker are the start-up of motors, welders, cycloconverters, and arc furnaces. A representation of a motor start, representing a rapid voltage change, is shown in Fig. 2 and a representation of a square-wave amplitude modulation repetitive voltage change is shown in Fig. 3.

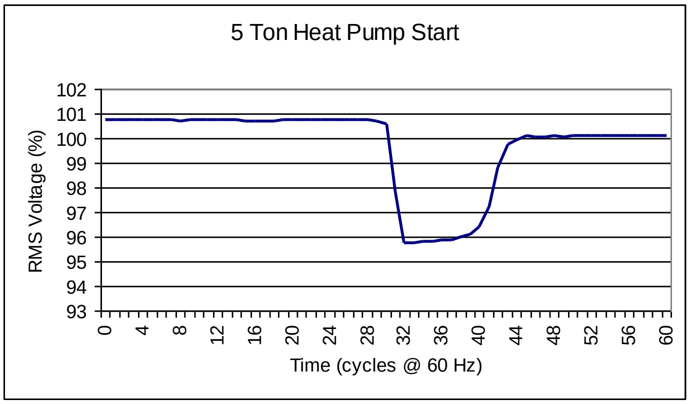


Fig. 2: Motor Start [4]

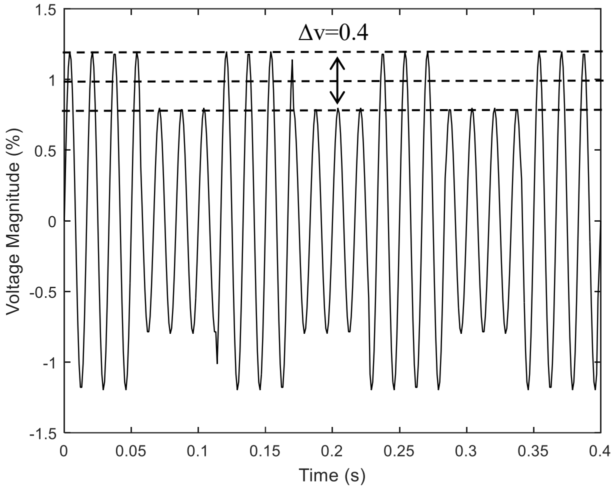


Fig. 3: Square Wave Amplitude Modulation

The light output of incandescent lamps is critically affected by the impressed voltage which leads to what is called flicker. IEEE and IEC have developed standards in order to quantify flicker based on a 60W incandescent lightbulb. Tests and analytical analyses have been carried out in many countries to assess what types of voltage variations cause light intensity variations that are perceivable and tolerated by humans. Of course, the point at which flicker is detectable and/or becomes irritating varies for each person.

In the United States, the General Electric (GE) Flicker Curve, shown in Fig. 4, was developed to serve as a guideline for assessing flicker. It was based on an experimental study where people were subjected to light fluctuations produced by several square wave modulations of the line voltage. They were asked to indicate when they were able to perceive the fluctuation and when it became irritating. Based on their responses, two thresholds of flicker were determined: visibility and irritation. A graphical chart of the average responses is known as a flicker curve. It is important to note the flicker curve assumptions: the shape of the fluctuation is a square wave, the fluctuation rate is periodic over time, and the lamp involved is a 60W incandescent bulb.

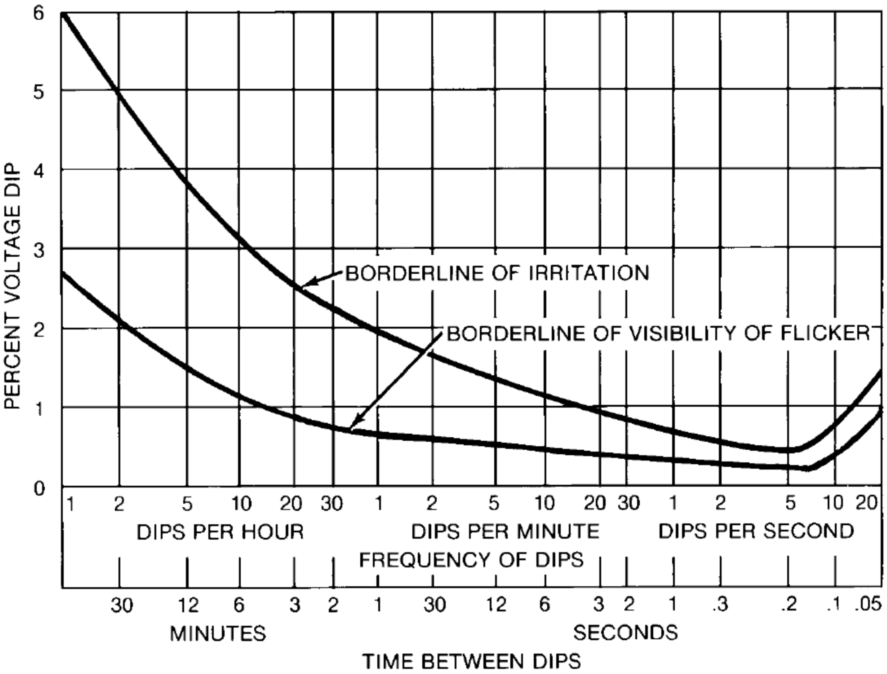


Fig. 4: General Electric (GE) Flicker Curve [6]

This curve was and is still used by many utilities in the United States to evaluate flicker. In reality, actual voltage fluctuations produced by common loads do not fit the flicker curve assumptions because they have varying amplitudes, multiple frequencies, they are not periodic, and the waveform modulation is not a square wave. Examples of actual voltage fluctuations showing actual characteristics are shown in Fig. 5(a) and Fig. 5(b).

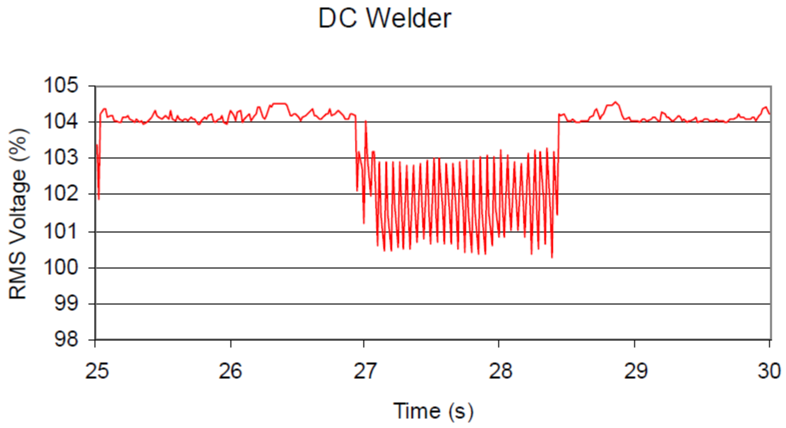


Fig. 5 (a): DC Welder Operation [4]

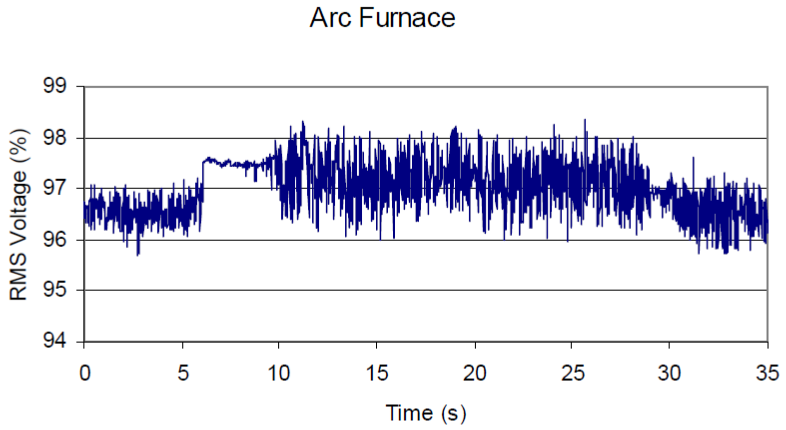


Fig. 5 (b): Arc Furnace Operation [4]

At the same time, the International Union for Electroheat (UIE) developed a guide which gave a functional and design specification of a flicker measuring instrument called a flicker meter. It has now been adopted by the IEC in Standard 61000-4-15 and it is intended to indicate the correct flicker perception and annoyance levels for all practical voltage fluctuation waveforms.

The advantages of the flicker meter are that it can process multiple frequency fluctuations, arbitrary rms voltage modulations, and aperiodic voltage changes such as the examples shown in Fig. 5. The flicker meter outputs defined to characterize the flicker severity are: instantaneous flicker sensation, P_{inst}, which is what we can perceive, short term flicker severity, P_{st}, which is the level of irritation, and long term flicker severity, P_{lt}. The flicker meter is designed to be able to simulate the response of an incandescent lamp and the eye-brain characteristics of human vision in addition to performing an on-line statistical analysis of the flicker signal to determine P_{st}, for which one value is obtained in a period of 10 min, and P_{lt}, for which one value is obtained in a period of two hours. A functional block diagram of the flicker meter based on 50Hz systems is shown in Fig. 6.

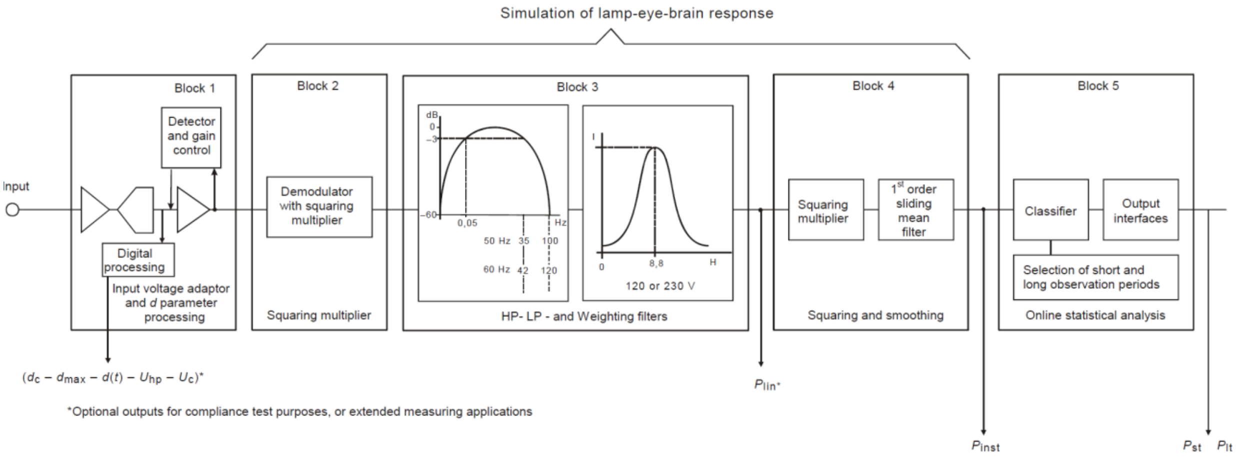


Fig. 6: Functional Block Diagram of Flickermeter [10]

The flicker meter is designed to produce an output value P_{st} where a value $P_{st}=1$ correlates with human objections to light flicker. The IEC also developed a curve, called the $P_{st}=1$ curve, which indicates the required rectangular voltage change amplitudes at different frequencies to produce $P_{st}=1$. The amplitude corresponding to $P_{st}=1$ for a particular rate of repetition can be obtained from the curve and then used to determine the actual P_{st} value for a particular actual voltage change. Although this curve is limited to rectangular fluctuations, shape factors can be applied to convert some common voltage change characteristic into equivalent square wave voltage changes. This is very useful for predicting flicker when it cannot be measured. Of course, using a simulation of the flicker meter is another more accurate way to predict P_{st}. The P_{st}=1 curve is shown in Fig. 7.

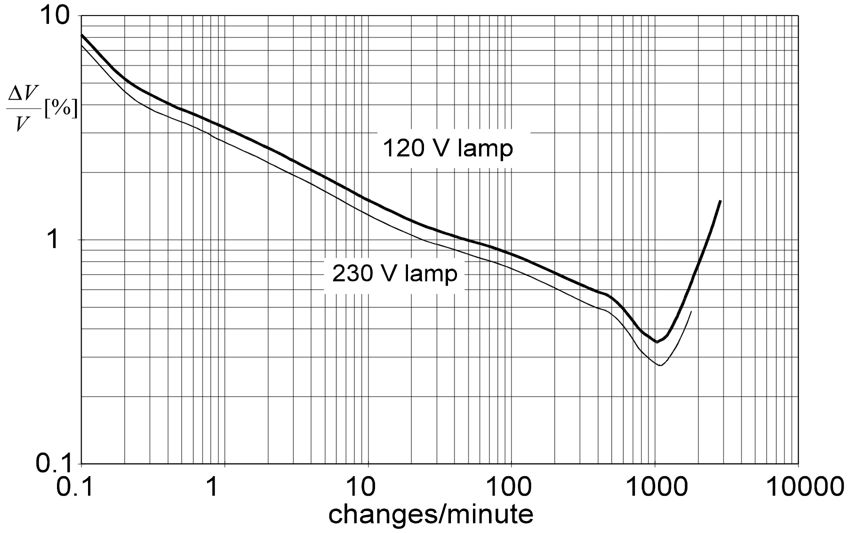


Fig. 7: IEC P_{st} = 1 Curve [9]

It is of historical interest to note that the curve in Fig. 7 for the 120 V / 60 Hz lamp is essentially identical to the widely-used (GE) Flicker Curve in the United Stated, shown in Fig. 4.

CHAPTER 3: POWER QUALITY MANAGEMENT

The International Electrotechnical Commission is a non-profit international standards organization that publishes International Standards for all electrical, electronic and related technologies. The IEC developed a series of PQ Standards and Technical Reports that are used by many countries in the world and which in some cases are adopted as requirements. The PQ standards fall into a category called Electromagnetic Compatibility Standards/Technical Reports. Electromagnetic compatibility (EMC) is defined as “the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in the environment” [9]. When an equipment or system is subjected to electromagnetic disturbances there is a possibility for electrical degradation, malfunction, or failure. When an equipment or system can operate correctly, does not emit any significant electromagnetic phenomena, and all other equipment in the electromagnetic environment can still operate, electromagnetic compatibility is achieved.

The IEEE also developed standards to manage disturbances, but the approaches and philosophies differ from those of the IEC. Some IEEE standards have the philosophy to manage disturbances as a “shared responsibility” between customers and utilities. Not necessarily the same philosophy is applied to manage all disturbances. The IEC philosophy to manage disturbances is applied to all electromagnetic disturbances in the same way. It is based on controlling EMC requirements and limitations on end-use equipment and installations. In order to understand how the IEC manages voltage fluctuation disturbances, the general philosophy used to manage all disturbances will be explained.

