Power Quality Issues Considering the Presence of Distributed Generation

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Who am I?

- Received PhD degree from Auburn University in 1993
  - Permanently employed by Auburn University
  - >75% of work is for electric utility and heavy industry companies
- Heavily involved in IEEE, IEC, and CIGRE activities
  - Chair, IEEE Std 519 (Harmonics)
  - Member, IEC TC77/SC77A WG1 (Harmonics) and WG8 (EMC)
  - Member, CIGRE/CIRED JWG C4.103 (EMC), 108 (Flicker Objectives), and 109 (PQ Assessment)

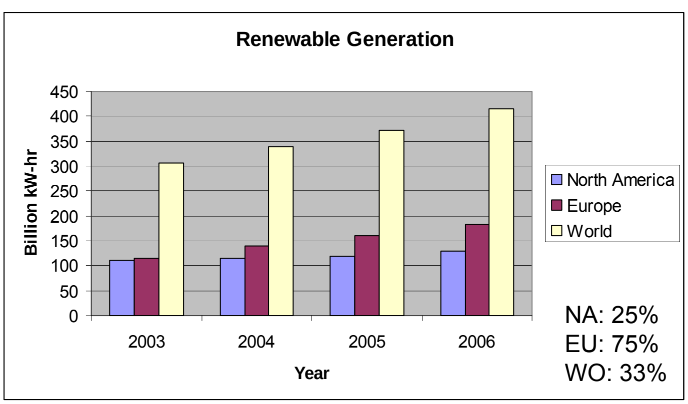
Presentation Outline

- Alternative energy background
  - US situation
  - Examples and economics
  - World trends
- Electromagnetic compatibility
  - Perspectives
  - Standards
  - Applications

"DG" is often used interchangeably with "AE." The correctness partially depends on the size involved. This presentation is about issues covering most of the spectrum and the terminology used is not overly critical

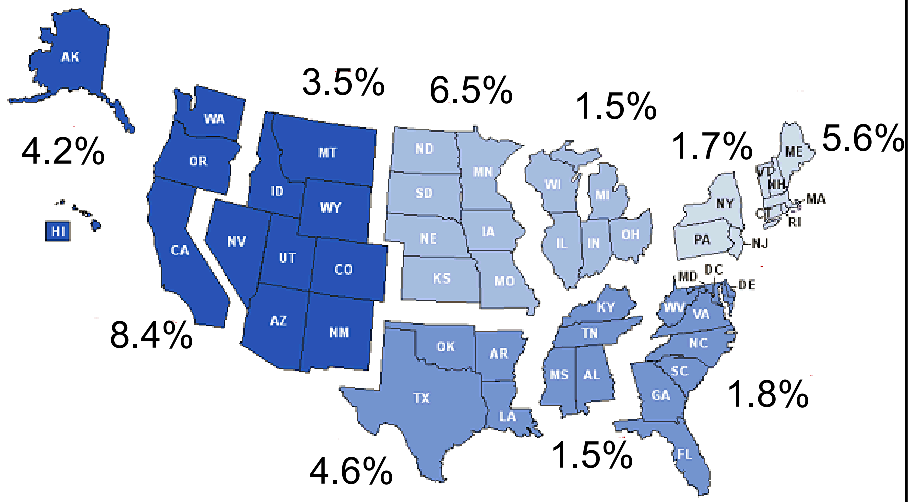
Global Renewable Energy Production

- Production is growing, but at various rates



Source: United States Department of Energy (June 2009)

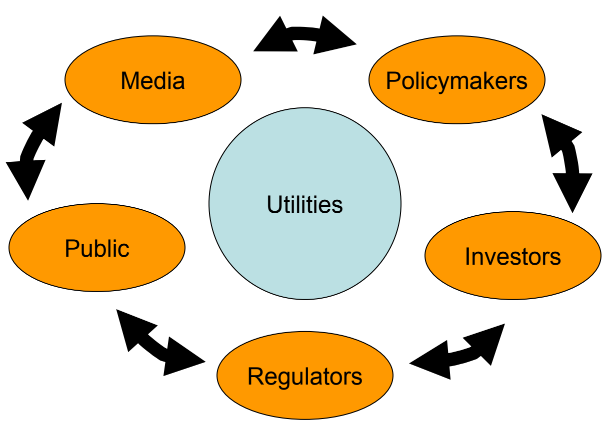
Energy from Renewable Generation (2009)



