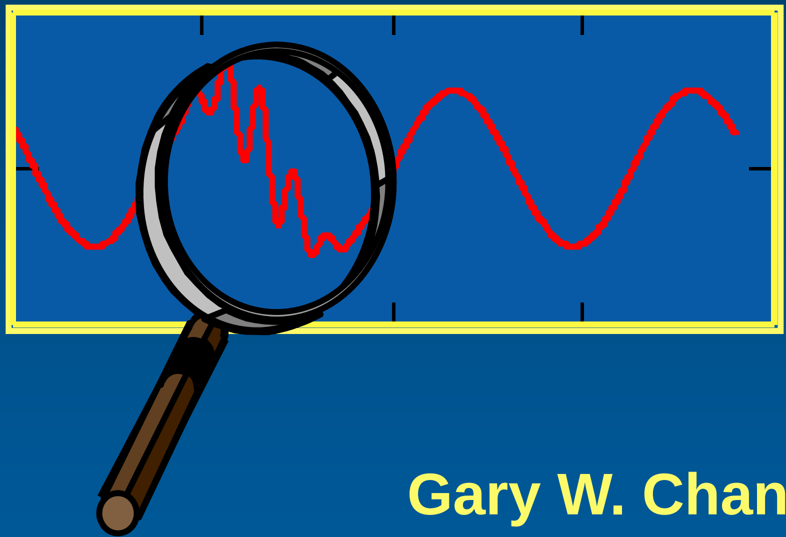
# Monitoring Power Quality of Power System – Smart Grid Aspect

## 智慧電網之電力品質監控



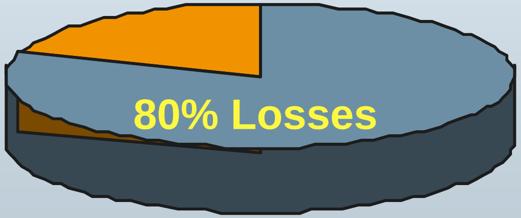
**Gary W. Chang, PhD, PE, FIEEE**
**Department of Electrical Engineering**
**National Chung Cheng University, Taiwan**

# Outline

- Smart Grid Driving Forces
- Overview of Power Quality Disturbances
- Power Quality and Smart Grid
- Power Quality Measurement Issues
- Advanced PQ Measurement Techniques
- Case Studies
- More PQ Measurement Issues under Smart Grid
- Conclusions

# Smart Grid Driving Forces

**Energy Efficiency**




**CO2 Emissions**


**Power Quality**

**Renewables**

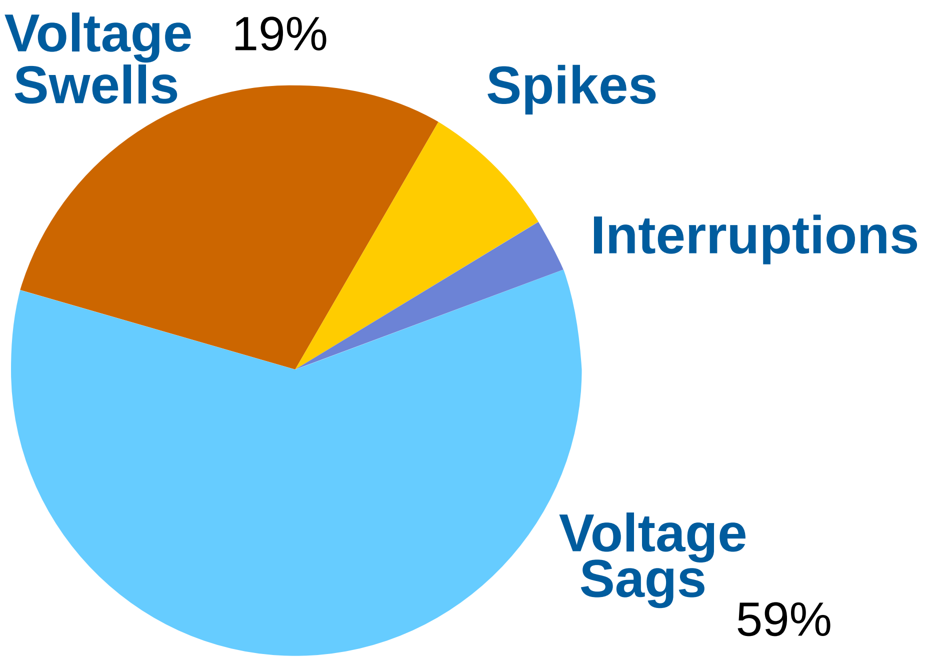
**Distributed Empowerment**

Source: Alstom Power

# Overview of Power Quality Disturbances

## What is Power Quality (PQ)?

- Any occurrence manifested in voltage, current, or frequency deviations that results in failure or malfunction of utilities' and customers' equipment.



# Typical PQ Disturbances

### *Voltage sags/swells/interruptions*

**Causes:** sudden change in load current, fault on feeder

**Effects:** process interruption, data loss, data transmission errors, PLC or computer malfunction

### *Transients*

**Causes:** lightning strikes, capacitor energizing, load or source switching

**Effects:** insulation breakdown, semiconductor device damage, shorts, accelerated aging, loss of data or stability

### *Harmonics*

**Causes:** power electronic devices, arcing, transformer saturation

**Effects:** equipment overheating, high voltage/current, protective device mis-operations

### *Voltage fluctuations*

**Causes:** high current loads, arc furnaces, windmill-generated power

**Effects:** illumination flickers, frequent operations of OLTC, malfunctions of electronic devices

# Power Quality Issues

- Harmonics/Interharmonics
- Imbalance
- Voltage Fluctuations
- Voltage Sags/Swells/Interruptions
- Transients
- Standards, Limits, Diagnostics, and Alternative Indices
- Combined Effects
- Power Quality Economics
- Measurement Protocols
- Probabilistic Approach
- Modeling & Simulation
- Advanced Techniques (Wavelet, Fuzzy Logic, Neural Net, GA)
- Integrated Perspective of Power Quality Programs