The objective of the IEC standards is to achieve EMC, so that equipment can function properly in its electromagnetic environment without introducing any intolerable disturbance. The disturbance level is defined as “the value of any given electromagnetic phenomena measured in a specified way” [9]. The maximum value of the disturbance level may be from either a superposition of different sources or a single source. In general, the disturbance level is not a single value, it varies with location and time; therefore, the statistical distribution of the disturbance must be considered. Because of this variance, it is difficult to determine what is the maximum level of disturbance because the highest value may appear very infrequently and therefore it is not practical to set as a target the highest value when it is not likely to be present.

The compatibility level is defined as “the specified electromagnetic disturbance level used as a reference level in a specified environment for co-ordination in the setting of emission and immunity levels” [9]. In practice, this level is not the maximum level of disturbance, it is a level that may be exceeded with a small probability and is such that the equipment can still operate in the environment the majority of the time. Normally, the compatibility level is the level of the disturbance that would be exceeded only 5% of the time. That allows the compatibility level to cover at least 95% of the situations considering both location and time.

It is important to note that the compatibility levels are individually set for each disturbance. In reality, several disturbances can occur at the same time in the same environment. Equipment can be affected by a particular combination of them even though each individual disturbance level is less than their corresponding compatibility level. Because of the number of disturbances and combinations that can occur, it is impossible to set compatibility levels for combinations of disturbances.

The immunity level is defined as “the maximum level of a given electromagnetic disturbance on a particular device, equipment or system for which it remains capable of operating with a declared degree of performance” [6]. This level should be greater than or equal to the compatibility level.

Electromagnetic susceptibility is defined as “the inability of equipment or the system to perform without degradation in the presence of an electromagnetic disturbance.” The susceptibility level should be greater than or equal to the immunity level for test purposes. Susceptibility levels are determined by manufacturers taking into account service conditions and specified immunity levels.

Emission levels are “the level of any given electromagnetic disturbance emitted from a particular device, equipment, system, or disturbing installation as a whole, assessed and measured in a specified way.” An emission limit is “the maximum emission level specified by the system operator/owner for a particular device, equipment, or system or disturbing installation as a whole” [6]. For some disturbances there are no emission limits applied because the emission sources are unpredictable and/or uncontrollable. Some examples of these type of phenomena are lightning, faults, and load switching. Other phenomena such as harmonics or flicker can be controlled because they arise from well known equipment operation, thus emission limits can be applied.

Lastly, the planning level is the level which is used as a reference value for setting emission limits for large loads and installations that are connected to MV, HV, EHV. Note that low frequency disturbances conduct in both directions between low voltage and high voltage networks, therefore planning levels are set for different voltage levels taking into account the disturbance contributions from upstream and downstream. The planning level of course cannot be greater than the compatibility level.

Again, the compatibility level is a reference value used for the coordination of disturbance and the immunity levels. For every phenomenon, if the disturbance level is sufficiently low and the immunity levels are sufficiently high then electromagnetic compatibility for the entire system may be achieved where all equipment and the system operates as intended. A graphical representation of the different levels, limits, and the relationship between them is illustrated in Fig. 8.

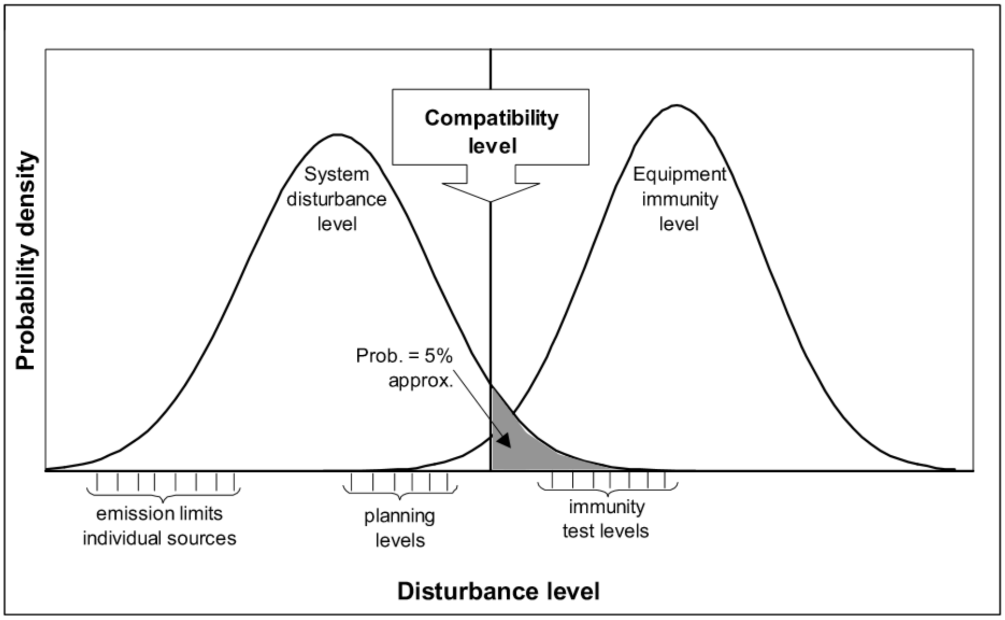


Fig. 8: Relation between Compatibility, Immunity, Planning, and Emission Levels [9]

From Fig. 8 it can be seen that the compatibility level is set in a way coordinated with both the equipment immunity level and the system disturbance level. The disturbance level should be low enough and the individual equipment immunity level should be high enough for achieving electromagnetic compatibility. It can also be noted that the compatibility level is set so that it can cover 95% of the situations for equipment to operate as intended.

Regarding flicker, the value of P_{st} =1 is defined as the compatibility level for flicker in low voltage systems. The compatibility levels for flicker in LV systems are shown in Table 4. It is also the limit applied to flicker at the supply terminals of equipment connected in LV systems. Manufacturers of equipment have to subject equipment to specific tests given by [11] and [12] in order to determine if a piece of equipment is compliant with the value P_{st} =1 requirement and can therefore be connected to the system.

Table 4: Compatibility Levels for Flicker in LV Systems [9]

Compatibility Levels	
P_{st}	1
P_{lt}	0.8

CHAPTER 4: IEC/TR 61000-3-7

At the system level, the IEC provides technical information for system owners/operators to determine emission limits at higher voltage levels so that the compatibility level is achieved in low voltage systems. IEC/TR 61000-3-7 is part of the EMC standards series, providing guidance for determining the requirements for the connection of fluctuating installations to MV, HV, and EHV public power systems.

Large fluctuating installations creating voltage changes can produce flicker, which propagates through the power system possibly creating problems at other locations. Control of disturbance levels is required to provide quality service for all installations connected to the power system. To control the disturbances, emission limits for individual installations are developed based on the effect that these emissions have on the total quality of the voltage. The goal is to help system operators/owners in providing adequate service quality for all connected customers.

This TR is not intended for equipment; individual pieces of equipment have to maintain their individual emission limits ($P_{st} \leq 1$). The system operator/owner is responsible for specifying requirements for the connection of fluctuating installations (including each customer's complete installation) to the system so as to control and limit flicker throughout the system as a whole. The problems related to voltage fluctuations, as mentioned before, are flicker effect from light sources and rapid voltage changes (even within the normal operational voltage tolerances). This TR primarily focuses on providing guidance for the coordination of flicker emissions between different voltage levels in order to meet the compatibility level in LV systems ($P_{st} \leq 1$).

The planning levels shown in Table 5 are suggested for use for determining emission limits for installations. When comparing the customer's emission limit with the actual emission level, probability levels should be used for determining compliance. The 95th and 99th percentile values of P_{st} (i.e., those values which are exceeded for 5% and 1% of the measurement period) should be calculated for a minimum time period of one week and compared with the emission limit.

Table 5: Planning Levels for Flicker in MV, HV, and EHV Power Systems [6]

	Planning Levels	
	MV	HV-EHV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

The emission level from an installation into the power system is the amount of flicker which the installation is producing at the point of evaluation (POE). The emission level should of course be less than the emission limit assigned. The POE should be the same point at which the planning levels are defined and where other customers could be connected.

4.1 ALLOCATION OF EMISSION LIMITS

The TR addresses the allocation of the capacity of the system to absorb disturbances. The approach is based on deriving the total absorption capacity of the system and then apportioning this to individual users according to the size of installation with respect to the total supply system capacity. Emission limits are assigned based on a supposed equitable sharing principle; larger system users receive a greater share of the total allowable disturbance level at a particular voltage level, while smaller users receive a smaller share.

Three stages of evaluation are defined, which may be used in sequence or independently. Stage 1 is mainly used to evaluate small installations with only a limited amount of fluctuating load which can possibly be connected without detailed evaluation of the emission characteristics and the supply system response. The connection will be accepted if the ratio of apparent power variations to the short circuit power at the POE are within the limits shown in Table 6.

Table 6: Stage 1 Limits as a Function of the Number of Changes per Minute [6]

r min^{-1}	$K=(\Delta S/S_{sc})_{max}$ (%)
$r > 200$	0.1
$10 \leq r \leq 200$	0.2
$r < 10$	0.4

The P_{st} produced by any of the installations that are accepted under Stage 1 will be well below the level associated with objectionable flicker, $P_{st}=1$. Stage 2 is used when an installation does not meet Stage 1 criteria. When an installation cannot comply with Stage 2 limits, Stage 3 is used to evaluate the installation where it can be allowed to have a higher emission level on a conditional basis. There is not a standard method for Stage 3, but it requires a more detailed analysis using more information about the system and other connected installations. For Stage 2, there is a standard method; therefore, it will be explained in more detail.

4.2 STAGE 2 PROCEDURE

In this stage, the customer's installation is evaluated against the absorption capacity of the system. The absorption capacity is derived from the planning levels and is apportioned to individual customers according to their demand with respect to the total system supply capacity. The principle of the approach is that if the system is operating at its designed capacity and all customers are injecting their maximum allowable emission level, then the total disturbance level due to all customers will be equal to the absorption capacity.

Planning levels should coordinate voltage fluctuations and attenuation between different voltage levels while allowing for upstream and downstream contributions. To enable this, transfer coefficients are used. These are defined to be the levels of disturbances that can be transferred between two parts of the power system, usually considered to be at different operating voltages. Ultimately, the emission limits for each installation are derived from the planning levels. The objective is to coordinate disturbance levels between users in order to meet the planning levels at all points in the network. The procedure used to determine emission limits for fluctuating installations connected to MV systems (Stage 2 in 3-7) is illustrated in Fig. 9 where the following definitions apply:

- $G_{Pst,MV}$ = Global allowable flicker level at MV;
- $L_{Pst,MV}$ = Planning level for flicker in MV system;
- $L_{Pst,US}$ = Planning level for flicker in the upstream system; and
- $T_{Pst,UM}$ = Transfer coefficient (of flicker) from the upstream system to the local MV system.

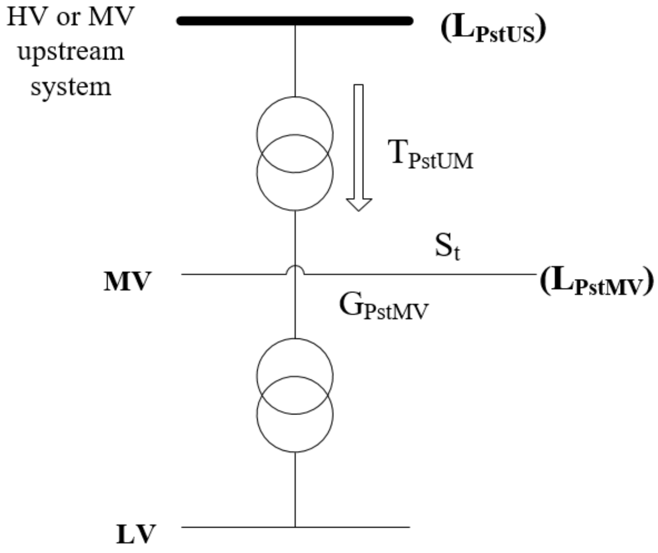


Fig. 9: IEC Emission Limit Procedure [6]

The total flicker level should not exceed the planning level of the MV system while considering the transfer coefficient from upstream. Transfers from any supplied LV networks or installations into the upstream MV system are usually assumed to be negligible (if appreciable levels exists at MV, there would be extremely high levels at LV). Only a fraction of the $G_{Pst,MV}$ is allowed for each customer. The approach taken considers the ratio between the agreed power S_i of each user i and the total supply capability S_t of the MV system, where S_t can be taken as the capacity of the HV-MV transformer or as the total downstream load, with a provision for possible future load growth. The individual emission limits are given by (1) where the summation law with an exponent of 3 is used to calculate $G_{Pst,MV}$ as shown in (2).

$$E_{Pst,i} = G_{Pst,MV} \sqrt[3]{\frac{S_i}{S_t}} \tag{1}$$

$$G_{Pst,MV} = \sqrt[3]{L^3_{Pst,MV} - T^3_{Pst,UM} \times L^3_{Pst,US}} \qquad (2)$$

In general, the summation law with an exponent with a value of 3 has been accepted for combining flicker severity caused by multiple installations [6].

4.3 IEC/TR 61000-3-7 METHOD DISCUSSION

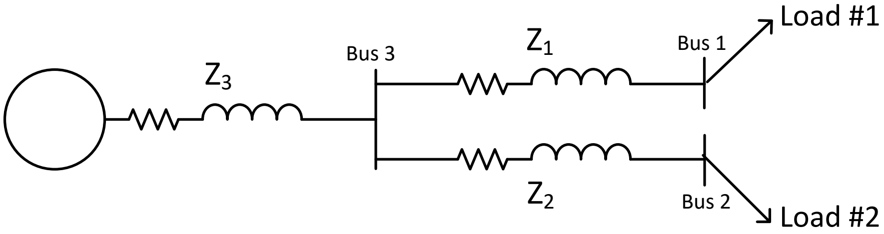
The approach used in the TR assumes that (1) the combined effect of all flicker disturbances in a power system is based on the general summation law, (2) flicker values present at a given voltage level will be transferred downstream with some attenuation, and (3) flicker contributions from downstream (to upstream) can be considered negligible. The system total allowable disturbance level, $G_{Pst,MV}$, depends on the flicker transfer coefficient. The difficulties of this approach are that total supply capacity, S_t, and the transfer coefficient, $T_{Pst,UM}$, can be difficult to determine. Uncertainty is introduced when deciding whether to use the transformer rating or the total load supplied as the total supply capacity. Provision for possible future load growth adds another complexity for determining S_t. Transfer coefficients include the combination of transfer impedances and attenuation factors due to flicker attenuating loads (e.g motors) which are difficult to determine.

Clearly, the determination of the emission limit for any specific installation in (1) is based only on its size with respect to the system capacity. The principle considered is that the agreed power of a user is linked with the user’s share of the investment costs of the power system. The principle appears to lead to a process of equitable (economic) allocation. One drawback of this approach is that when an installation is of small size, the emission limits can be extremely low.