Source: US DOE

The State of AE Today

- In many ways, this can be described as a circus…



The Utility Perspective

- Utility participants are trying to make a profit while delivering a valuable product in a reliable manner
  - What to do and when to do it are economic variables for maximizing profit
  - Where and how to do it are technical variables for maximizing system performance
- Generation owners are usually in the first group
  - Politics and public perception give much support to this group
- System owner/operators are usually in the second group
  - These entities push desperately to have technical standardization to minimize problems

Power quality and EMC are some of the major areas of activity

Goals of EMC Standardization

- To maximize EMC on a system-wide basis by limiting disturbances
  - Produced by individual equipment
  - Produced by complete facilities
  - Propagated throughout a given voltage level
  - Transferred between voltage levels
- These goals must be pursued while recognizing
  - the economic and political aspects of limits on equipment and users
  - The physical realities of the total power supply system

The Impact of AE/DG

- AE/DG may directly contribute EMC problems through their disturbing (electrical) emissions
- The impacts of AE/DG on existing EMC practices depends on the type of AE/DG
  - Static interface equipment does not appreciably alter S_{SC} whereas rotary interface equipment often does
- The EMC challenge of AE/DG is therefore two-fold
  - Manage AE/DG emissions as “users”
  - Incorporate AE/DG presence in existing allocation practices

IEEE and IEC EMC Standards

- IEC 61000-3-x series
  - Product-family standards (e.g., 3-2, -3, -11, -12) for harmonics and flicker applicable at LV
  - System EMC management standards (e.g. 3-6, -7, -13) for harmonics, flicker, and unbalance applicable at MV, HV, and EHV
- IEEE 519
  - Harmonic control at LV, MV, HV, and EHV
- IEEE 1453
  - Flicker measurement with limited recommendations on planning levels, etc., at MV, HV, and EHV

Two Approaches to EMC

- DG can be managed two ways
  - As a "product" with specific type tests under specified conditions
  - As a "user" with emissions managed according to existing allocation practices
- What makes sense depends on several factors
  - Size of DG installation
  - Voltage of interconnection
  - Expected degree of resource penetration

IEEE 1547

"IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems"

- Evolving from early PV interconnections, 1547 deals with DG EMC issues along the lines of "product standards"
  - Up to 10 MVA size with no voltage specified
  - Voltage regulation ±5% (American National Standards Institute, ANSI C84.1, "Range A")
  - IEEE 519 for harmonics based on worst-case conditions (most restrictive short-circuit-to-load ratio)
  - P_{st}=1 Curve ("GE Curve") for flicker
    - IEEE 1453 incorporates IEC 61k-4-15 and is (slowly) replacing the simple curve
  - No definitive standard for unbalance
    - Typical utility guidelines are 5% unbalance (neg/pos)

IEC 61000-3-15 (2CD)

"Assessment of Low Frequency Electromagnetic Immunity and Emission Requirements for Dispersed Generation Systems in LV Networks"

- This CD (second) considers existing product family standards
  - Applicable to LV only with current < 16 A or <75 A (16-75 kVA)
    - IEC 61000-3-2 and -12 (harmonics)
    - IEC 61000-3-3 and -11 (flicker and rapid voltage changes)
    - Compatibility levels (61000-2-2) for unbalance
- Many details remain open regarding the use of existing product family standards for DG
- Recommendations are given regarding the need for review of system-level standards
- Significant local regulations in many countries
  - CD (second) provides country-by-country practices