⋮

# Importance of PQ-related Issues

- **Proliferation of highly sensitive computerized equipment places more stringent demands on PQ**
  - Semiconductor industry
  - Computers and computer-related businesses
  - Variable-speed drives or robots
  - Programmable logic controllers
- **Nonlinear loads result in more PQ problems**
- **Impact to High-tech Firms**
  - One cycle interruption causes a silicon device worthless
  - Five-minute shut down of a chip fabrication plant makes delay from a day to a week
  - One-second power outage causes e-commerce sites lose millions of dollars worth of business
- **Cost of PQ Losses**: *$20~25 billion/year (US)*

# Power Quality and Smart Grid

## Characteristics of Smart Grid

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) states that the "Modern Grid" will have the following characteristics:

- Self-Heals
- Motivates and Includes the Consumer
- Resists Attack
- **Provides Power Quality for 21st Century Needs**
- Accommodates All Generation and Storage Options
- Enables Markets
- Optimizes Assets and Operates Efficiently

# Power Quality and Smart Grid *(cont.)*

**The use of advanced information and communication technologies to link all aspects of the electric grid together with sensors and intelligent devices to provide the following enhanced operational capabilities:**

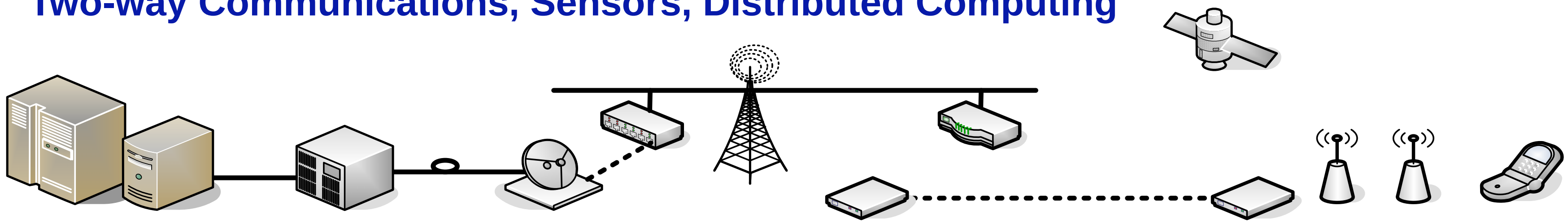
**1) Engage CONSUMERS with the ability to wisely use electricity, electric devices and new services**

**2) Ensure EFFICENCY of using the electric grid (optimizing current assets while integrating emerging technologies such as renewables and storage devices); and**

**3) Enhance RELIABILITY (protecting the grid from cyber and natural attacks, increasing power quality and self-healing capabilities).**

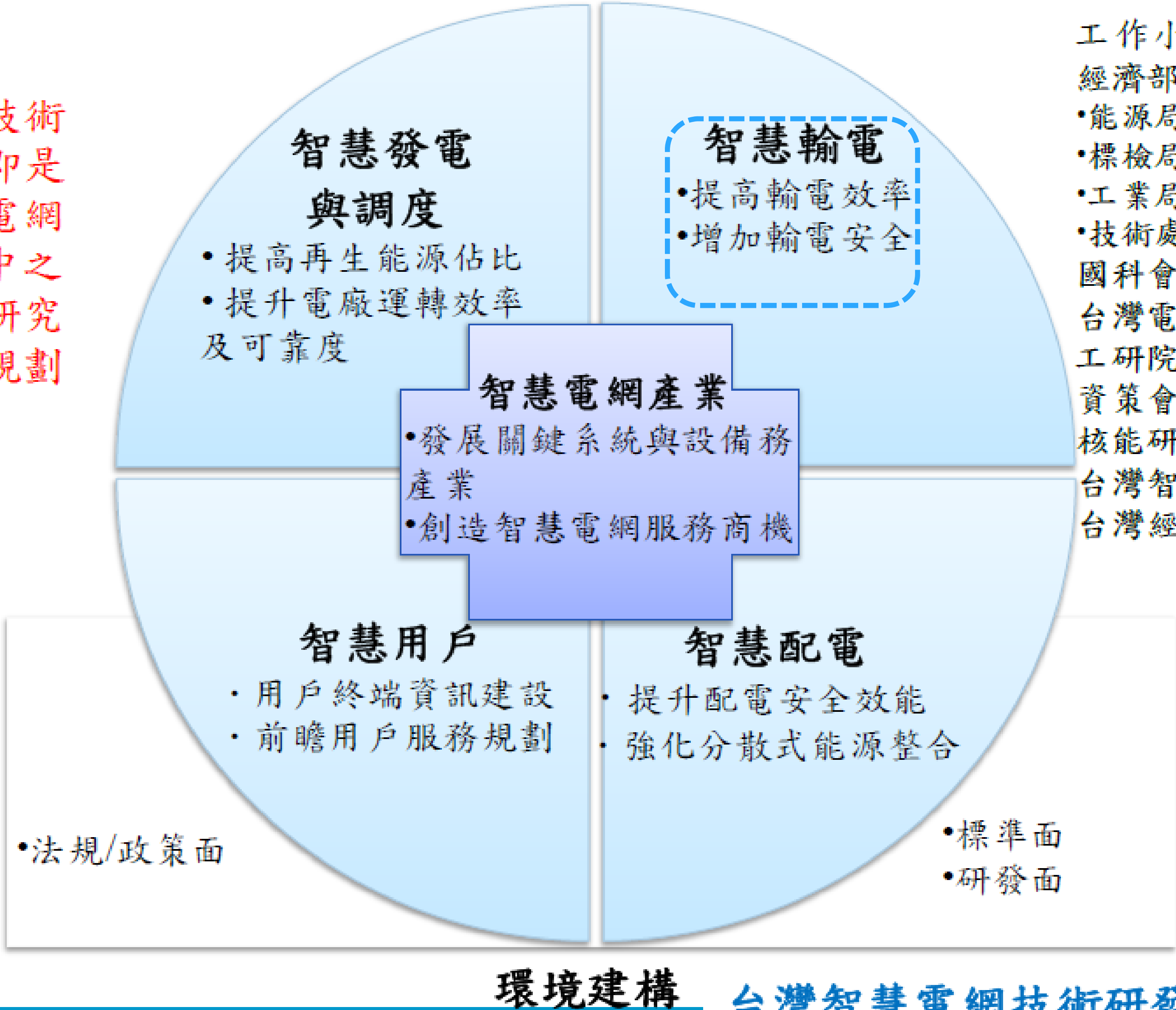
**Generation** | **Transmission** | **Distribution** | **Consumer**