(For this reason, all users are granted a minimum limit E_{Pst}=0.35 regardless of their size.) On the other hand, larger customers will receive a greater share of the global allowable level at MV. No consideration is given for the fact that users will impact the network differently depending on their location.

The only way limits can be proportional to size and independent of location is for all users to be connected at the same point in the network. This implies that all users have the same supply impedance. For simplicity, most practitioners of the IEC approach take this common connection point to be the MV substation bus. Because the summation of all voltage disturbances must be less than or equal to the global allowable disturbance level, the IEC approach indeed enforces global compliance at the MV substation bus. It is important to recognize that the IEC procedure allocates emission limits according to the contribution of all users to the total voltage disturbance effect at the MV substation bus (LV side of the transformer).

In reality, voltage fluctuation disturbance levels at any point depend on the user load currents (their size) and the impedances throughout the system. Because of this dependence of flicker level on fluctuating currents and system impedances, the results of the existing procedures may not be equitable from a system performance perspective. To visualize this concept, consider a more realistic situation as shown in Fig. 10.



$$\Delta V_1 \approx \Delta I_1(Z_3 + Z_1) + \Delta I_2(Z_3)$$
$$\Delta V_2 \approx \Delta I_1(Z_3) + \Delta I_2(Z_2 + Z_3)$$
$$\Delta V_3 \approx \Delta I_1(Z_3) + \Delta I_2(Z_3)$$

Fig. 10: Voltage Fluctuations Depends on Users Location

Assuming they are the same size, the only place in the network that both loads have the same voltage fluctuation effect is at bus 3. For this reason, the IEC approach is often said to result in limits which would be valid if all users were connected to the substation bus. Clearly, the voltage fluctuations produced at bus 1 and bus 2 are greater than at bus 3 because there is greater impedance. In order for both users to comply with their assigned fluctuation limit (which is based on the effect each user has on bus 3), they have to reduce their fluctuating current to comply with the limits at their own location.

Furthermore, if both users are of the same size, according to IEC, S_1 and S_2 are assigned the same P_{st} limit. If Z_1 is greater that Z_2 there will be more fluctuating voltage at bus 1. Therefore, load 1 must have less fluctuating current to operate at its assigned P_{st} limit because the impedance, therefore fluctuating voltage, is greater at bus 1. Otherwise, the total flicker level at bus 1 will exceed $G_{Pst,MV}$. It is clear that equitable allocation is not achieved in an economic sense because load 1 needs make operational changes to reduce its fluctuating current while load 2 (of the same size) does not. In order to obtain economic equality, the installation at bus 2 must also reduce its fluctuating current. This results in under-utilization of system resources. A new limit determination process, based on the concept of voltage droop and which more fully utilizes the system capability to absorb disturbances, is the subject of the remainder of this thesis.

CHAPTER 5: A NEW PROCEDURE FOR ALLOCATING VOLTAGE FLUCTUATION LIMITS IN POWER SYSTEMS

A new allocation process for the system disturbance absorption capacity using the concept of “voltage droop” [13]-[14] is proposed which allocates emission limits according to contributions to the total voltage disturbance level at the weakest point in the system. Total voltage droop is the sum of all the voltage drops between the transmission system and the customer with the lowest voltage. Every load contributes to the total voltage droop. No voltage control equipment, such as regulators, is considered in the determination of total voltage droop. As a result, the total voltage droop represents only the complex interaction between distributed loads and network impedances. Note the connection of this concept with Fig. 10 in the previous chapter.

The approach is based on the 3-7 requirements and provides an effective theoretical foundation for the allocation process. In addition to determining emission limits according to contributions to the total voltage disturbance at the weakest point in the network, it can in general determine emission limits according to the contribution to the total voltage disturbance anywhere in the network. Therefore, the IEC allocation results (at the substation bus) can also be obtained with the new method. In addition to promoting greater utilization, the concept of voltage droop is preferable because it is mathematically defined, utilizes data that is available to system operators, and does not require complicated calculations or assumptions.

5.1 Voltage Droop

Voltage droop at any point in the network is the summation of all the individual voltage drops in the distribution network between the transmission system represented by a Thevenin equivalent and the network point being considered. Voltage drop is caused by the distributed load currents interacting with the system impedances. The total voltage drop between a source and a load point is the sum of the individual voltage drops associated with each point-to-point impedance in the supply path. Voltage increases (or decreases) due to control equipment operation (e.g., regulators) would also be considered in the summation. Total voltage droop, however, does not consider the effects of any control equipment. A distribution network voltage drop and voltage droop profile is illustrated in Fig. 11.

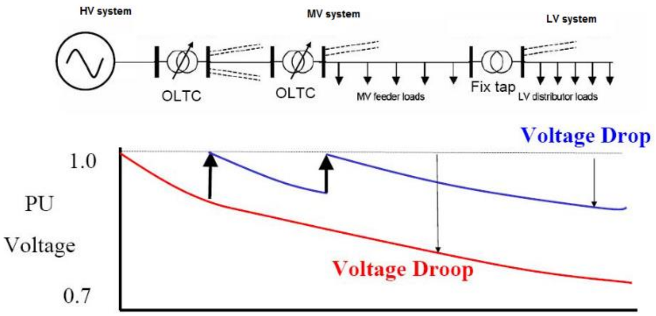


Fig. 11: Distribution Voltage Drop and Droop

In Figure 11 it is shown that total voltage droop in a network is the sum of all voltage drops between the transmission system and the lowest voltage user. No voltage control equipment, such as regulators, is considered in the determination of total voltage droop. In operational practice, voltage droop must be such that the combined action of all upstream voltage regulators will keep the voltage drop within the acceptable range, typically ±5%. The number and location of voltage control devices establishes the maximum allowable voltage droop. All known credible future load conditions and scenarios are normally considered as an integral part of the distribution planning process, so assuming all regulation equipment is operating at “full boost” and summing the maximum boost percentages gives a conservative but credible maximum droop value.

The principle considered is that controlling voltage levels within specified limits at the weakest point in the network typically ensures that other locations in the network will be within the limits required by distribution planning standards. Because flicker is a voltage phenomenon, operating the network with this philosophy normally insures that controlling voltage fluctuations within specified limits at the weakest point in the network typically ensures that other locations will be within the specified voltage fluctuation limits. With this philosophy, network resources are fully utilized but it may or may not correlate well with decisions taken based solely on equitable economic allocation of resources. Associating and allocating flicker limits based on equitable utilization (via the droop concept) is therefore a defensible method to avoid under-utilizing system resources while meeting overall flicker management objectives.

A more realistic representation of a typical US distribution network and voltage drop and droop profiles are shown in Figs. 12(a)-(c). Distribution planners frequently deal with these types of networks. No matter how large a network is, the lowest voltage location can be found with a load flow. In Figure 12(b) the voltage drop profile for the network is shown where the effect of regulators for controling voltage at the weakest point is clearly seen. Regulators could disguise the location where the interaction of currents and impedances is the greatest. Therefore, they are not considered for determining the actual lowest voltage location. The voltage profile of the network without the effect of voltage regulators can also be easily determined as shown in Fig. 12(c). In order to differentiate these two voltage profiles, we call voltage droop the cummulative effect of all currents interacting with network impedances without the effect of regulators; voltage droop is equal to voltage drop when no regulation or control is present.

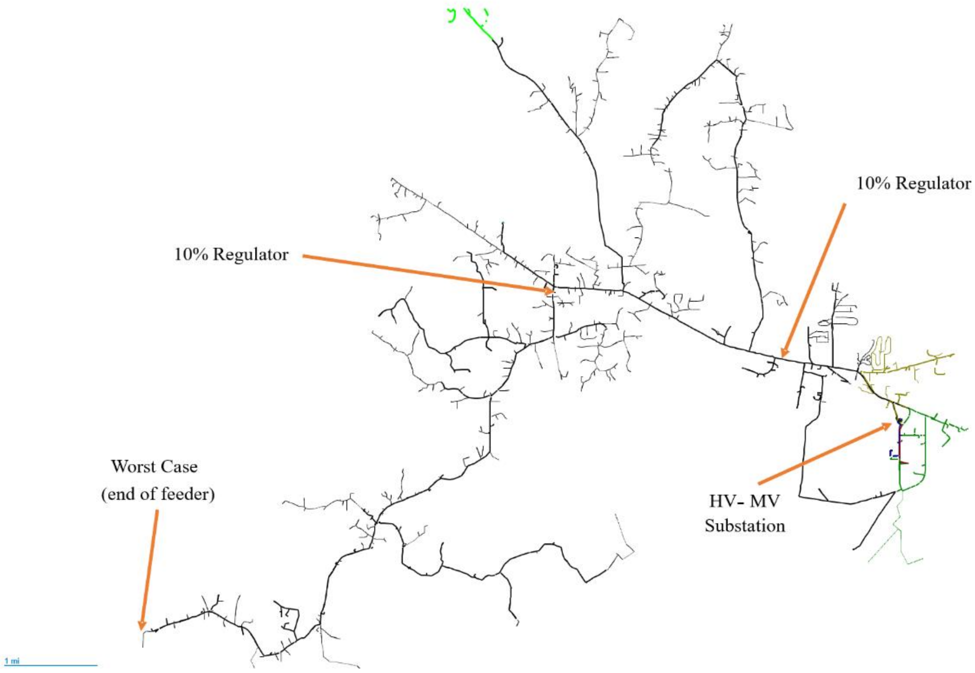


Fig. 12 (a): Typical US Distribution Network

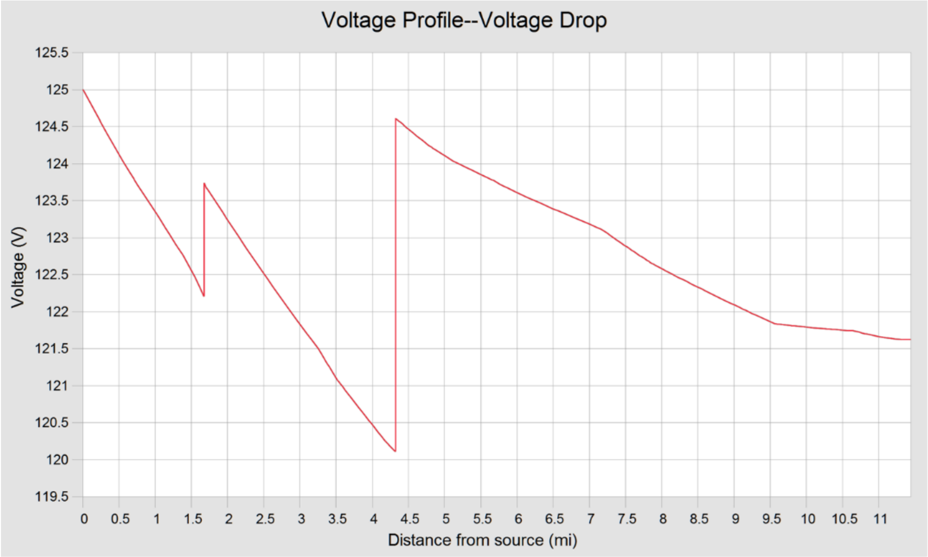


Fig. 12 (b): Voltage Drop Profile

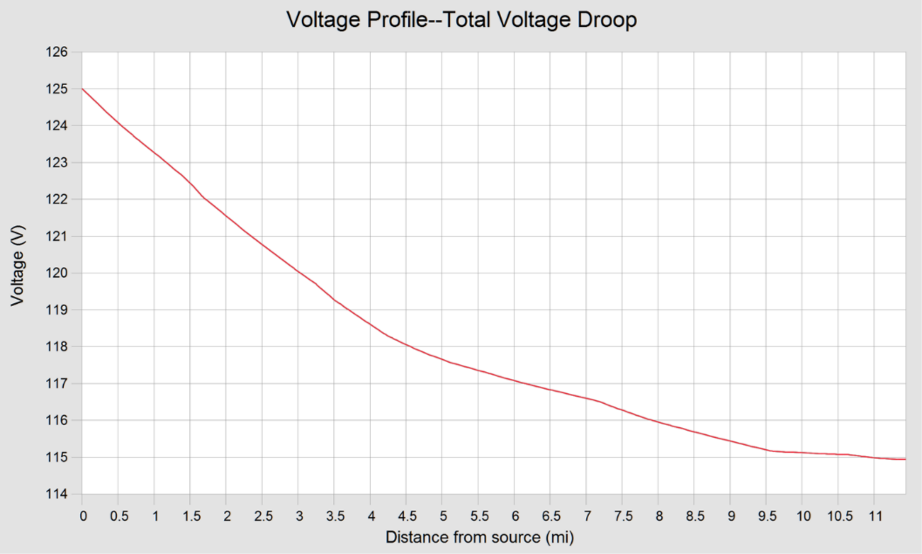


Fig. 12 (c): Voltage Droop Profile 1

Because flicker is based on voltage fluctuations, it propagates through the power system and may maintain a level sufficient to create disturbances at other points in the network. The concept of "flicker transfer" is based on this exact principle; measured or calculated flicker levels at any location can be transferred to any other location using an impedance ratio and possibly combined with other transferred values to produce a single flicker severity value at any point of interest. The transfer impedance Z_{ji} plays an important role in the determination of how much flicker is transferred from one bus i to another bus j as shown in (3). Nearby loads with a large transfer impedance have a large contribution whereas distant loads with a small transfer impedance have a small contribution to the most critical point.

$$P_{st,j} = P_{st,i} \times \frac{Z_{ji}}{Z_{ii}} \tag{3}$$

A review of the network theory necessary to build an impedance matrix is needed to see the effects of the transfer and Thevenin impedances as covered in the following section.

5.2 NETWORK THEORY

A general n-port linear network impedance description is expressed in matrix notation as shown in (4).

$$\begin{bmatrix} \overline{V}_1 \\ \vdots \\ \overline{V}_i \\ \overline{V}_j \\ \vdots \\ \overline{V}_n \end{bmatrix} = \begin{bmatrix} \overline{Z}_{11} & \cdots & \cdots & \cdots & \cdots & \overline{Z}_{1n} \\ \vdots & \ddots & & & & \vdots \\ \overline{Z}_{i1} & \cdots & \overline{Z}_{ii} & \overline{Z}_{ij} & \cdots & \overline{Z}_{in} \\ \overline{Z}_{j1} & \cdots & \overline{Z}_{ji} & \overline{Z}_{jj} & \cdots & \overline{Z}_{jn} \\ \vdots & & & & \ddots & \vdots \\ \overline{Z}_{n1} & \cdots & \cdots & \cdots & \cdots & \overline{Z}_{nn} \end{bmatrix} \begin{bmatrix} \overline{I}_1 \\ \vdots \\ \overline{I}_i \\ \overline{I}_j \\ \vdots \\ \overline{I}_n \end{bmatrix} \tag{4}$$

The diagonal entries are the Thevenin equivalent impedances at nodes *i*, *j*, etc., and the off-diagonal entries are the transfer impedances between two nodes *i* and *j*. The transfer impedance, Z_{ji}, indicates the voltage produced at node *j* due to the current injection at node *i*. The total voltage at node *j* depends on the source (Norton form) current, always at bus 1 in this work, and all load currents as shown in (5) [15].

$$\overline{V_j} = \overline{Z}_{j1}\overline{I}_1 + \cdots + \overline{Z}_{ji} I_i + \overline{Z}_{jj}\overline{I}_j + \cdots + \overline{Z}_{jn}\overline{I}_n \tag{5}$$

While (5) without the source contribution is clearly a total voltage drop (it is a summation of all point-to-point voltage drop contributions), it is also the total voltage droop because no control equipment contributions are taken into account. To visualize the concept of voltage droop and the effect of network impedances, consider the network shown in Fig. 13.