IEEE 1547 (519) Approach

Maximum Harmonic Current Distortion in Percent of I_L

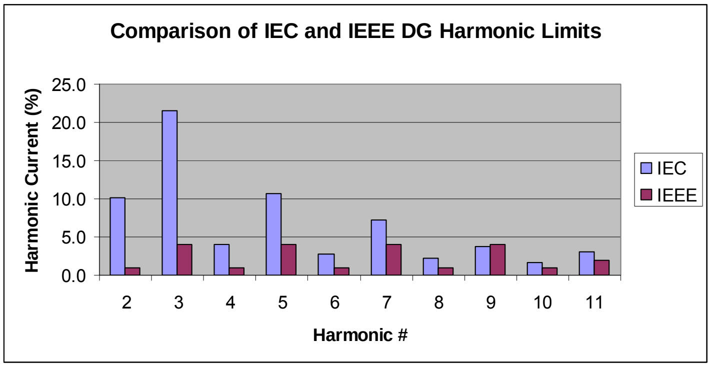
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤*h*< 17	17≤*h*< 23	23≤*h*< 35	35≤*h*	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Harmonic current limit table shown for 120V-69kV connections. More restrictive values exist for higher voltage levels.

I_L for an AE/DG unit could be taken as the equipment rated current

IEEE vs IEC Comparison

- Assuming LV connection, 16A operation



It is clear that significant differences exist; most pronounced at lower and higher orders

User Size vs. System Strength

- Users which are small relative to system strength are unlikely to create EMC problems
- The size of a particular user relative to the system strength is indicative of the financial (infrastructure) contributions made by the user to the system
  - 25% of bill is for energy
  - 75% of bill is for everything else
- The user should be able to access an amount of “emission absorption capability” in the system which is proportional to the amount paid

The presence of DG usually corrupts this long-standing concept

IEEE System Level EMC Coordination

- Harmonics—IEEE Standard 519
  - Voltage harmonics are fixed
    - 3% individual, 5% THD (MV)
  - Current limits (also fixed) are "derived" based on a shared-responsibility concept
    - Key assumption: many users operating at limiting current distortion values will not create excessive voltage distortion
- Flicker—IEEE Standard 1453
  - Compatibility and planning levels from IEC 61000 series
  - No clear allocation process
- Unbalance—No dedicated IEEE standard

IEEE Harmonic Voltage Limits

- Utility is responsible for voltage quality

Bus Voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
1.0 kV and below	5.0	8.0
1.001 kV through 69 kV	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

IEEE Harmonic Current Limits

- Users are responsible for harmonic currents

Maximum Harmonic Current Distortion in Percent of I_L						
	Individual Harmonic Order (odd harmonics)					
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<20	4.0	2.0	1.5	0.6	0.3	5.0
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100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Multiple tables exist—The one shown is for 120V-69kV PCCs

System-Level EMC Limits

- Harmonic emission limits can be derived following either the IEC or IEEE approach

$$E_{Uhi} = G_{hMV+LV}\left(\sqrt[\alpha]{\frac{S_i}{S_t}}\right) \quad \text{(IEC)}$$

$$I_{hi} = I_{Li}(\text{Fixed Value})_h \quad \text{(IEEE)}$$

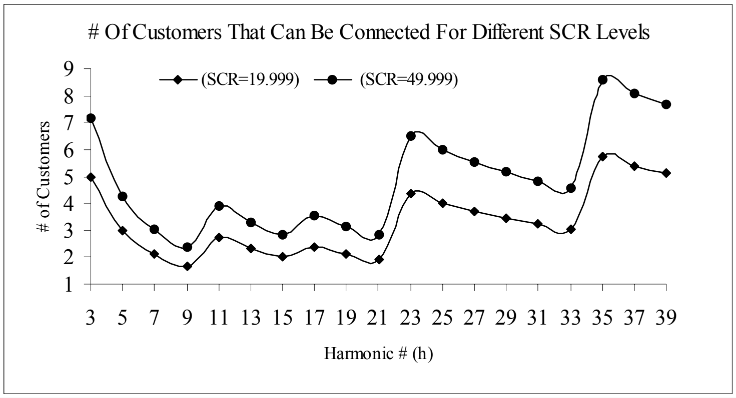
$$\Rightarrow (\text{Fixed Value})_h \text{ decreases as } S_{SCi} \text{ decreases}$$

- Flicker and unbalance have similar approaches in IEC (less in IEEE)

Note the dependence on short-circuit-to-load ratio in both approaches

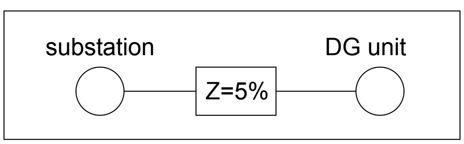
Harmonics Example

- How many DG units can be interconnected assuming each complies with IEEE 1547 (519) harmonic limits before voltage compatibility levels (taken from IEEE 519) are exceeded?