**Two-way Communications, Sensors, Distributed Computing**



# 台灣智慧電網總體規劃 (2011~2030)

智慧電網技術研發方向即是根據智慧電網整體規劃中之短中長期研究項目進行規劃

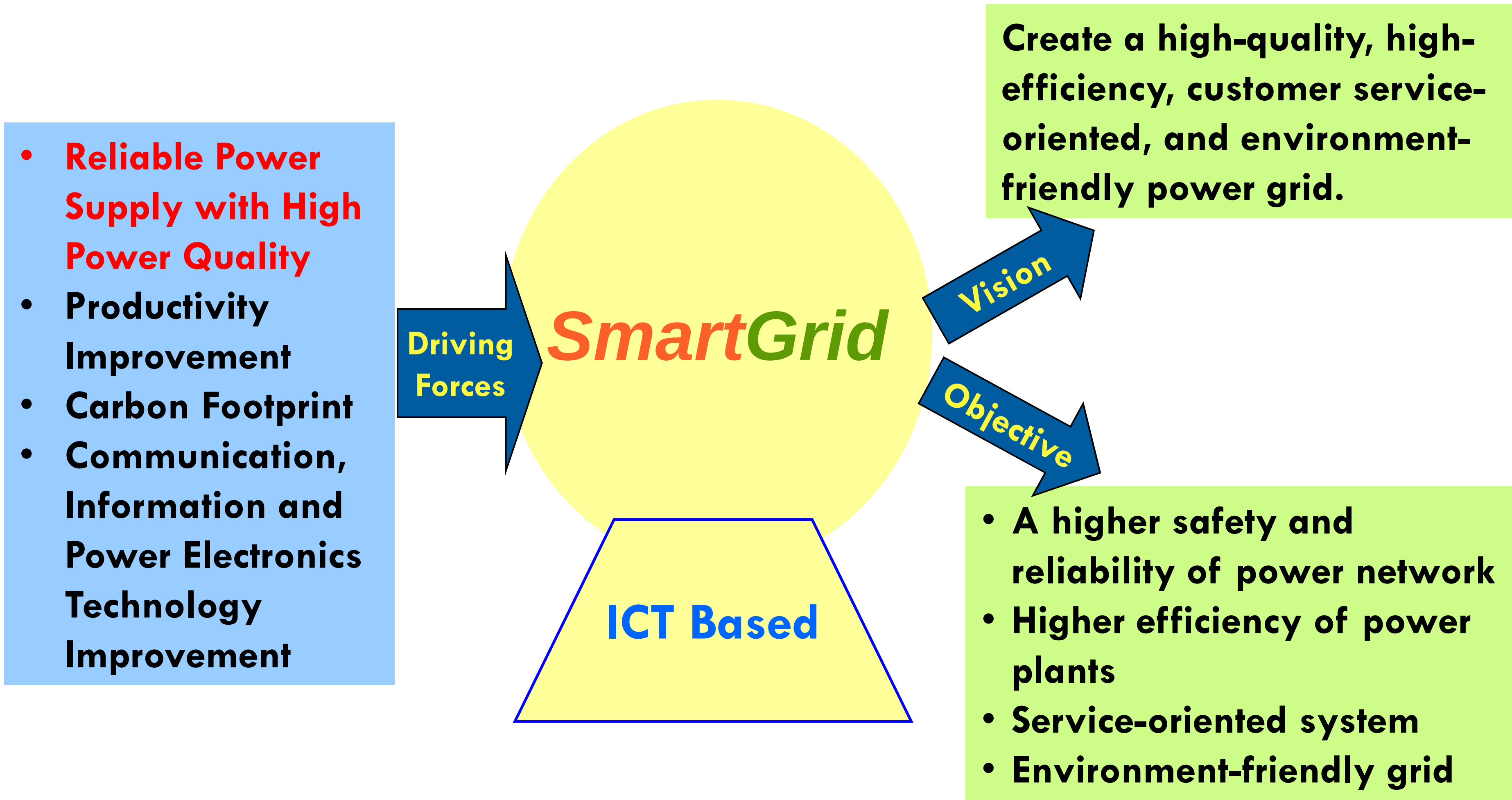



工作小組：
經濟部
•能源局
•標檢局
•工業局
•技術處
國科會
台灣電力公司
工研院
資策會
核能研究所
台灣智慧電網產業協會
台灣經濟研究院



Source: 能源國家型 智電主軸計畫辦公室

# Power Quality and Smart Grid *(cont.)*




## Taipower's Vision on Smart Grid

Source: TPC

# Power Quality and Smart Grid *(cont.)*

- Classic sensing remote terminal units (RTUs) are relatively simple and low-resolution devices that report only the most basic parameters of the power system.
- IEDs at substations lack unified communication and information protocols and interoperationability.
- In today's Smart Grid, we need additional information about the state of the system. The additional information provided by permanently installed and network-connected power quality monitoring enables operators and engineers to measure the quality of service, react more effectively to unexpected system events, and provide the forensic information necessary to determine cause, effect and future mitigation methods for more serious system events.

# Power Quality and Smart Grid *(cont.)*

- Monitors, diagnoses, and responds to PQ issues
- Supplies various grades of power quality at different pricing levels
- Greatly reduces consumer losses due to PQ
- Quality Control for the grid
- Performs continuous self-assessments
- Detects, analyzes, responds to, and restores grid components or network sections
- Handles problems too large or too fast-moving for human intervention
- Self heals - acts as the grid's *immune system*
- Supports grid reliability, security, and power quality

| *Today* | *Tomorrow* |
|---|---|
| Focus on outages not PQ<br>Protect assets following disruption | Premium power options<br>Prevent disruptions, minimize impacts, fast restoration (FDIR) |

# Power Quality and Smart Grid *(cont.)*

- Advanced metering is a generic term referring to “smart” hardware and software for intelligently measuring the consumption of electricity.
- Three functions that make a meter smart:
  - The ability to take interval measurements, measuring both what was consumed and when.
  - Automatic transmission of the resulting data, eliminating the need for manual reading.
  - Two-way communications: the ability to both “listen” and “talk.”
- Those benefits offered by advanced metering: outage management, system reliability, power quality, time-of-use rates, on-demand reads, distribution automation, declining total cost of ownership.