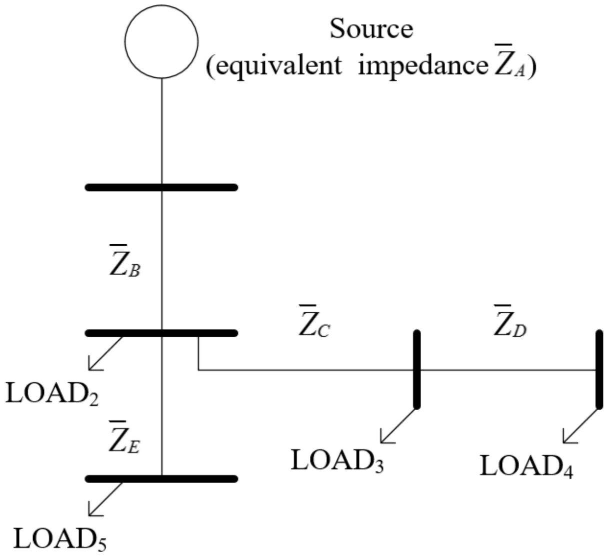


Fig. 13: Network Example

The impedance matrix can be formulated following a step-by-step method working from branch impedance values as described in [15]. This method allows building the impedance matrix from scratch. Consider adding a branch impedance $\bar{Z}_b$ between two buses. There can be three different types of buses: an old bus *j*, existing before $\bar{Z}_b$ is added, a new bus *k*, created after $\bar{Z}_b$ is added, and the reference bus *r*, where the reference voltage is 0. The impedance $\bar{Z}_b$ may be considered in five different ways [15]:

1. Add $\bar{Z}_b$ from a new bus to reference;
2. Add $\bar{Z}_b$ from a new bus to an old bus;
3. Add $\bar{Z}_b$ from an old bus to reference;

4. Connect $\bar{Z}_b$ between two old buses; and
5. Connect $\bar{Z}_b$ between two new buses.

The technique is based on modifying an existing impedance matrix in possibly five different ways. For the purpose of this example, and for radial networks in general, building the impedance matrix requires the use of only the first two types of modifications. Therefore only type 1 and type 2 modifications will be described. The impedance matrix will be an mxm size matrix before modification, defined as $[\bar{Z}_{old}]$ and the new matrix, $[\bar{Z}_{new}]$, will be an $(m+1)\times(m+1)$ size matrix. The off-diagonal impedances $\bar{Z}_{ij}$ and $\bar{Z}_{ji}$ are equal, making the matrix diagonally symmetric. The sign convention used for voltage and current is as shown in Fig. 14.

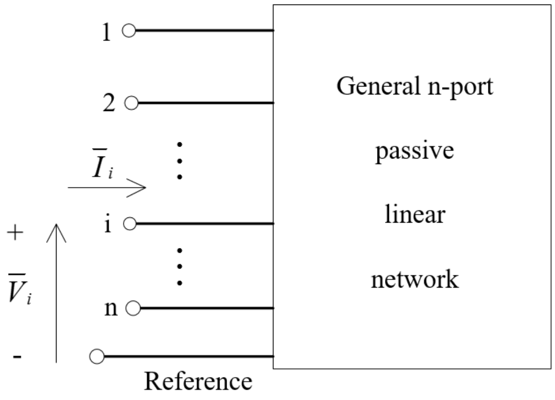


Fig. 14: General n-Port Network

A type 1 modification is defined as adding a branch impedance $\bar{Z}_b$ from a new bus k to reference. The modification to $[\bar{Z}_{old}]$ is to add a k^{th} row and column, where the definitions in (6) apply and the complete $[\bar{Z}_{new}]$ matrix is shown in (7).

$$\bar{Z}_{ki}=\bar{Z}_{ik}=0 \qquad i=1,2,\ldots,\mathrm{n} \tag{6}$$

$$\bar{Z}_{kk}=\bar{Z}_b$$

$$[\bar{Z}_{new}]=\left[\begin{array}{ccc|c} & [\bar{Z}_{old}] & & 0 \\ & & & \vdots \\ & & & 0 \\ \hline 0 & \cdots & 0 & \bar{Z}_b \end{array}\right] \tag{7}$$

A type 2 modification is defined as adding a branch $\bar{Z}_b$ from a new bus k to an old bus j. The modified $[\bar{Z}_{new}]$ is as shown in (8).

$$[\bar{Z}_{new}]=\left[\begin{array}{cccc|c} & & & & \bar{Z}_{1j} \\ & [\bar{Z}_{old}] & & & \bar{Z}_{2j} \\ & & & & \vdots \\ & & & & \bar{Z}_{nj} \\ \hline \bar{Z}_{j1} & \bar{Z}_{j2} & \cdots & \bar{Z}_{jn} & \bar{Z}_{jj}+\bar{Z}_b \end{array}\right] \tag{8}$$

With these two simple building rules, the impedance matrix of a radial network can be constructed from scratch. Referring back to the example network shown in Fig. 13, a type 1 modification will be used first to add the source impedance, which is an impedance from a new bus, k=1, to reference. The process begins with a 0×0 matrix thus the new matrix is as shown in (9).

$$[\bar{Z}_{new}]=[\bar{Z}_A] \tag{9}$$

The next steps are to add the branch impedances in sequential order. The process continues by adding the branch impedance $\bar{Z}_B$ from a new bus k=2 to an old bus j=1. The new matrix is as shown in (10).

$$[\bar{Z}_{new}] = \begin{bmatrix} [\bar{Z}_{old}] & \bar{Z}_{11} \\ \bar{Z}_{11} & \bar{Z}_{11}+\bar{Z}_B \end{bmatrix} = \begin{bmatrix} \bar{Z}_A & \bar{Z}_A \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B \end{bmatrix} \tag{10}$$

Next the branch impedance $\bar{Z}_C$ from a new bus k=3 to an old bus j=2 is added. The new matrix is as shown in (11).

$$[\bar{Z}_{new}] = \begin{bmatrix} [\bar{Z}_{old}] & & \bar{Z}_{12} \\ & & \bar{Z}_{22} \\ \bar{Z}_{21} & \bar{Z}_{22} & \bar{Z}_{22}+\bar{Z}_C \end{bmatrix} = \begin{bmatrix} \bar{Z}_A & \bar{Z}_A & \bar{Z}_A \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C \end{bmatrix} \tag{11}$$

Next the branch impedance $\bar{Z}_D$ from a new bus k=4 to an old bus j=3 is added. The new matrix is as shown in (12).

$$[\bar{Z}_{new}] = \begin{bmatrix} & & & \bar{Z}_{13} \\ & [\bar{Z}_{old}] & & \bar{Z}_{23} \\ & & & \bar{Z}_{33} \\ \bar{Z}_{31} & \bar{Z}_{32} & \bar{Z}_{33} & \bar{Z}_{33}+\bar{Z}_D \end{bmatrix} = \begin{bmatrix} \bar{Z}_A & \bar{Z}_A & \bar{Z}_A & \bar{Z}_A \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C+\bar{Z}_D \end{bmatrix} \tag{12}$$

Finally, the branch impedance $\bar{Z}_E$ from a new bus k=5 to an old bus j=2 is added. The new matrix is as shown in (13).

$$[\bar{Z}_{new}]=\begin{bmatrix} & [\bar{Z}_{old}] & & & \bar{Z}_{12} \\ & & & & \bar{Z}_{22} \\ & & & & \bar{Z}_{32} \\ & & & & \bar{Z}_{42} \\ \bar{Z}_{21} & \bar{Z}_{22} & \bar{Z}_{23} & \bar{Z}_{24} & \bar{Z}_{22}+\bar{Z}_E \end{bmatrix}=\begin{bmatrix} \bar{Z}_A & \bar{Z}_A & \bar{Z}_A & \bar{Z}_A & \bar{Z}_A \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C & \bar{Z}_A+\bar{Z}_B \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C & \bar{Z}_A+\bar{Z}_B+\bar{Z}_C+\bar{Z}_D & \bar{Z}_A+\bar{Z}_B \\ \bar{Z}_A & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B & \bar{Z}_A+\bar{Z}_B+\bar{Z}_E \end{bmatrix} \quad (13)$$

With the complete impedance matrix and known current injections it is possible to solve for all the voltages in the network as shown in (14).

$$\begin{bmatrix} \overline{V_1} \\ \overline{V_2} \\ \overline{V_3} \\ \overline{V_4} \\ \overline{V_5} \end{bmatrix}=[\bar{Z}_{new}]\begin{bmatrix} \overline{I_1} \\ \overline{I_2} \\ \overline{I_3} \\ \overline{I_4} \\ \overline{I_5} \end{bmatrix} \quad (14)$$

Suppose the worst voltage droop is located at bus 5. From (5), the total voltage at bus 5 is derived in (15) and expressed in (16) according to the network considered in Fig. 13.

$$\overline{V}_5=\overline{Z}_{51}\overline{I}_1+\overline{Z}_{52}\overline{I}_2+\overline{Z}_{53}\overline{I}_3+\overline{Z}_{54}\overline{I}_4+\overline{Z}_{55}\overline{I}_5 \quad (15)$$

$$\overline{V}_5=\overline{V}_s-\left(\overline{Z}_A+\overline{Z}_B\right)\overline{I}_2-\left(\overline{Z}_A+\overline{Z}_B\right)\overline{I}_3-\left(\overline{Z}_A+\overline{Z}_B\right)\overline{I}_4-\left(\overline{Z}_A+\overline{Z}_B+\overline{Z}_E\right)\overline{I}_5 \quad (16)$$

Note that to be consistent with the sign convention defined in the multi-port network modeling theory shown in Fig. 14, currents injected into nodes (i.e., sources) are considered to be positive and currents flowing out of nodes (i.e., loads) are taken as negative. Load currents in (16), therefore, have the negative sign included. Note also that network theory can prove that the first term in the summation in (15) is always equal to the equivalent source voltage. From the full impedance matrix derivation shown in (13), it can be seen that the first term in every row is always equal to the source impedance. This occurs when there is only one source in the network, thus the substitution is made for clarity in (16). Voltage droop, $V_{droop,j}$, is represented in (17) where it is expressed as the magnitude of the vector difference between the source voltage and the lowest voltage (maximum droop), taken as being at bus *j*, in the network considered. Each load current term represents the complex contribution of the load at bus *i* to the total complex droop at bus *j* as shown in (17).

$$V_{droop,j}=\left|\overline{V}_1-\overline{V}_j\right| = \left|\sum_{i=2}^{n}\overline{Z}_{ji}\,\overline{I}_i\right|=\left|\sum_{i=2}^{n}\left\{\left(R_{ji}+jX_{ji}\right)\left(I_{iR}+jI_{iX}\right)\right\}\right| \tag{17}$$

5.3 NEW FLICKER LIMIT ALLOCATION METHOD BASED ON VOLTAGE DROOP

Voltage droop and voltage fluctuations are generated by user load currents interacting with network impedances. The proposed new method limits a user’s voltage fluctuations to a level governed by their contribution to the total voltage droop assessed at the worst-case (maximum droop) network location. Because droop and fluctuation are voltage phenomena, they are obviously closely related; allocating flicker limits based on droop contributions is possible using this relationship but the summation of voltage fluctuation effects follows different rules than the summation of voltage drops. We begin by assuming both phenomena sum with no cancellation or diversity effects being considered. This is the normal practice for summating individual voltage drop contributions to determine the total droop, but some diversity is normally considered when summating flicker and will be included later.

Case with no diversity

In this first method, every load *i* is given an allocated fluctuating current limit $E_{1,i}$ proportional to its fundamental current I_i as shown in (18). Due to the linear relationship between voltage (fluctuation) and flicker, the load at bus *i* will produce a flicker contribution $E_{Pst,i}$ at bus *i* as shown in (19) where the impedance *Z* to be used will be further specified later in this section.

$$E_{I,i} = k_a I_i \tag{18}$$

$$E_{Pst,i} = k_a I_i Z \tag{19}$$

In (18) and (19), k_a is an "allocation constant" which must be determined for the particular power system under consideration. The location of the worst-case droop, due to the summated contributions of voltage drops created by all load currents, will be the same as the location of the worst-case flicker level because both are voltage phenomena driven by load currents and network impedances. While the summation of voltage drops is called V_{droop}, the summated flicker level is referred to as the "global" level, G_{Pst}. Knowing where the maximum voltage droop is, taken as bus *j* in (20), the total or global flicker level including contributions from all fluctuating loads, $G_{Pst,j}$, can be found as shown in (20). Note that $\bar{Z}_{ji}$ represents the transfer impedance from bus *i* to bus *j*.

$$G_{Pst,j} = \left| \sum_{i=2}^{n} (k_a \bar{I}_i \bar{Z}_{ji}) \right| = k_a \left| \sum_{i=2}^{n} (\bar{I}_i \bar{Z}_{ji}) \right| = k_a V_{droop,j} \tag{20}$$

To ensure that the maximum global flicker level is acceptable, it must be less than the total allowable global contribution at MV, called $G_{Pst,MV}$, as shown in (21) where (22) is derived to determine the allocation constant k_a which can be used with (19) to determine a flicker limit for each user.

$$G_{Pst,MV} \geq k_a V_{droop,j} \tag{21}$$

$$k_a = \frac{G_{Pst,MV}}{V_{droop,j}} \tag{22}$$

To ensure that the global emission level is maintained at all system locations, (19) is modified as shown in (23) where the impedance to be used in the flicker limit allocation is the transfer impedance, $\bar{Z}_{ji}$, where i is the node of each user and j is the node of the worst-case (maximum droop) location.

$$E_{Psti,i} = k_a I_i Z_{ji} \tag{23}$$

The transfer impedances represent the effects that each load has on the worst case location. It is very important to note that the actual fluctuating current that each load will produce when operating at its assigned flicker limit will be equal to the flicker limit level produced at their location divided by the Thevenin impedance at their location. Because the transfer impedance is always less than or equal to the Thevenin impedance, the fluctuating current limit will possibly be reduced. This possible effect is derived using (24) and it is shown in (25).

$$E_{Pst,i} = k_a I_i Z_{ji} \tag{24}$$

$$E_{l,i} = \frac{E_{Pst,i}}{Z_{ii}} = k_a I_i \frac{Z_{ji}}{Z_{ii}} \leq k_a I_i \tag{25}$$

The important concept to draw from fluctuating load currents is that the fluctuating voltage produced at any other location is based on the interaction of fluctuating load currents and transfer impedances. The effects on the worst-case location (maximum droop) will be the fluctuating load current interacting with the transfer impedance to the worst case location. Thus when the flicker limits are derived with the transfer impedance to the worst-case location, then the actual flicker produced at the worst-case location will be smaller. This approach leads to reduced fluctuating load currents and the global flicker level will never be exceeded at any location. Thus the transfer impedance restricts flicker at the user location, and in all locations in the network, to maintain the worst-case location below the global allowable level. This conservatively accurate approach is suitable for Stage 2 procedures as described in [1].