Voltage Fluctuations and Flicker

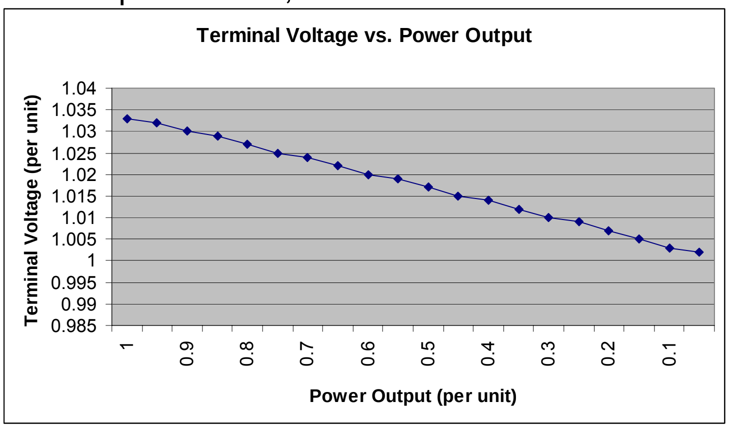
- Can DG create objectionable voltage fluctuations?
- Consider a simple example MV distribution feeder
  - Substation source with regulated 1 pu voltage
  - 5% feeder impedance, X/R=1
  - DG unit at remote end @ pf=1



Many issues are associated with the choices for these example numbers!

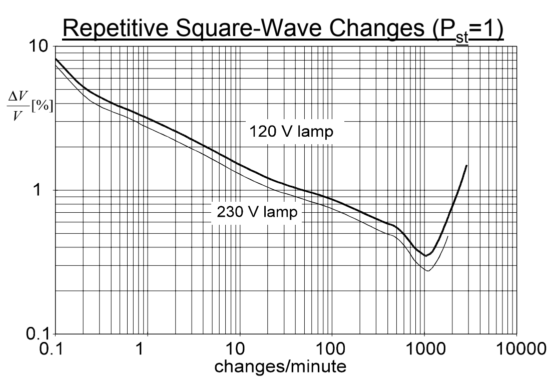
Voltage Variations

- Power output of DG can clearly fluctuate from maximum to (near) zero
  - Wind speed varies; Clouds move across



Flicker and Rapid Voltage Changes

- IEC 61000-3-3, -5, -7, -11, and 4-15 and IEEE 1453 address voltage flicker



RMS voltage changes

So-called RVCs are limited to 3-6% in standards and practice

Clearly the 3% voltage variation in the example can create an EMC issue—flicker!

IEC 61000-3-15 (2CD): Flicker

- The 2CD document recommends
  - P_{st}=1 for non-exporting DG units
  - P_{st}=0.5 for exporting DG units
- Suppose multiple exporting DG units are connected at LV
  - Flicker summation laws are used to combine the multiple contributions

Flicker Summation

- Flicker from multiple sources can be summated using a exponential summation law

$$P_{st} = \sqrt[m]{\sum P_{st,i}^{m}}$$

- The exponent “m” takes different values
  - m=1 when multiple sources significantly overlap
  - m=4 when multiple sources specifically operated to not overlap
  - m=3 recommended for general use
- Experience has shown the value of m also depends on percentiles chosen for daily/weekly statistical analysis