# Power Quality and Smart Grid *(cont.)*

- Utility customers think the reliable electric power is both free of interruption and disturbance (i.e. clean power).
- Advanced components will apply the latest in superconductivity, energy storage, and power electronics to improve power quality.
- The Smart Grid will employ appropriate measures to prevent PQ disturbances from feeding back into the grid.
- PQ problem identification will happen quickly because modern communicating meters will find and report it immediately.
- Smart Grid technologies require the coordinated efforts of government, utilities, regulators, and standards bodies.

# Power Quality Standards

The key power quality measurement standards include:

- *IEC 61000-4-30* – basic power quality monitoring functionality
- *IEC 61000-4-15* – light flicker measurement
- *IEC 61000-4-7* – harmonics and interharmonics measurement
- *EN 50160* – voltage characteristics of electricity supplied by public electricity networks
- *IEEE 1159* – standardized power quality disturbance categorization and best practices
- *IEEE 1159.3* – standardized power quality data interchange format

:

- *Standards should enable future functionality of the Smart Grid (e.g. NIST Framework and Roadmap for Smart Grid Interoperability Standards, NIST PAP 0~17)*
- *Global standards are needed*
- *Need to be robust & up-to-date*

# Power Quality Measurement Issues

In general, the PQ measurement system should include the following elements to implement the Smart Grid through well-integrated applications:

- Service-based architecture
- Technology layering and isolation and ability to be easily upgraded
- Well-defined interfaces and points of interoperability
- Information models and discoverability
- Application of industry and international standards
- Distributed computing (modular, network connected components)
- Network and system management

# Power Quality Measurement Issues *(cont.)*

- Two emerging trends in PQ measurement important to utilities:
  - Consumers’ rising energy requirements are causing the load on each phase to rise.
  - An accelerated increase in the use of non-sinusoidal loads
- Key attributes of PQ measurement system under Smart Grid
  - Embedded grid intelligence measures power quality metrics
  - Measures voltage, current, harmonic distortion, and more
  - Sag and swell logging with configurable threshold and duration
  - Neighborhood meter network data analysis
  - PQ-affiliated logging and alarms built-in and configurable through software

# PQ Measurement for Power Network

**For Transmission System:**

- Automated Asset Condition Assessment
- Automated Fault Location
- Waveform Capture & Fault Classification
- Wide Area Monitoring & Control

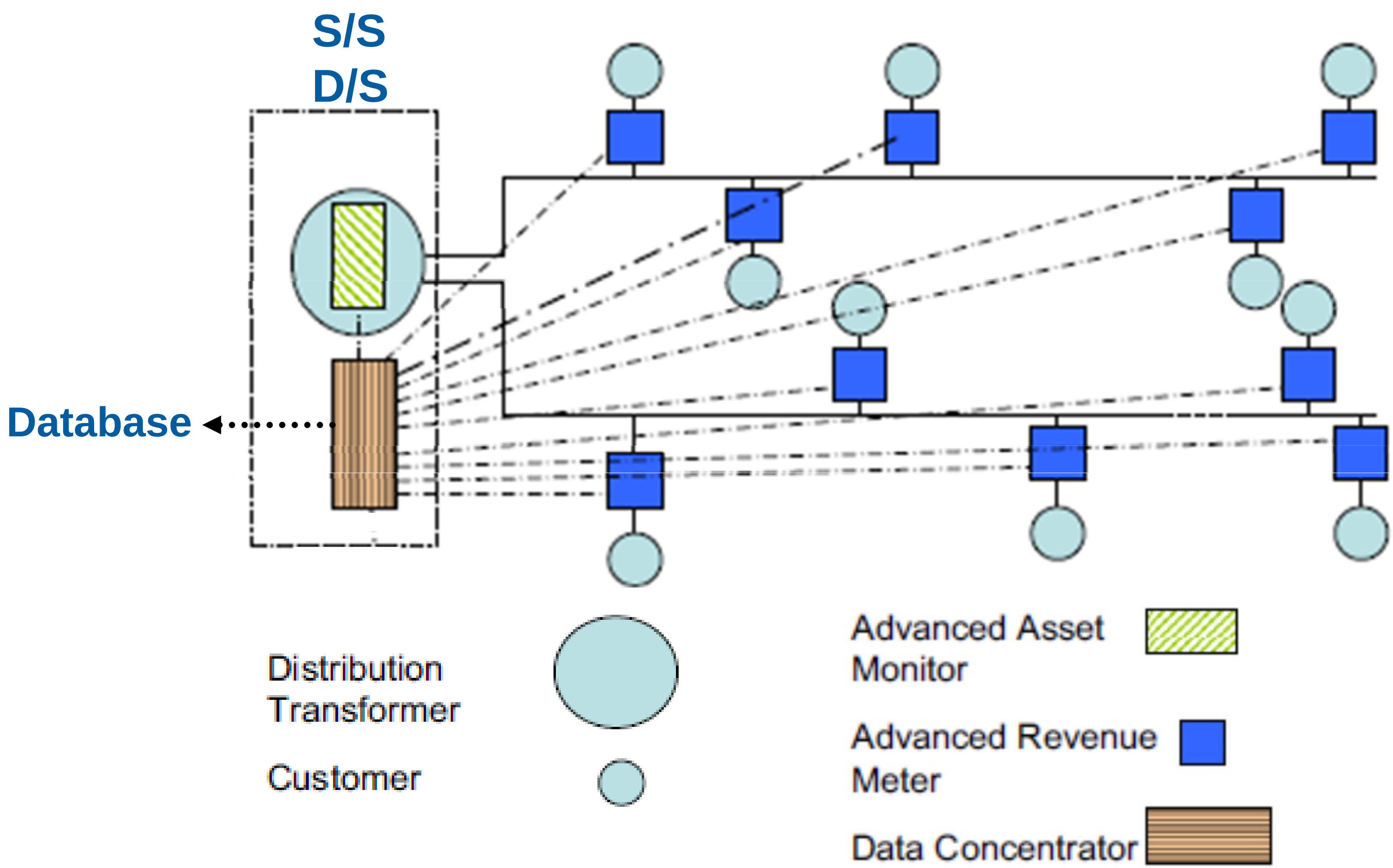
.
.