For the case where no diversity is considered, greater resource utilization can be obtained. Equation (19) can be modified as shown in (26) where the impedance to be used in the flicker limit allocation is the Thevenin impedance, Z_{ii}. This impedance allows greater flicker levels at each user location, and in the local area, while maintaining the target level at the worst-case location.

$$E_{Pst,i} = k_a I_i Z_{ii} \tag{26}$$

Because the no diversity case assumes voltage fluctuations summate linearly, in the same way as voltage drops, maintaining the target flicker level at the worst-case location guarantees all other locations experience lower total flicker level. As will be shown in the following section, this guarantee does not exist when diversity is considered due to the nonlinear summation of voltage fluctuation effects.

Diversity represented by the summation law

A general method for the combination of flicker effects caused by multiple installations is shown in (27) where the summation law is used with an exponent of 3. This method has been widely used and is recognized by IEC standards [1].

$$P_{st} = \sqrt[3]{\sum P_{st,i}{}^{3}} \tag{27}$$

To account for the summation law, each user is assumed to have a fluctuating current which is related to their size as shown in (28). Multiplying this current limit by the transfer impedance to the worst case location *j* yields the flicker level at *j* due to the user's current at *i* as shown in (29). The summation of all contributions *i*=2…*n* at location *j* is the total flicker level at *j*, and the cubic summation law can be directly applied as shown in (30) and (31) to obtain the total global flicker level at *j* as shown in (32). Setting the total flicker level at *j* equal to the global allowable emission level allows the determination of k_a as shown in (33).

$$E_{I,i} = k_a \left(I_i\right)^{1/3} \left(Z_{ji}\right)^{-2/3} \tag{28}$$

$$P_{st,ji} = k_a \left(I_i\right)^{1/3} \left(Z_{ji}\right)^{-2/3} \left(Z_{ji}\right) = k_a \left(I_i\right)^{1/3} \left(Z_{ji}\right)^{1/3} \tag{29}$$

$$P_{st,ji}^{3} = k_a^{3} \left(I_i\right)\left(Z_{ji}\right) \tag{30}$$

$$\sum_{i=2}^{N} P_{st,ji}^{3} = k_a^{3} \left| \sum_{i=2}^{N} \left(\bar{I}_i\right)\left(\bar{Z}_{ji}\right) \right| \tag{31}$$

$$G^3_{Pst,j} = k_a^3 V_{droop,j} \tag{32}$$

$$k_a = \frac{G_{Pst,j}}{V^{1/3}_{droop,j}} = \frac{G_{Pst,MV}}{V^{1/3}_{droop,j}} \tag{33}$$

In (23) and (26), $E_{Pst,i}$ represents the i^{th} emission level to be summated at the worst-case location j. To represent diversity using the summation law, (23) is modified as shown in (34) for conservative Stage 2 and (26) as shown in (35) for specific Stage 3 where j represents the maximum droop location.

$$E_{Pst,i} = k_a \left(I_i\right)^{1/3} \left(Z_{ji}\right)^{-2/3} \left(Z_{ji}\right) \tag{34}$$

$$E_{Pst,i} = k_a \left(I_i\right)^{1/3} \left(Z_{ji}\right)^{-2/3} Z_{ii} \tag{35}$$

It is important to recognize that the limit for each user in (34) or (35) is based on the effect that their fluctuating current has on the voltage at the worst-case droop location. In the diversity case the same concepts as in the no diversity case apply. The Thevenin equivalent impedance at each user's location will always be greater than or equal to the transfer impedance to any other location, thus the fluctuating current may have to be reduced to meet the limits of (34) at every user's location. The net result of these reductions is that summated flicker levels will rarely exactly equal the allowable global level but are guaranteed to never exceed it at any network location when (34) is used.

Operation at limits based on (35), in Stage 3, requires more careful consideration at other locations. Attention is required to avoid exceeding the global limit at some location other than the maximum droop location. The reason that the global limit at some other location may be exceeded when using limits based on (35) is shown in the following equations. Using each user's current limit in (28), the total flicker level at some other location k is as shown in (36) where the substitution for the allocation constant has been applied. From (36) it can be seen that the total flicker level at location k, $G_{Pst,k}$, depends on the ratio Z_{ki}/Z_{ji} as shown in (37).

$$G_{Pst,k}=\frac{G_{Pst,MV}}{\sum_{i=2}^{n}(\bar{I_\iota})^{1/3}\left(\bar{Z}_{ji}\right)^{1/3}}\ \sum_{i=2}^{n}(\bar{I}_i)^{1/3}\left(\bar{Z}_{ji}\right)^{-2/3}Z_{ki} \tag{36}$$

$$G_{Pst,k}=\frac{G_{Pst,MV}}{\sum_{i=2}^{n}(\bar{I_\iota})^{1/3}\left(\bar{Z}_{ji}\right)^{1/3}}\ \sum_{i=2}^{n}(\bar{I}_i)^{1/3}\left(\bar{Z}_{ji}\right)^{1/3}\frac{Z_{ki}}{Z_{ji}} \tag{37}$$

The total flicker level at a particular location depends on the impedance ratio weighting terms in the summation shown in (37). When the Thevenin impedance of location k is greater than the transfer impedance from location k to the maximum droop location j it seems that the total flicker level at location k could be greater than the total flicker level at location j. Therefore, attention is needed when a particular Thevenin impedance is much greater than the transfer impedance to the worst-case droop location. In the case where $k=j$ and the substitution is made in (38) and (39) from (36) and (37), it can be seen that the ratio of the transfer impedances is equal to 1. Therefore, the summation terms in the numerator and denominator cancel and the total flicker level at location j

equals the target level $G_{Pst,MV}$. For the case $k \neq j$, the summated flicker at location k could be greater than, less than, or equal to $G_{Pst,MV}$ depending on the impedance ratio effects in (37).

$$G_{Pst,k} = \frac{G_{Pst,MV}}{\sum_{i=2}^{n} (\overline{I_\iota})^{1/3} \left(\bar{Z}_{ji}\right)^{1/3}} \ \sum_{i=2}^{n} (\bar{I}_i)^{1/3} \left(\bar{Z}_{ji}\right)^{-2/3} Z_{ji} \tag{38}$$

$$G_{Pst,k} = \frac{G_{Pst,MV}}{\sum_{i=2}^{n} (\overline{I_\iota})^{1/3} \left(\bar{Z}_{ji}\right)^{1/3}} \ \sum_{i=2}^{n} (\bar{I}_i)^{1/3} \left(\bar{Z}_{ji}\right)^{1/3} \frac{Z_{ji}}{Z_{ji}} = G_{Pst,MV} \tag{39}$$

CHAPTER 6: EXAMPLE APPLICATIONS

For demonstration purposes, the modified IEEE 13 node test feeder [16] shown in Fig. 15 was used to evaluate the flicker allocation process and the concepts of the previous chapter. Balanced three phase loads were assumed; therefore, some of the data in [16] was modified. The actual data used for the analysis is shown in Tables 7-9. Power values are three-phase totals and the power base used for the per-unit conversions was 5000 kVA.

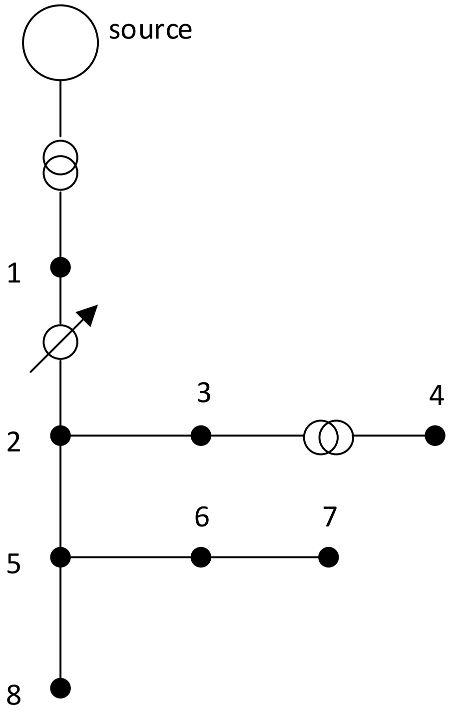


Fig. 15: Test Feeder

Table 7: Load Data

Bus	P(kW)	Q(kvar)
1	0	0
2	100	58
3	400	290
4	400	290
5	1255	718
6	170	151
7	843	462
8	300	200

Table 8: Line Data

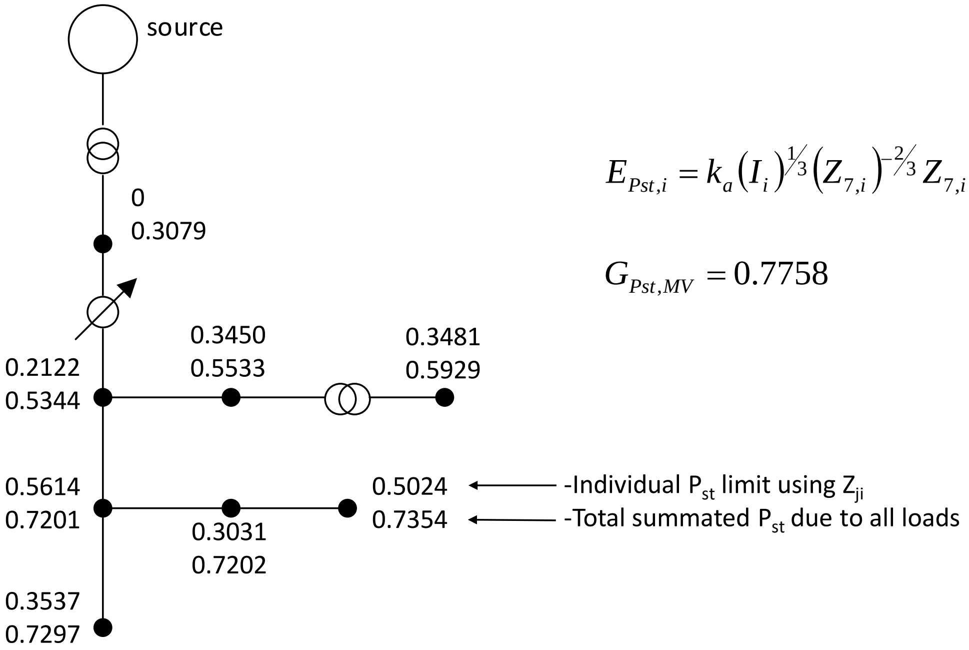
From	To	R(pu)	X(pu)
1	2	0.0208	0.0565
2	3	0.0163	0.0207
2	5	0.0208	0.0565
5	6	0	0.0001
5	8	0.0104	0.0282
6	7	0.0131	0.0113

Table 9: Transformer Data

Bus	kVA	Turns Ratio	R(pu)	X(pu)
Source-1	5000	115/4.16kV	0.01	0.08
3-4	500	4.16/0.48kV	0.011	0.02

To determine the voltage droop at each location, the simulation software PSS/E was used to perform a load flow analysis on the modified IEEE 13 node test feeder. The voltage regulator was blocked at the neutral tap (0% voltage change) so that the converged voltage solution directly gives the voltage droop. From the converged solution, the largest voltage droop is at bus 7 where the voltage is $0.8653\underline{/-6.9}^{\circ}$.

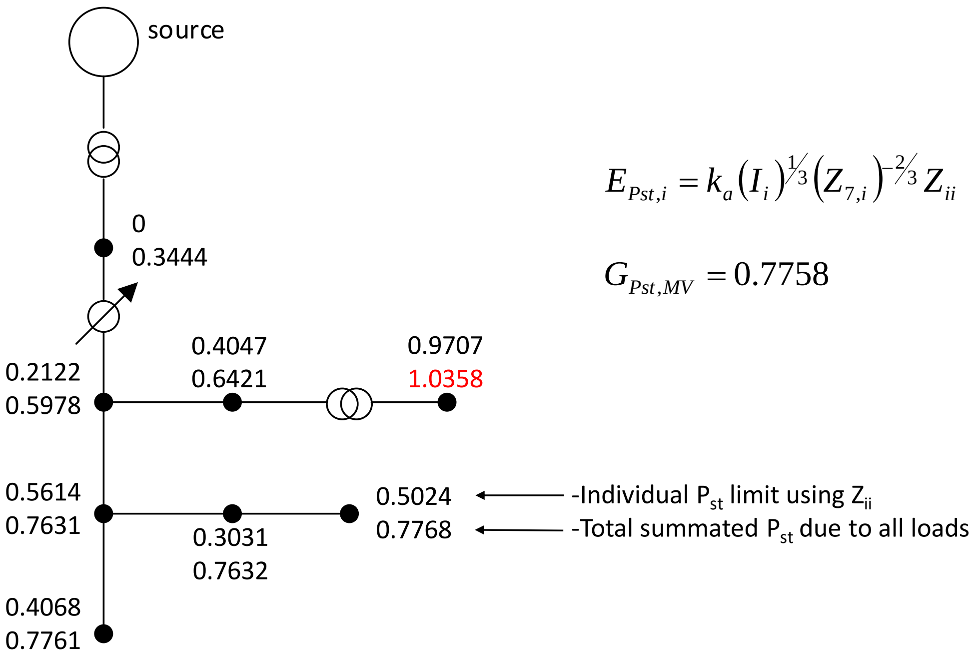
At bus 7, the total $P_{st,7}$ should not exceed the global allowable disturbance level which was determined to be $G_{Pst,MV} = 0.775$ using (2) and the recommended parameters from [1]. The results for the calculations without diversity are not shown here due to the fact that the results are very conservative and are not realistic for voltage fluctuation phenomenon. In reality, diversity should be accounted for in voltage fluctuations and the results for stage 2 and stage 3 procedures are shown in Figs. 16 and 17, respectively. Note that stage 2 makes use of (34), whereas stage 3 uses (35).



$$E_{Pst,i} = k_a \left(I_i\right)^{1/3} \left(Z_{7,i}\right)^{-2/3} Z_{7,i}$$

$$G_{Pst,MV} = 0.7758$$

Fig. 16: Flicker Allocation Results with Diversity using Transfer Impedances



$$E_{Pst,i} = k_a \left(I_i\right)^{1/3} \left(Z_{7,i}\right)^{-2/3} Z_{ii}$$

$$G_{Pst,MV} = 0.7758$$

Fig. 17: Flicker Allocation Results with Diversity using Thevenin Impedances

This example illustrates the salient points discussed in the previous section where the use of the transfer impedances in the limit allocation process may restrict users. It can be verified that with these reductions the summated flicker levels at the worst-case location does not exactly equal the global allowable disturbance level. Every location in the system is guaranteed to be below the global allowable flicker level because the fluctuating currents affecting the worst-case location (shown in Fig. 16) are reduced. In addition, this example illustrates the consequences of using (33) in Stage 3 situations where, without careful consideration, the summated flicker level at bus 4 exceeds the global allowable level (shown in Fig 17). Moreover, note that the excessive level at bus 4 exists despite the fact that the global allowable level is exactly reached at bus 7 (worst-case droop location).