Summation and DG

- Practical considerations suggest that DG voltage fluctuations will occur closely together in time
  - Cloud cover or wind speed variation is likely to affect geographically close AE/DG units at the same time

$$1.0 = \sqrt[1]{\sum 0.5_i^1} \qquad i = 2$$

$$1.0 = \sqrt[3]{\sum 0.5_i^3} \qquad i = 8$$

Only 2 DG units allowable if practical considerations are included

8 DG units allowable if general summation law exponent is used

Unbalance

- Three major components of voltage unbalance EMC are considered
  - System unbalance
    - Largely due to untransposed lines
  - Load unbalance
    - Due to asymmetrical loading in three-phase systems
  - Load compensation
    - Induction machines appreciably compensate unbalance

AE/DG EMC: Unbalance

- Rotating machine interface
  - Compensating effects of asynchronous motors well known
  - Likely to be a net benefit for EMC (unbalance)
- Static (power electronic) interface
  - Compensation depends on control
    - Harmonic emissions are balance-dependent
    - Advanced control could balance phases
  - Could be good or bad for EMC (unbalance)

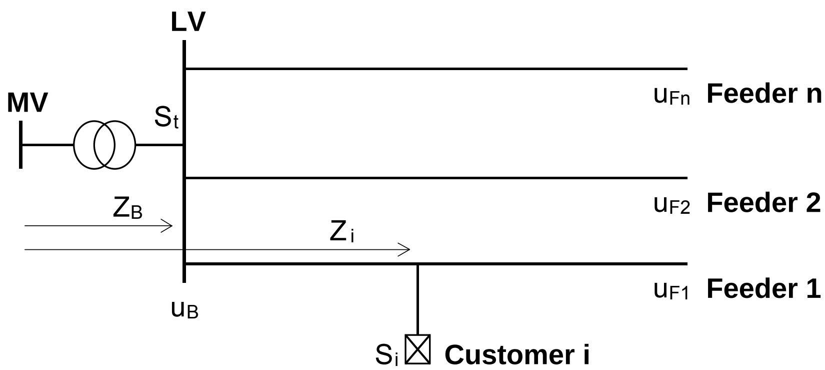
IEC 61000-3-14

(under development by IEC TC77-SC77A-WG8)

- Deals exclusively with LV systems
  - Similar philosophy to 61000-3-6, -7, and -13
    - Harmonics
    - Flicker
    - Unbalance
  - Applicable to LV installations above some minimum size, S_{min}
    - Small installations covered by product family standards
    - Purposefully excludes single-family residential dwellings
  - Procedures incorporate significant EMC variations through each LV system
- Emission limit derivations are based on current for harmonics and unbalance
  - Easy implementation
  - Flicker limit derivations remain in terms of voltage

IEC 61000-3-14

- LV systems can be simple or complex



Individual limits E_i remain a function of the total global disturbance level G_{LV} and the ratio of customer power S_i total power S_t

$$E_i \approx kG_{LV}\left(\sqrt[\alpha]{\frac{S_i}{S_t}}\right)$$

The concept is the same for harmonics, flicker, and unbalance

Comparing IEEE and IEC Approaches

- IEC methods allocate emission limits based on a ratio of consumer power to total (area) served power
- IEEE methods allocate emission limits based on a ratio of consumer power to short-circuit power
- The presence of AE/DG
  - May increase area served power
    - Smaller emissions in IEC methods
    - No direct effect in IEEE methods
  - May increase short-circuit power
    - Indirect (possibly) effects in IEC methods
    - Larger emissions in IEEE methods (harmonics specifically)

The presence of AE/DG may break the relationship between short-circuit and total (area) served power!

The Present and Future of AE/DG EMC

- Present penetration levels are seldom sufficient to create large-scale EMC problems
  - Who covers mitigation costs depends largely on the socio-political situation
- Large-scale penetration is likely to lead to EMC problems requiring system-level coordination of emission limits and mitigation
  - Product family standards can not cover full penetration levels and insure EMC
  - System-level standards were developed assuming polluting installations were "loads"

Conclusions

- DG will increase in terms of size and penetration
- Pressure will increase on system owner/operators
  - Existing EMC standards for interconnected DG are largely based on product-family standards
  - Future EMC coordination will require system-level standards
- The long-standing concept of deriving emission limits considering short-circuit-to-load ratio may have to be abandoned
  - What new approach will be both fair and (relatively) simple so that it can be adopted by all parties???