**For Distribution System:**

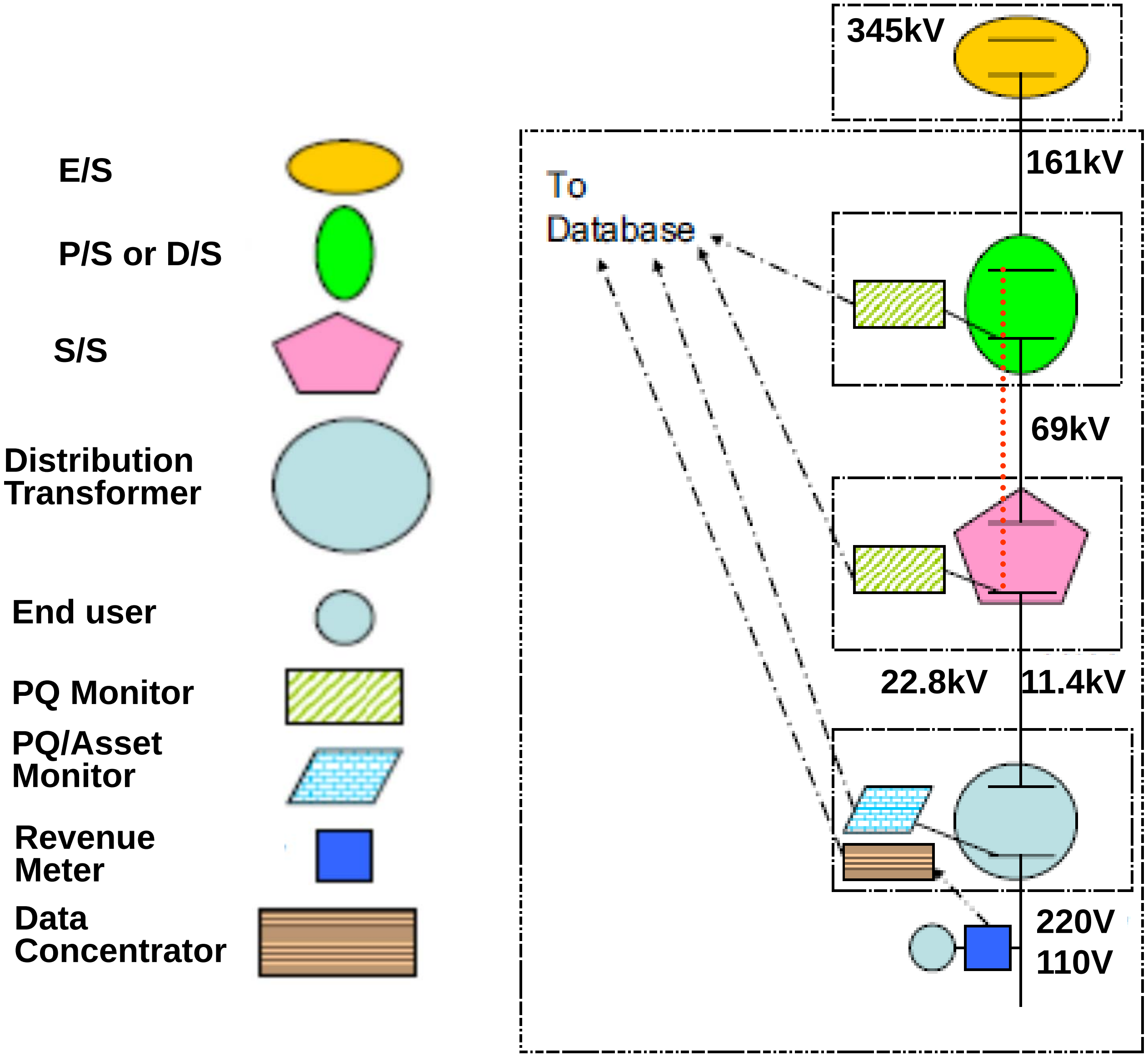
- Feeder Automation
- Remote Monitoring of Fault Indicator
- Equipment Condition Monitoring
- Substations Automation
- Micro-Grid Management
- Large Customers

.
.