Also, note that the results for the worst-case droop are within the band of control of the 10% regulator plus an allowance of 5% total voltage drop (including the control action). As a conservative approximation, it is possible to estimate the worst-case droop as simply the sum of all voltage control devices (maximum boost) plus the additional 5% allowance; systems with two 10% regulators could conservatively be assumed to have a worst-case droop of 25%. This type of assumption avoids the need for load flow calculations while retaining conservatism.

Limits determined using the proposed method taking into account the effect that users have on the worst-case location were shown in Figs. 16 and 17. The exact same procedure can be applied to develop limits taking into account the effect that users have on any other location, including the MV substation bus. Recall that the IEC procedures effectively develop limits based on the effect at the substation bus of all users as if they were connected to the substation bus. The proposed method can be expected to produce the same limits as the IEC procedure when they are derived taking into account the effect that all users have on the substation bus.

Results obtained using the IEC procedure described in [1] and (1) and the results of the proposed allocation method are shown in Table 10. In Table 10, E_{IEC} is calculated using S_t as the total downstream load (4090 kVA) which is less conservative than using the HV-MV transformer rating (5000kVA). $E_{D@MV}$ represents the limits derived with the proposed allocation method based on the effect that users have on the substation bus. $E_{D@WC}$ represents the limits derived with the proposed allocation method based on the effect that users have on the worst-case location (maximum droop).

Table 10: Flicker Emission Limits Comparison

E_{IEC}	$E_{D@MV}$	$E_{D@WC}$
0	0	0
0.2363	0.2339	0.2122
0.3835	0.3804	0.3450
0.3835	0.3837	0.3481
0.5485	0.5496	0.5614
0.2961	0.2967	0.3031
0.4788	0.4804	0.5024
0.3453	0.3462	0.3537

In Table 10 it is shown that the proposed method can be adapted to different philosophies for deriving limits. As expected, the flicker limits derived with the proposed allocation method, $E_{D@MV}$, are extremely close to the ones derived with the IEC allocation method, E_{IEC}. The results clearly indicate the validity of the proposed approach because when applying IEC assumptions the results are the same for both procedures.

When comparing E_{IEC} with $E_{D@WC}$ it is informative to note that the locations that are close to the worst-case location are given a greater limit allocation with the droop method. The principle applied is that users which do not have significant effects on the worst-case location (small transfer impedances) do not need a larger fluctuation limit. On the other hand, users that have larger fluctuating effects on the worst-case location (greater transfer impedances) need a greater fluctuating limit. Clearly the results of the proposed method align with those of [1] for the system evaluated. However, the determination of S_t and provision for future load growth is totally avoided because it is automatically accounted for in the droop value based on information and calculations that are a normal part of distribution system planning studies.

To further demonstrate the proposed limit allocation process, a real rural MV network in France was analyzed where the network diagrams are shown in Figs. 18-20.

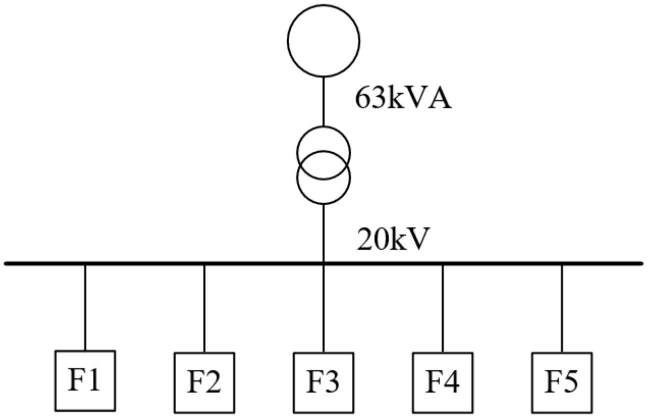


Fig. 18: Simplified Rural MV Network

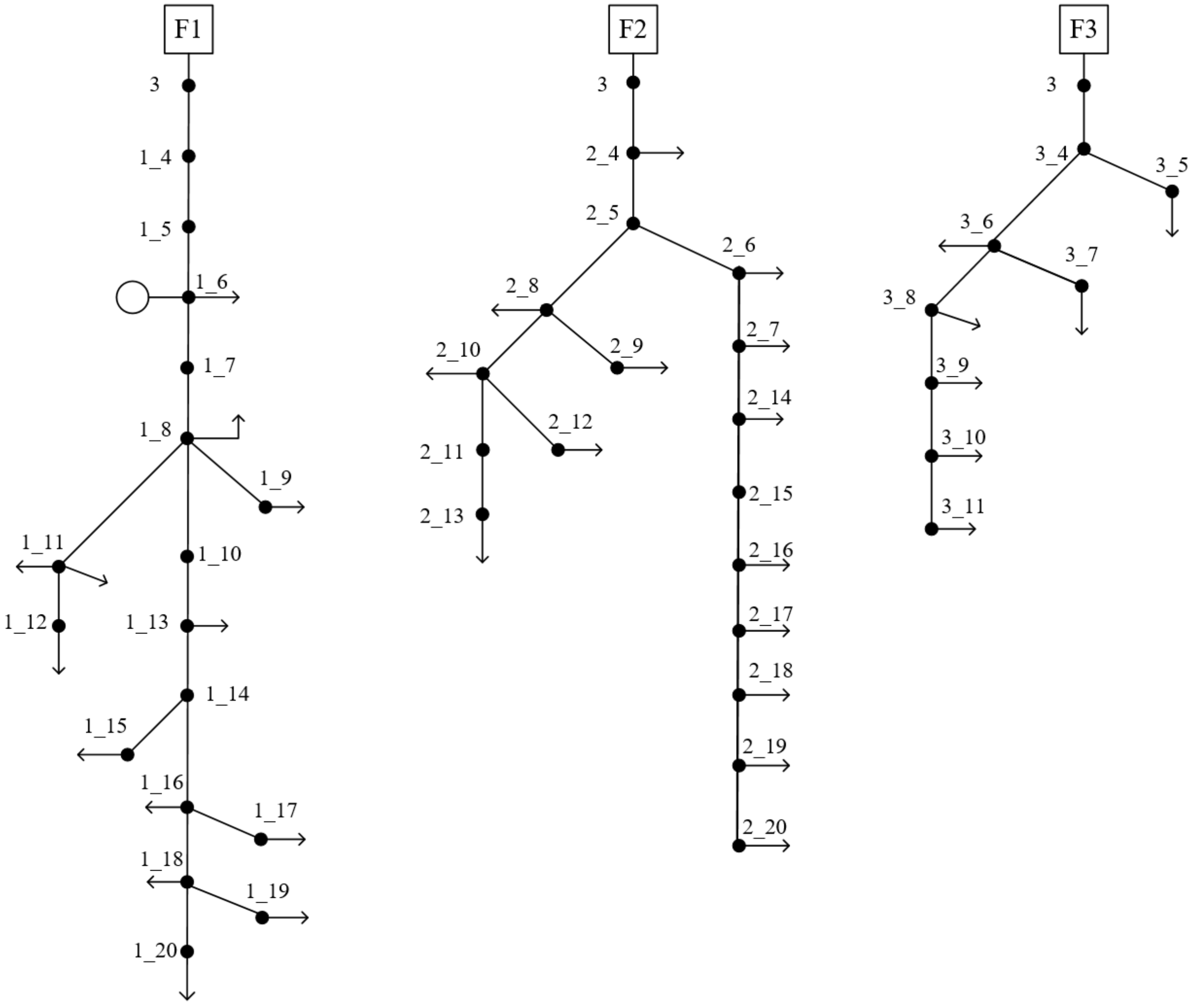


Fig.19: Feeders 1-3 Diagram

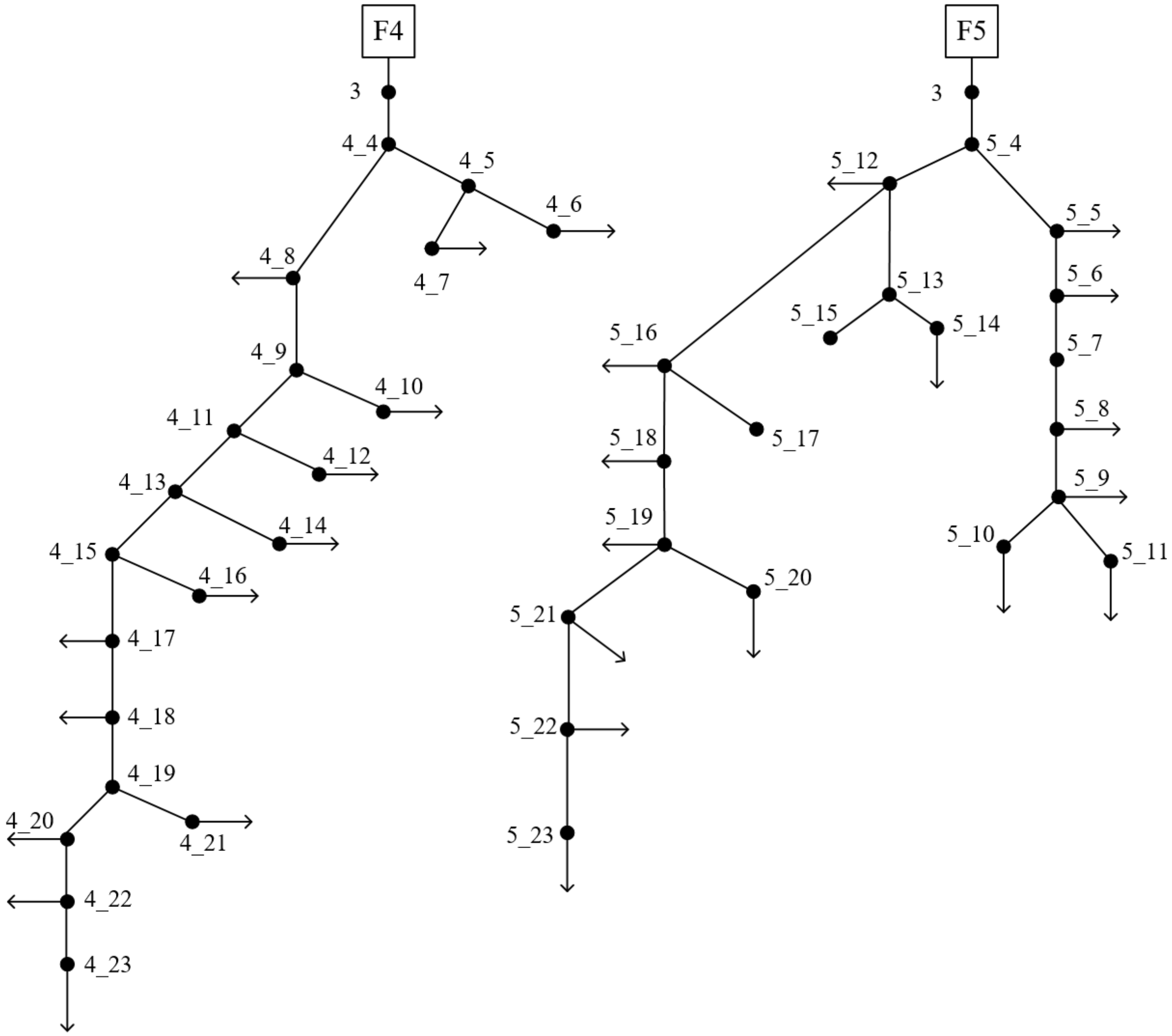


Fig.20: Feeders 4-5 Diagram

The network consists of five feeders supplied by a 63-20kV transformer where all the network data used is shown in Appendix A. The worst case voltage was again determined with a load flow analysis using the simulation software PSS/E. There were no regulators in this case but there was a source in Feeder 1. Recall that voltage fluctuation phenomena follow different rules when taking into account the total effect of voltage fluctuations. All source and load contributions to voltage fluctuations add up while on the other hand source and load contributions to voltage drop can cancel out. Sources, therefore, can contribute to a greater voltage fluctuation while they reduce voltage drop. For this reason, the source was considered as a load in the load flow case in order to determine the worst-case voltage fluctuation location.

From the converged solution, the largest voltage droop is at bus 19 in Feeder 1 where the voltage is $0.8651\underline{/-9.5}^{\circ}$. Again, at bus 19, the total $G_{Pst,19}$ should not exceed the global allowable disturbance level $G_{Pst,MV.}$. The results are shown in Tables A5-A7 in Appendix A. In Table A5 the limits derived with the IEC procedure and the proposed procedure adopting IEC criteria (global allowable level G_{Pst} enforced at MV bus) are displayed. The comparison of IEC limits with the limits derived with the proposed procedure for stage 2 and stage 3 applications are shown in Table A6. Lastly, the total flicker levels at each location are shown in Table A7 for the IEC and droop (based on a maximum droop location at bus 19) procedures.

From the results shown in Table A5, it can be concluded that the proposed allocation approach is accurate because when utilizing IEC criteria the same results as with the IEC procedures are obtained. The results shown in Table A6 illustrate the concept that deriving limits with the Thevenin impedance allocates greater individual limits because the Thevenin impedances are greater than the transfer impedances to the worst-case location. The consequences of these greater individual limits are illustrated in Table A7 where the total summated flicker at many locations is greater than the global allowable level (shown in red). Also, it can be noted that when applying stage 2 criteria with the new approach the results obtained align with those of IEC procedure as shown in Table A6. In some instances, there are noticeable differences where the limits derived for locations close to the worst-case location are greater with the new method than with IEC procedures. The reason that the results of both procedures are very similar is because there is only a small voltage difference between the various locations in the network. This means that most of the users see a very similar system impedance and the fact that all users see the same impedance is what IEC procedures inherently apply. It is important to note that the similarities in the results shown may very well not occur when there is a greater (steady-state) voltage variation between locations.

From these two examples it can be seen that with the proposed procedure there is a greater resource utilization. With the proposed procedure the global flicker level at the worst-case location is greater in both networks. In the IEEE 13 node test feeder, the total flicker levels at the worst-case droop location (bus 7) are 0.7234 and 0.7354 for the traditional IEC and the proposed allocation methods, respectively. This translates into a percent difference of 1.66% which is not significant. In the EDF network, the total flicker levels at the worst-case droop location (bus 19) are 0.5530 and 0.616 for the two methods, resulting in a percentage difference of 11.39%. Such a large percentage difference could lead to alternative investment decisions in system infrastructure.

CHAPTER 7: MAGNITUDE VS VECTOR CALCULATIONS DISCUSSION

A description of realistic networks and a discussion on using complex or magnitude quantities for calculations is provided in this chapter, the latter of which can significantly simplify calculations. Based on (17), voltage droop has both resistive and reactive components. Voltage droop in phasor terms for the five-node network example shown in Fig.13 is illustrated in Fig. 21. In Fig. 21, the source voltage is taken as the reference and the individual voltage drop contributions are subtractive. The vector difference between the source voltage and the bus *j* voltage is the (voltage) droop vector. The magnitude of the droop vector is shown in (39) which is derived from (17) as shown in (37) and (38).

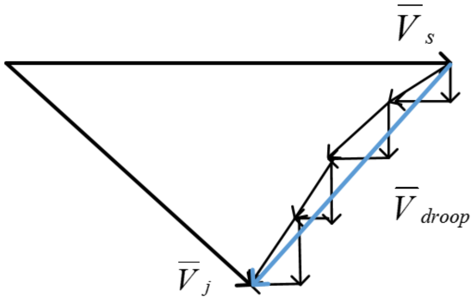


Fig.21: Phasor Representation of Voltage Droop

$$\left|\overline{V}_1-\overline{V}_j\right|=\left|\sum_{i=2}^{n}\left\{R_{ji}I_{iR}+R_{ji}(jI_{iX})+\left(jX_{ji}\right)I_{iR}+\left(jX_{ji}\right)(jI_{iX})\right\}\right| \tag{37}$$

$$\left|\overline{V}_1-\overline{V}_j\right|=\left|\sum_{i=2}^{n}\left\{\left(R_{ji}I_{iR}-X_{ji}I_{iX}\right)+j\left(R_{ji}I_{iX}+X_{ji}I_{iR}\right)\right\}\right| \tag{38}$$

$$V_{droop}=\sqrt{(\sum V_{iR})^2+(\sum V_{iX})^2} \tag{39}$$

In Fig. 21, it is important to realize that the summation of the magnitudes of the individual voltage drop terms is not generally equal to the magnitude of the droop vector. However, if the angles of the individual voltage drop terms are reasonably close to the angle of the droop vector, they would be approximately equal. To visualize the difference between magnitude and complex calculations consider Fig. 22(a). In Figure 22(a), $\overline{V}_{droop,j}$ (droop vector) is shown as the vector difference between the source voltage and the lowest voltage in the network. The magnitude difference is also illustrated in Fig. 22(a) where $\widehat{V}_{droop,j}$ is taken as the magnitude difference of the source voltage and the worst case location.

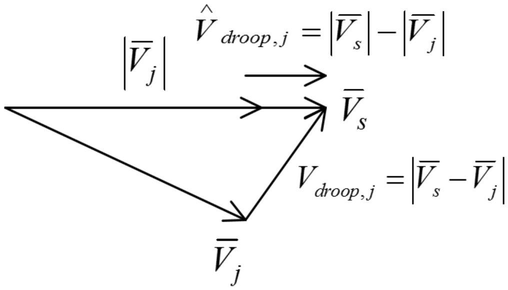


Fig. 22 (a): Droop Vector vs. Difference of Magnitudes

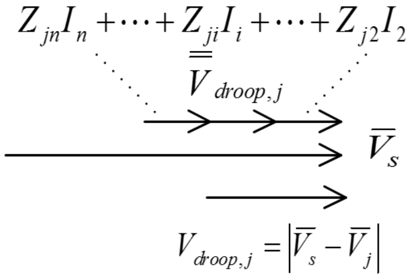


Fig. 22 (b): Droop Vector vs. Sums of Magnitudes

Note that $\widehat{V}_{droop,j}$ in Fig. 22(a) will be always smaller than the actual voltage droop vector magnitude, $V_{droop,j}$. In Figure 22(b), if only the magnitudes of the individual voltage drop terms $Z_{ji}I_i$ are used, they will be in phase with the source voltage V_s and can be linearly summated. When using current and impedance magnitudes in the summation, the individual contributions are typically greater than when using complex calculations. Because the derivation of individual limits does not involve any complex summation, the limits can be derived using only magnitude quantities. When summating individual flicker contributions, for the global flicker at the worst bus j, $G_{Pst,j}$, to be equal to the global allowable level, $G_{Pst,MV}$, the equality shown in (40) should be true. If only individual magnitudes are used as shown in (41), it will be approximate. Depending on the information available, the knowledge of the network, and assumptions that can be made, the use of only magnitudes may be implemented.

$$V_{droop,j} = \left| \sum_{i=2}^{n} \overline{Z}_{ji} \overline{I}_{i} \right| \tag{40}$$

$$V_{droop,j} = \sum_{i=2}^{n} Z_{ji} I_{i} \tag{41}$$

Having knowledge of the network is important so that the simplest method can be implemented. The previous discussion related to Figs. 21 and 22 suggests that a potentially wide variation in the phase angles of individual voltage drop vectors could exist, but practical considerations related to flicker-producing loads can be introduced to improve the approximate equality. Usually loads causing flicker are (1) large and located relatively close to the substation, (2) have a poor power factor (approximately 80% corresponding to a current angle $\theta_i = -37°$), and (3) are supplied by an effective impedance with an X/R of 2 to 4 (corresponding to impedance angles ranging from 63° to 75°). Considering these realistic assumptions, the load-produced individual voltage drop contribution phase angle can range as shown in (42).

$$\overline{\mathrm{V}}_{\mathrm{z}}=\mathrm{ZI}\angle(\theta_{\mathrm{z}}+\theta_{\mathrm{i}}) \xrightarrow{\text{yields}} 26° \leq \theta_{\mathrm{Vz}} \leq 38° \tag{42}$$

Furthermore, considering that the system is normally controlled to have no more than 5% voltage drop at the location of the worst-case customer, voltage regulators may be required. With one or two 10% boost regulators in place and assuming a maximum voltage phase angle of -5° to -10°, the phasor voltage droop angle can credibly range from 33° to 37° as derived in (43).

$$\begin{gathered}\overline{V}_{droop}=1\angle 0° - 0.8\angle -10° = 0.2536\angle 33° \\ \overline{V}_{droop}=1\angle 0° - 0.9\angle -5° = 0.2536\angle 37°\end{gathered} \tag{43}$$

Taking into account these reasonable assumptions, the angle on voltage drops (26°-38°) is close to the angle on the voltage droop phasor (33°-37°) for many realistic conditions and magnitude-only calculations can probably be used. If the angles are not close, a correction factor k_f is needed to account for the effects of ignoring phase angles and using only magnitudes. The theoretical correction factors that could be applied, depending on the information available, are as shown in (44) and (45).

$$k_f = \frac{\left|\overline{V}_s\right| - \left|\overline{V}_j\right|}{\left|\overline{V}_s - \overline{V}_j\right|} \tag{44}$$

$$k_f = \frac{\sum_{i=2}^{n} I_i Z_{ji}}{\left| \sum_{i=2}^{n} \bar{I}_i \bar{Z}_{ji} \right|} \tag{45}$$

The ratio of the magnitude of the complex quantity to the magnitude-only quantity is the correction factor. When the correction factor is applied, it is as if the calculations were made taking into account angles. Note that if the angles are known, then it is recommended to use directly the complex quantities and not include any correction factor. In practice, when the angles are not known, then these correction factors cannot be applied. From experience, its seems that the best correction factor that can be applied is as shown in (46) where the summation law has been applied.

$$k_f^{\,1/3} = \frac{G_{Pst,MV}}{\sqrt[3]{\sum_{i=2}^{n} \left(k_a I_i^{1/3} Z_{ji}^{1/3} \right)^3}} \tag{46}$$

Recall that if the worst-case location is at j and if calculations were made using all complex quantities (without reducing fluctuating load currents), then the total flicker level at j would be equal to $G_{Pst,MV}$. Therefore, if magnitude-only calculations are used, and the correction factor in (46) is used, the result would be $G_{Pst,MV}$. From experience, the conclusion is that calculations using only magnitude quantities may be used with a single correction factor applied to all calculation results. However, attention is required to make sure that all users are treated equally.

To illustrate the use of the correction factor, limits were derived again for the modified IEEE 13 node test feeder using only magnitude quantities. The results are shown in Table 11 and compared against the results using only complex quantities where, as before, bus 7 is the worst-case droop location and all limits are derived based on user effects at this location. For this specific network, it can be shown that calculations can be done only with magnitudes and with the correction factor as shown in (46) applied to each individual user. With the use of a single correction factor, results are extremely close to the flicker limits and global levels derived with complex calculations as shown in Tables 11-12.

Table 11: Flicker Limits Magnitude vs. Complex Calculations

$E_{Pst,i}$ (mag)	$E_{Pst,i}$ (kf)	$E_{D@WC}$
0	0	0
0.2317	0.2119	0.2122
0.3768	0.3446	0.3450
0.3801	0.3477	0.3481
0.6131	0.5607	0.5614
0.3310	0.3027	0.3031
0.5486	0.5018	0.5024
0.3862	0.3532	0.3537

Table 12: Global Flicker Levels Magnitude vs. Complex Calculations

$G_{Pst,I}$ (kf)	$G_{Pst,i}$
0.3075	0.3079
0.5337	0.5344
0.5526	0.5533
0.5922	0.5929
0.7192	0.7201
0.7193	0.7202
0.7344	0.7354
0.7288	0.7297

CHAPTER 8: CONCLUSIONS AND FUTURE WORK

The fundamental principle of 3-7 is to limit total flicker levels throughout a network based on each user's agreed power S_i. This procedure is intended to provide equality with regard to the user's share of the total supply capacity which can lead to very small limits, particularly for smaller installations. The inherent principle of the IEC procedure is that all users are connected directly at the MV substation bus. This implies that the IEC procedure develops voltage fluctuation limits based on the effect that each user has on the MV substation bus. No consideration is given for the fact that users will impact the network differently depending on their location. Furthermore, the guidelines in [1] are complex and are based on simplifying assumptions. The overall difficulties of this approach are that the total supply capability is virtually impossible to assess without making simplifying (and perhaps unjustifiable) assumptions and that there is no direct provision for future loads.

A new method for flicker limit allocation has been proposed in this thesis using the concept of voltage droop which does not suffer from the same limitations as the approach in [1] while providing a limit allocation process which results in greater overall system utilization. It has been mathematically proven to work and to be simple to apply with data that is readily available to system operators. The proposed approach does not rely on the determination of the total supply capacity and the provision for future loads is automatically included as a part of the distribution planning process.

For future work, the effects of regulators down the line need to be studied. Because of the use of tap transformers, the impedance matrix loses its symmetry. It appears that some locations are going to be affected differently when the regulators are operating, and these effects are of interest. Another area that needs more study is what to do when sources are present, particularly what to assume and how to treat them in order to derive limits. There is a general belief that because sources are being paid to be connected and to produce energy, they should be subject to very stringent limits. The effects of reducing limits for sources and allocating the rest of the absorption capacity to the loads in the network needs to be studied. Furthermore, other types of realistic networks need to be studied to determine if the proposed approach works for a wider range of realistic networks.

REFERENCES

[1] ANSI C84.1, American National Standard for Electric Power Systems and Equipment, 2011.

[2] IEEE Std. 1100, IEEE Recommended Practice for Powering and Grounding Electronic Equipment, 1999.

[3] IEC 61000-4-30, Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods, year?

[4] ELEC 6970, Special Topics in Electrical Engineering: Power Quality, Mark Halpin, Auburn University, 2015

[5] Arnold Wilkins, Jennifer Veitch, Brad Leham, LED Lighting Flicker and Potential Health Concerns: IEEE Standard PAR1789 Update, Sept, 2010.

[6] IEC 61000-3-7, Electromagnetic compatibility (EMC) – Part 3-7: Assessment of the emission limits for the connection of fluctuating load installations to MV, HV, and EHV power systems.

[7] IEC 61000-2-5, Electromagnetic Compatibility (EMC) – Part 2-5: Environment – Classification of electromagnetic environments, 2005.

[8] IEEE Std 1159, IEEE Recommended Practice for Monitoring Electric Power Quality, 2009.

[9] IEC 61000-2-2, Electromagnetic Compatibility (EMC) – Part 2-2: Environment – Compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems.

[10] IEC 61000-4-15, Electromagnetic Compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications.

[11] IEC 61000-3-3, Electromagnetic Compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment rated current ≤ 16A per phase and not subjected to conditional connection, Basic EMC Publications, 2013, Ed. 3.0.

[12] IEC 61000-3-11, Electromagnetic Compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤ 75A and subject to conditional connection

[13] R.A. Barr and V.J Gosbell, "Introducing Power System Voltage Droop as a New Concept for Harmonic Current Allocation", IEEE, International Conference on Harmonics and Quality Power, Sept, 2010, Bergamo, Italy.

[14] V.J Gosbell and R.A Barr, "Harmonic Allocation Following IEC Guidelines Using the Voltage Droop Concept, IEEE, Harmonics and Quality of Power (ICHQP), Sept, 2010, Bergamo, Italy.

[15] Charles A. Gross, Power System Analysis (2ed), John Wile & Sons, 1986.

[16] IEEE 13 Node Test Feeder, http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html, 2016.