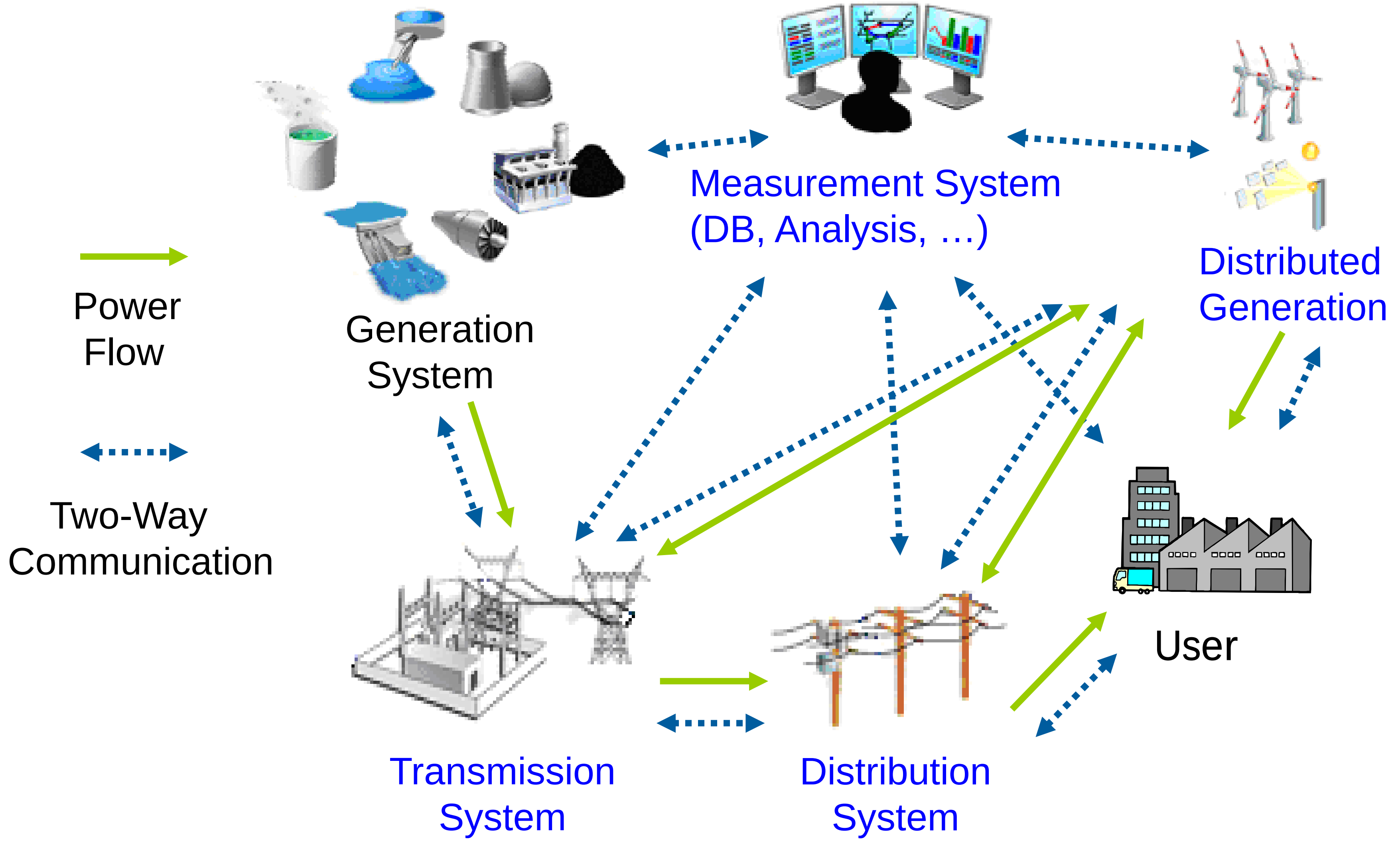
# Distribution System Monitoring Scheme



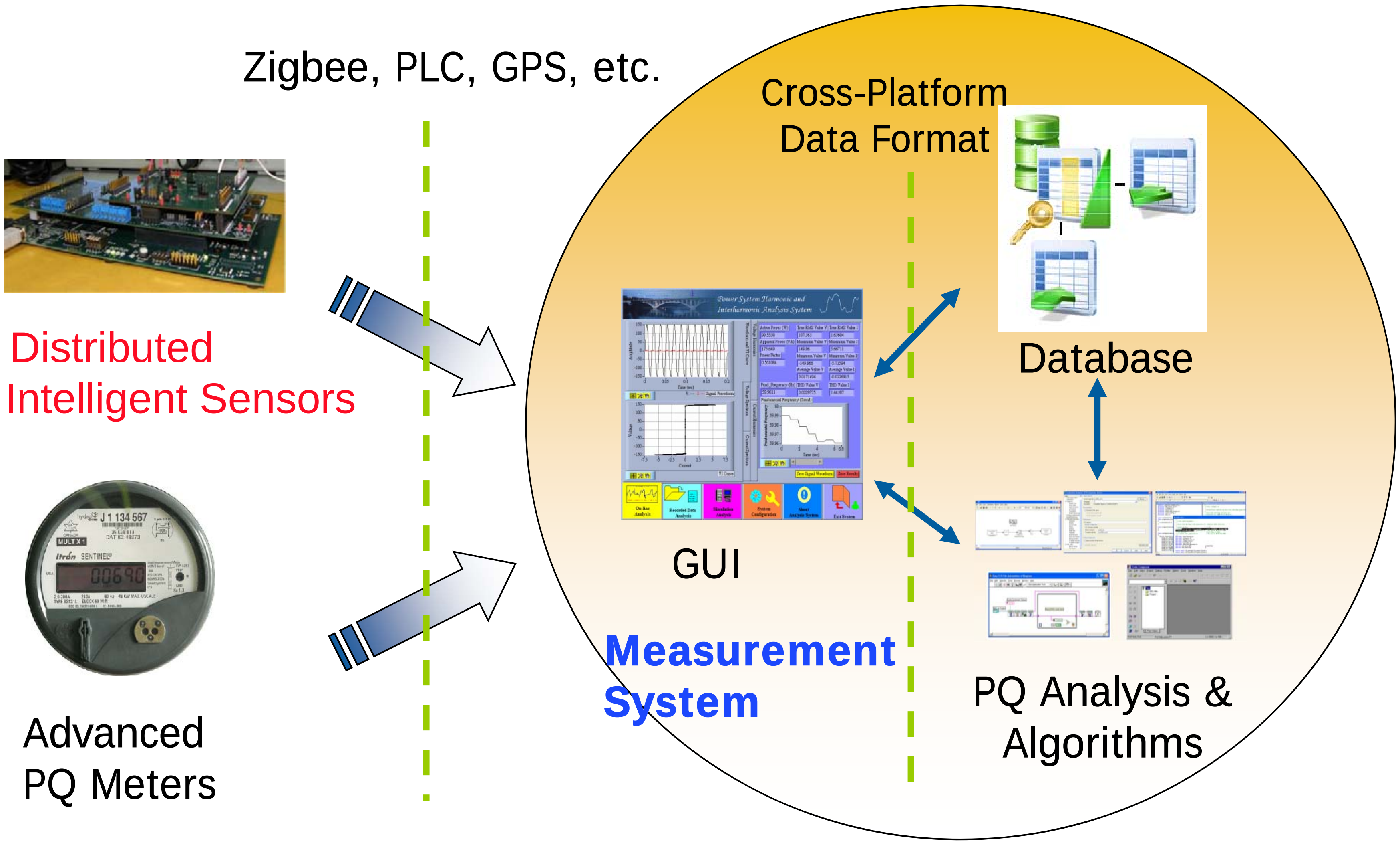
# Distribution System Monitoring Scheme *(cont.)*



# Smart PQ Monitoring Scheme



# Smart PQ Monitoring Scheme *(cont.)*



# PQ Disturbance Emission and Immunity

| Disturbance | Immunity | Emissions |
|---|---|---|
| Sags and Swells | ITIC/SEMI F47 | Protection Settings; Impedances; fault characteristics |
| Waveform Distortion | 61000-3-2,4,12 | 61000-3-6 |
| Voltage Fluctuations & Flicker | 61000-3-3,5,11 | 61000-3-7 |
| Transients | BIL | Not prescribed |
| Imbalance | Varies greatly for types of equipment | 61000-3-13 |