APPENDIX A: NETWORK DATA AND RESULTS FOR THE MV RURAL NETWORK EXAMPLE

Table A1: Line Data

From	To	R(ohms)	X(ohms)	From	To	R(ohms)	X(ohms)
3	1_4	0.5352	0.84	3_4	3_5	0.3429	0.1575
1_4	1_5	0.36354	0.2905	3	4_4	0.45269	0.7105
1_5	1_6	1.0512	0.84	4_4	4_8	0.26314	0.413
1_6	1_7	0.15	0.08625	4_8	4_9	1.11504	0.644
1_7	1_8	0.18834	0.1505	4_9	4_11	1.19382	0.6895
1_8	1_9	0.85618	0.3115	4_11	4_13	0.21816	0.126
1_8	1_11	0.254	0.14605	4_13	4_15	0.71508	0.413
1_11	1_12	0.508	0.2921	4_15	4_17	0.72114	0.4165
1_8	1_10	0.26058	0.1505	4_17	4_18	1.27181	0.3115
1_10	1_13	0.192	0.1104	4_18	4_19	0.4545	0.2625
1_13	1_14	0.61812	0.357	4_19	4_20	0.60882	0.4865
1_14	1_16	0.41208	0.238	4_20	4_22	0.7446	0.595
1_14	1_15	0.46	0.2645	4_22	4_23	1.50894	0.8715
1_16	1_17	1.31794	0.4795	4_19	4_21	0.8979	0.7175
1_16	1_18	0.91506	0.5285	4_15	4_16	1.08706	0.3955
1_18	1_19	1.20036	0.294	4_13	4_14	0.78884	0.287
1_18	1_20	0.544	0.3128	4_11	4_12	0.56758	0.2065
3	2_4	0.26091	0.4095	4_9	4_10	0.3636	0.21
2_4	2_5	0.8103	0.6475	4_4	4_5	0.909	0.525
2_5	2_8	1.85712	1.484	4_5	4_7	0.38212	0.1435
2_8	2_10	0.446	0.25645	4_5	4_6	0.962	0.35
2_10	2_11	0.144	0.0828	3	5_4	0.61102	0.959
2_11	2_13	1.58772	0.917	5_4	5_12	0.5352	0.84
2_10	2_12	0.8177	0.2975	5_12	5_16	1.01202	0.5845
2_8	2_9	0.98136	0.987	5_16	5_18	1.15746	0.6685
2_5	2_6	0.092	0.0529	5_18	5_19	2.19336	0.798
2_6	2_7	1.062	0.61065	5_19	5_21	0.456	0.2622
2_7	2_14	0.196	0.1127	5_21	5_22	1.59692	0.581
2_14	2_15	0.162	0.09315	5_22	5_23	1.3468	0.49
2_15	2_16	0.09696	0.056	5_19	5_20	0.85618	0.3115
2_16	2_17	0.14	0.0805	5_16	5_17	1.1063	0.4025
2_17	2_18	0.30906	0.1785	5_12	5_13	0.61568	0.224
2_18	2_19	1.2506	0.455	5_13	5_15	1.27946	0.4655
2_19	2_20	0.114	0.06555	5_13	5_14	1.91438	0.6965
3	3_4	0.76489	1.2005	5_4	5_5	0.49692	0.287
3_4	3_6	0.52182	0.819	5_5	5_6	1.17364	0.427
3_6	3_8	0.238	0.13685	5_6	5_7	0.32708	0.119
3_8	3_9	0.218	0.12535	5_7	5_8	0.244	0.1403
3_9	3_10	0.382	0.21965	5_8	5_9	0.226	0.12995
3_10	3_11	0.068	0.0391	5_9	5_11	0.132	0.0759
3_6	3_7	0.73112	0.266	5_9	5_10	0.7696	0.28

Table A2: Load Data

Bus	P(kW)	Q(kvar)	Bus	P(kW)	Q(kvar)
1_4	50	20	3_11	330	120
1_5	170	70	3_7	230	100
1_6	370	150	3_5	290	120
1_6	-550	0	4_8	130	50
1_8	360	140	4_10	40	20
1_11	570	220	4_12	170	70
1_11	270	90	4_14	160	60
1_12	420	90	4_16	110	40
1_9	130	40	4_17	70	30
1_13	890	260	4_18	150	50
1_15	390	60	4_20	160	50
1_16	110	40	4_22	60	30
1_17	500	170	4_23	140	30
1_18	100	40	4_21	90	40
1_19	320	110	4_7	160	70
1_20	240	30	4_6	120	50
2_4	130	50	5_12	100	40
2_8	400	130	5_16	230	90
2_10	510	120	5_18	110	20
2_13	310	100	5_19	110	50
2_12	580	220	5_21	230	50
2_9	160	50	5_22	120	50
2_6	480	150	5_23	90	10
2_7	220	90	5_20	90	30
2_14	360	140	5_17	150	60
2_16	550	220	5_15	110	40
2_18	340	150	5_14	50	20
2_19	300	120	5_5	330	130
2_20	700	210	5_6	330	130
3_6	100	40	5_8	520	210
3_8	360	100	5_9	290	120
3_9	320	100	5_10	260	90
3_10	330	70	5_11	240	80

Table A3: Source Data

	From	To	Ssc(MVA)	V_{LL}(kVA)	X/R	R(Ω)	X(Ω)
Source	1	2	680	63	5	1.1447	5.7234

Table A4: Transformer Data

	From	To	Rating (3ΦMVA)	HV Rating (kV)	LV Rating (kV)	Z(pu)	X/R	R(Ω)	X(Ω)
Transformer	3	4	20	63	20	0.12	8	0.2977	2.3815

Table A5: IEC Limits Results

Bus Name	IEC	Droop$_{@MV}$	Bus Name	IEC	Droop$_{@MV}$
SOURCE	0	0	3_9	0.205	0.203
XFMR HV	0	0	3_10	0.205	0.204
XFMR LV	0	0	3_11	0.208	0.206
1_4	0.111	0.110	4_4	0	0
1_5	0.168	0.167	4_5	0	0
1_6	0.217	0.221	4_6	0.149	0.148
1_6	0.234	0.239	4_7	0.165	0.163
1_7	0	0	4_8	0.153	0.151
1_8	0.215	0.215	4_9	0	0
1_9	0.152	0.152	4_10	0.105	0.104
1_10	0	0	4_11	0	0
1_11	0.250	0.237	4_12	0.168	0.166
1_11	0.194	0.184	4_13	0	0
1_12	0.222	0.223	4_14	0.164	0.162
1_13	0.287	0.289	4_15	0	0
1_14	0	0	4_16	0.144	0.143
1_15	0.216	0.218	4_17	0.125	0.124
1_16	0.144	0.145	4_18	0.159	0.159
1_17	0.238	0.240	4_19	0	0
1_18	0.140	0.141	4_20	0.163	0.162
1_19	0.205	0.207	4_21	0.136	0.135
1_20	0.184	0.185	4_22	0.120	0.119
2_4	0.153	0.151	4_23	0.154	0.154
2_5	0	0	5_4	0	0
2_6	0.234	0.233	5_5	0.209	0.207
2_7	0.183	0.182	5_6	0.209	0.207
2_8	0.221	0.221	5_7	0.000	0.000
2_9	0.163	0.163	5_8	0.243	0.242
2_10	0.238	0.238	5_9	0.200	0.199
2_11	0	0	5_10	0.192	0.191
2_12	0.251	0.252	5_11	0.186	0.186
2_13	0.203	0.203	5_12	0.140	0.139
2_14	0.215	0.215	5_13	0	0
2_15	0	0	5_14	0.111	0.110
2_16	0.248	0.248	5_15	0.144	0.143
2_17	0	0	5_16	0.185	0.184
2_18	0.212	0.212	5_17	0.161	0.160
2_19	0.202	0.203	5_18	0.142	0.141
2_20	0.265	0.266	5_19	0.146	0.145
3_4	0	0	5_20	0.134	0.134
3_5	0.200	0.198	5_21	0.182	0.181
3_6	0.140	0.139	5_22	0.149	0.149
3_7	0.186	0.184	5_23	0.132	0.132
3_8	0.212	0.211			

Table A6: New Limits Allocation Results vs IEC Results

Bus Name	IEC	Droop Stage 2	Droop Stage 3	Bus Name	IEC	Droop Stage 2	Droop Stage 3
SOURCE	0	0	0	3_9	0.205	0.185	0.350
XFMR HV	0	0	0	3_10	0.205	0.185	0.373
XFMR LV	0	0	0	3_11	0.208	0.187	0.382
1_4	0.111	0.110	0.110	4_4	0.000	0.000	0.000
1_5	0.168	0.171	0.171	4_5	0.000	0.000	0.000
1_6	0.217	0.246	0.246	4_6	0.149	0.134	0.238
1_6	0.234	0.265	0.265	4_7	0.165	0.148	0.240
1_7	0.000	0.000	0.000	4_8	0.153	0.137	0.195
1_8	0.215	0.245	0.245	4_9	0.000	0.000	0.000
1_9	0.152	0.173	0.194	4_10	0.105	0.094	0.176
1_10	0.000	0.000	0.000	4_11	0.000	0.000	0.000
1_11	0.250	0.270	0.281	4_12	0.168	0.151	0.349
1_11	0.194	0.209	0.218	4_13	0.000	0.000	0.000
1_12	0.222	0.254	0.287	4_14	0.164	0.148	0.362
1_13	0.287	0.336	0.336	4_15	0.000	0.000	0.000
1_14	0.000	0.000	0.000	4_16	0.144	0.130	0.365
1_15	0.216	0.261	0.280	4_17	0.125	0.113	0.308
1_16	0.144	0.178	0.178	4_18	0.159	0.144	0.445
1_17	0.238	0.294	0.342	4_19	0.000	0.000	0.000
1_18	0.140	0.181	0.181	4_20	0.163	0.147	0.517
1_19	0.205	0.275	0.275	4_21	0.136	0.123	0.448
1_20	0.184	0.236	0.253	4_22	0.120	0.108	0.415
2_4	0.153	0.137	0.158	4_23	0.154	0.140	0.614
2_5	0.000	0.000	0.000	5_4	0.000	0.000	0.000
2_6	0.234	0.212	0.310	5_5	0.209	0.188	0.282
2_7	0.183	0.166	0.298	5_6	0.209	0.188	0.338
2_8	0.221	0.201	0.432	5_7	0.000	0.000	0.000
2_9	0.163	0.148	0.385	5_8	0.243	0.220	0.433
2_10	0.238	0.216	0.498	5_9	0.200	0.181	0.371
2_11	0.000	0.000	0.000	5_10	0.192	0.173	0.395
2_12	0.251	0.229	0.582	5_11	0.186	0.169	0.353
2_13	0.203	0.184	0.539	5_12	0.140	0.126	0.212
2_14	0.215	0.195	0.363	5_13	0.000	0.000	0.000
2_15	0.000	0.000	0.000	5_14	0.111	0.100	0.235
2_16	0.248	0.225	0.439	5_15	0.144	0.130	0.281
2_17	0.000	0.000	0.000	5_16	0.185	0.167	0.331
2_18	0.212	0.193	0.406	5_17	0.161	0.145	0.331
2_19	0.202	0.184	0.457	5_18	0.142	0.128	0.304
2_20	0.265	0.242	0.610	5_19	0.146	0.132	0.398
3_4	0.000	0.000	0.000	5_20	0.134	0.122	0.400
3_5	0.200	0.180	0.276	5_21	0.182	0.165	0.525
3_6	0.140	0.126	0.222	5_22	0.149	0.135	0.500
3_7	0.186	0.167	0.324	5_23	0.132	0.120	0.497
3_8	0.212	0.191	0.350				

Table A7: Total P_{st} at Every Bus with Different Approaches

Bus Name	Total P_{st} IEC	Total P_{st} Stage 2	Total P_{st} Stage 3	Bus Name	Total P_{st} IEC	Total P_{st} Stage 2	Total P_{st} Stage 3
SOURCE	0	0.000	0.000	3_9	0.4554	0.434	0.768
XFMR HV	0.0759	0.074	0.127	3_10	0.4597	0.437	0.777
XFMR LV	0.3853	0.378	0.643	3_11	0.4601	0.438	0.778
1_4	0.4256	0.436	0.668	4_4	0.3947	0.385	0.668
1_5	0.4447	0.463	0.681	4_5	0.3997	0.389	0.674
1_6	0.5077	0.548	0.728	4_6	0.4020	0.391	0.677
1_6	0.5077	0.548	0.728	4_7	0.4011	0.390	0.675
1_7	0.5140	0.556	0.733	4_8	0.3993	0.389	0.683
1_8	0.5239	0.569	0.741	4_9	0.4067	0.394	0.721
1_9	0.5251	0.571	0.743	4_10	0.4071	0.395	0.721
1_10	0.5296	0.578	0.747	4_11	0.4177	0.402	0.777
1_11	0.5283	0.574	0.745	4_12	0.4193	0.403	0.781
1_11	0.5283	0.574	0.745	4_13	0.4194	0.403	0.787
1_12	0.5310	0.578	0.748	4_14	0.4214	0.405	0.793
1_13	0.5341	0.584	0.751	4_15	0.4239	0.407	0.819
1_14	0.5415	0.596	0.759	4_16	0.4255	0.408	0.825
1_15	0.5436	0.599	0.762	4_17	0.4282	0.410	0.850
1_16	0.5455	0.603	0.764	4_18	0.4337	0.413	0.895
1_17	0.5508	0.610	0.771	4_19	0.4357	0.415	0.912
1_18	0.5503	0.611	0.770	4_20	0.4383	0.417	0.937
1_19	**0.5530**	**0.616**	**0.772**	4_21	0.4369	0.416	0.922
1_20	0.5515	0.613	0.771	4_22	0.4398	0.418	0.955
2_4	0.4045	0.393	0.683	4_23	0.4419	0.419	0.982
2_5	0.4439	0.425	0.772	5_4	0.4194	0.405	0.716
2_6	0.4471	0.427	0.777	5_5	0.4322	0.415	0.737
2_7	0.4774	0.451	0.844	5_6	0.4547	0.432	0.780
2_8	0.4837	0.457	0.901	5_7	0.4605	0.437	0.792
2_9	0.4863	0.459	0.911	5_8	0.4663	0.441	0.804
2_10	0.4911	0.463	0.926	5_9	0.4695	0.444	0.812
2_11	0.4915	0.463	0.928	5_10	0.4722	0.446	0.819
2_12	0.4965	0.467	0.944	5_11	0.4701	0.444	0.813
2_13	0.4968	0.467	0.954	5_12	0.4307	0.414	0.753
2_14	0.4832	0.456	0.858	5_13	0.4316	0.414	0.756
2_15	0.4871	0.459	0.868	5_14	0.4328	0.415	0.759
2_16	0.4895	0.461	0.874	5_15	0.4336	0.416	0.760
2_17	0.4916	0.463	0.880	5_16	0.4403	0.421	0.791
2_18	0.4966	0.467	0.895	5_17	0.4426	0.423	0.797
2_19	0.5096	0.477	0.940	5_18	0.4465	0.426	0.829
2_20	0.5108	0.478	0.944	5_19	0.4569	0.433	0.904
3_4	0.4200	0.405	0.701	5_20	0.4577	0.434	0.909
3_5	0.4221	0.407	0.703	5_21	0.4590	0.435	0.920
3_6	0.4466	0.427	0.751	5_22	0.4617	0.437	0.947
3_7	0.4490	0.429	0.755	5_23	0.4627	0.437	0.959
3_8	0.4518	0.431	0.761				