# PQ Monitor Specifications

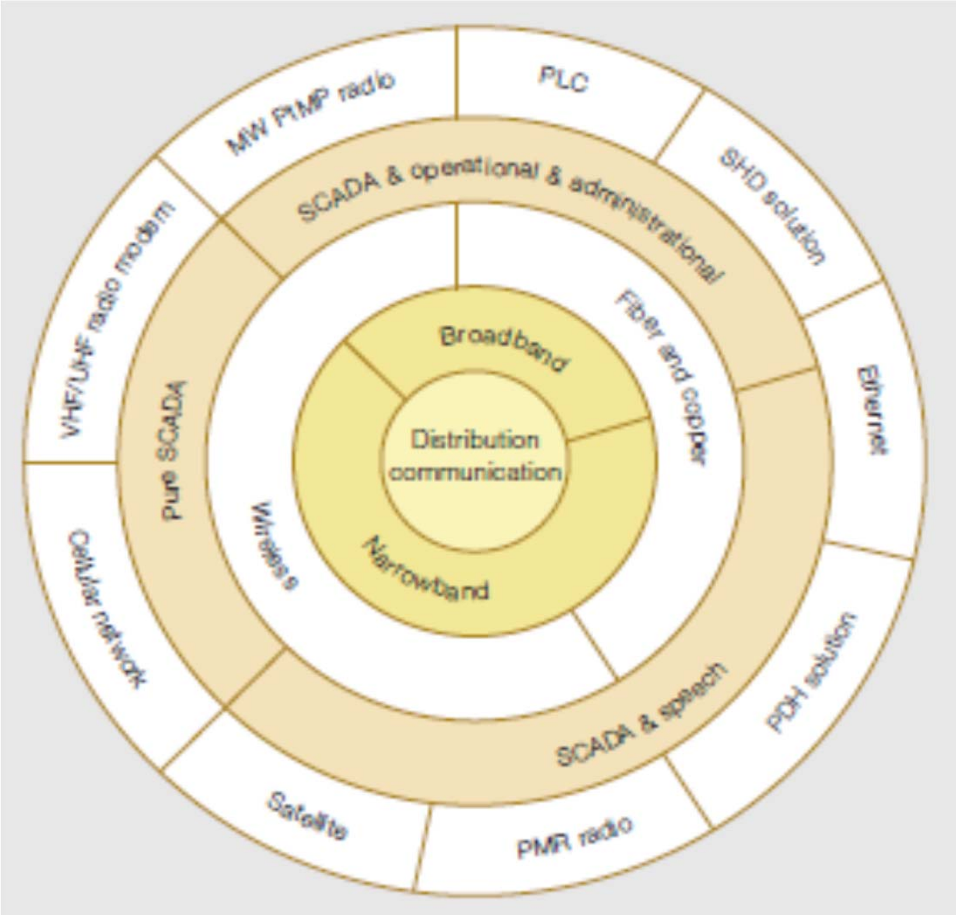
| | | |
|---|---|---|
| Designed for energy usage metering<br>Collect fundamental voltage/current/power<br>Some have minor PQ functions<br>Cheaper than dedicated PQ monitors | Suitable for S/S or D/S<br>Supply 10-,15- or 30-minute data<br>Useful for network planning and asset management<br>Some PQ functions | Highly accurate<br>Measure full range of PQ disturbances<br>Comply with major PQ monitoring standards<br>May have two-way communication capability<br>Expensive |
|  |  |  |

# Location of PQ Monitors

- Network Monitor Sites
  - A small number of complex substation sites
  - A large number of simple distribution substation sites
  - A much larger number of customer sites
- Monitor Location Strategies
  - Network topology including future changes to meet forecast loads
  - Availability of suitable transducers
  - Monitoring technologies
  - Other required or desirable monitoring functions

# Communication Systems

- Need considerable improvement to fully realize an intelligent network
- Wireless and/or non-wireless communications
- Various radio schemes
- Optic fiber would be ideal
- Dedicated network may provide infrastructure
- Comply with major protocols for substation, distribution, & feeder automations (IEC 61850, DNP3, …)




**Communication options for distributed communication for the smart grid**

Source: ABB

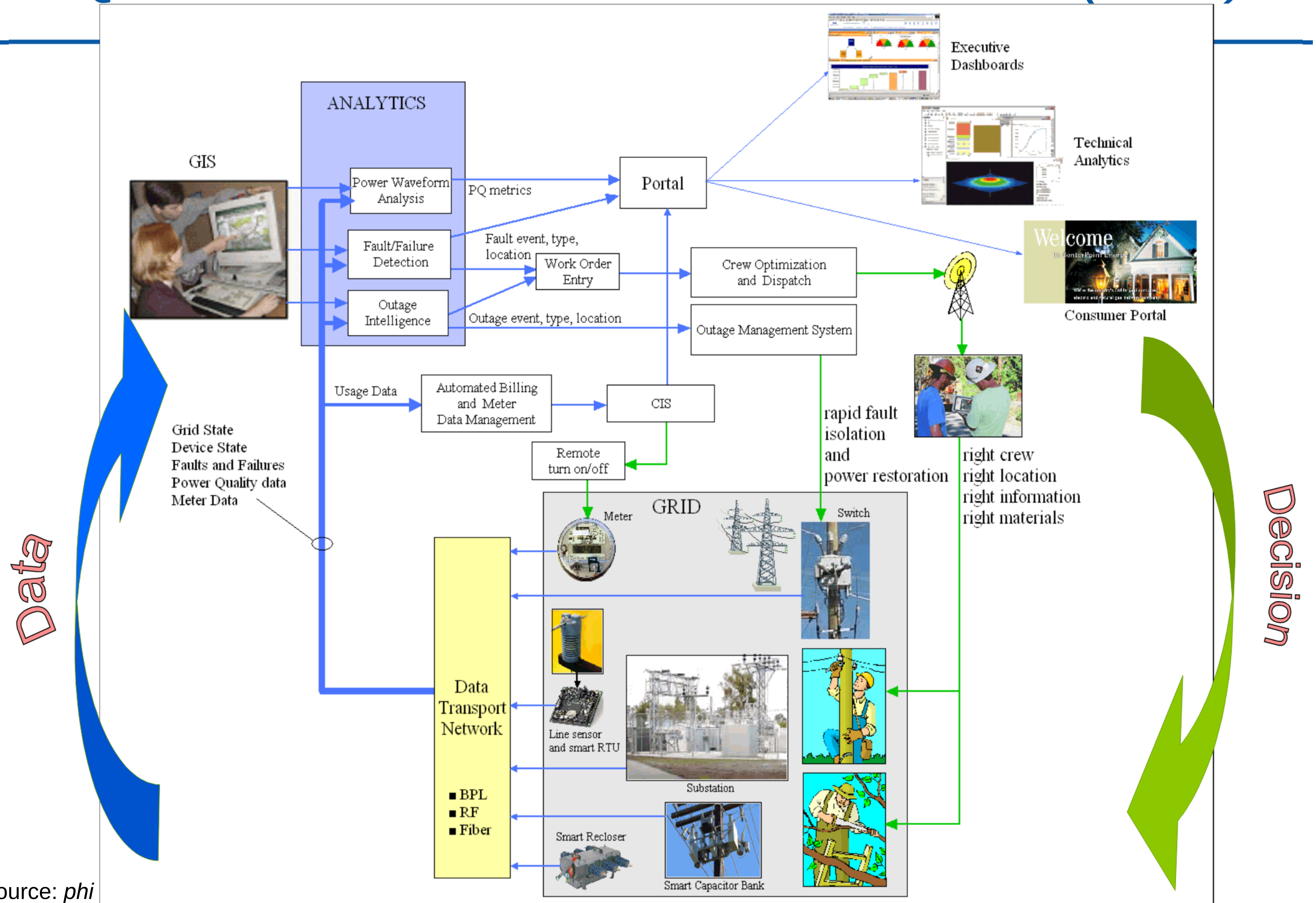
# Data Management Issues

- Managing a large and growing database
- Backing up data
- Extracting data (Data Mining)
- Data quality affected by
  - Instrument transformer errors
  - Secondary wiring issues
  - Faulty PQ monitors
  - Communication failures
  - Data corruption
  - Reduce raw data to something understandable without the loss of important detail
- Use reporting indices
  - Continuous disturbance indices based on statistical methods
  - Advanced visualization and decision support

# Metrics for PQ Measuring Progress

- Number of PQ measurement points divided by number of customers
- Number of PQ incidents that you can identify and even better anticipate over time
- Number of devices divided by the improvement in reliability indices
- Number of customer complaints regarding PQ issues
- Number of jurisdictions that have defined electric rate structure for PQ service levels based on societal and market needs

# PQ Measurement for Power Network *(cont.)*

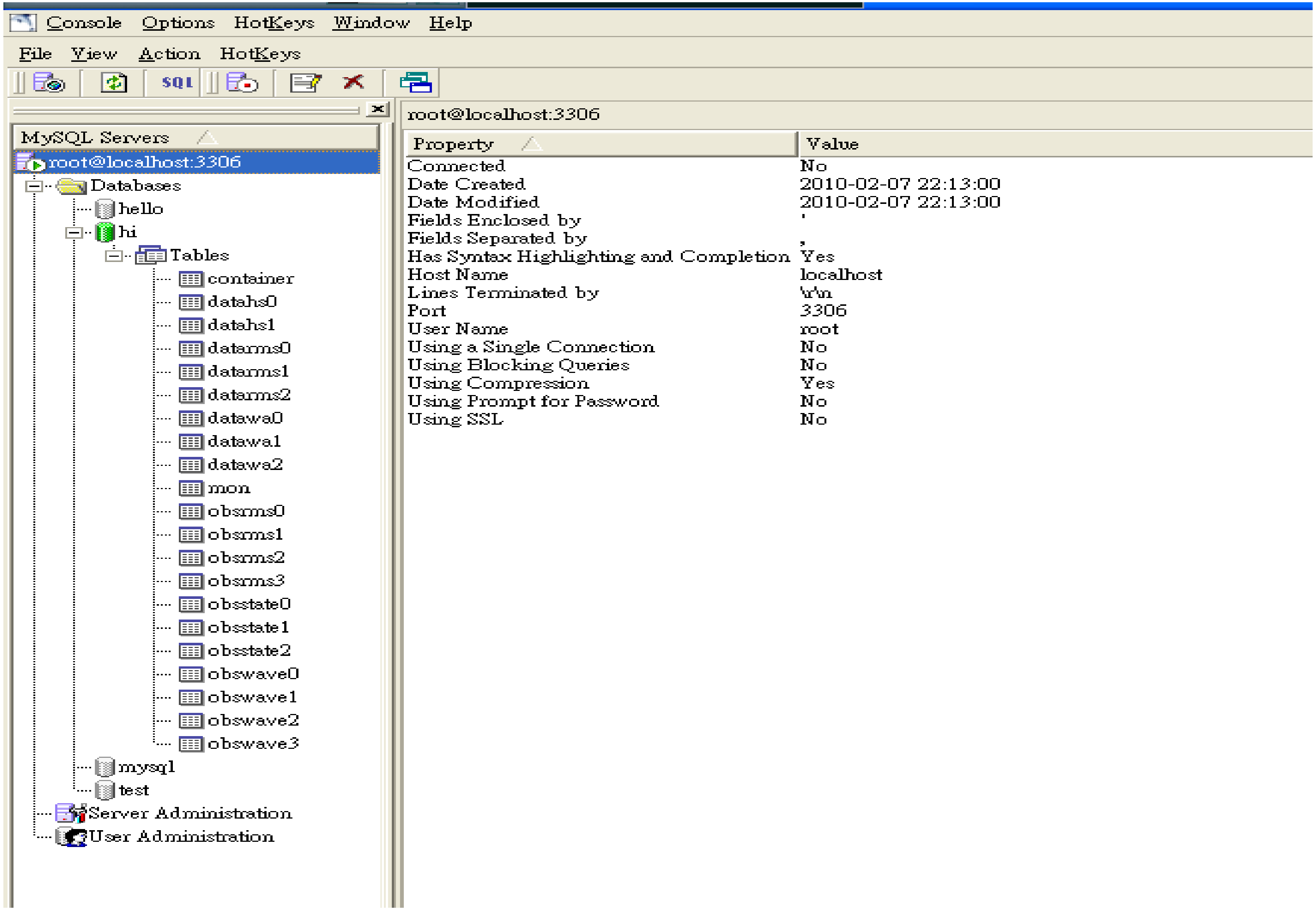



Source: *phi*

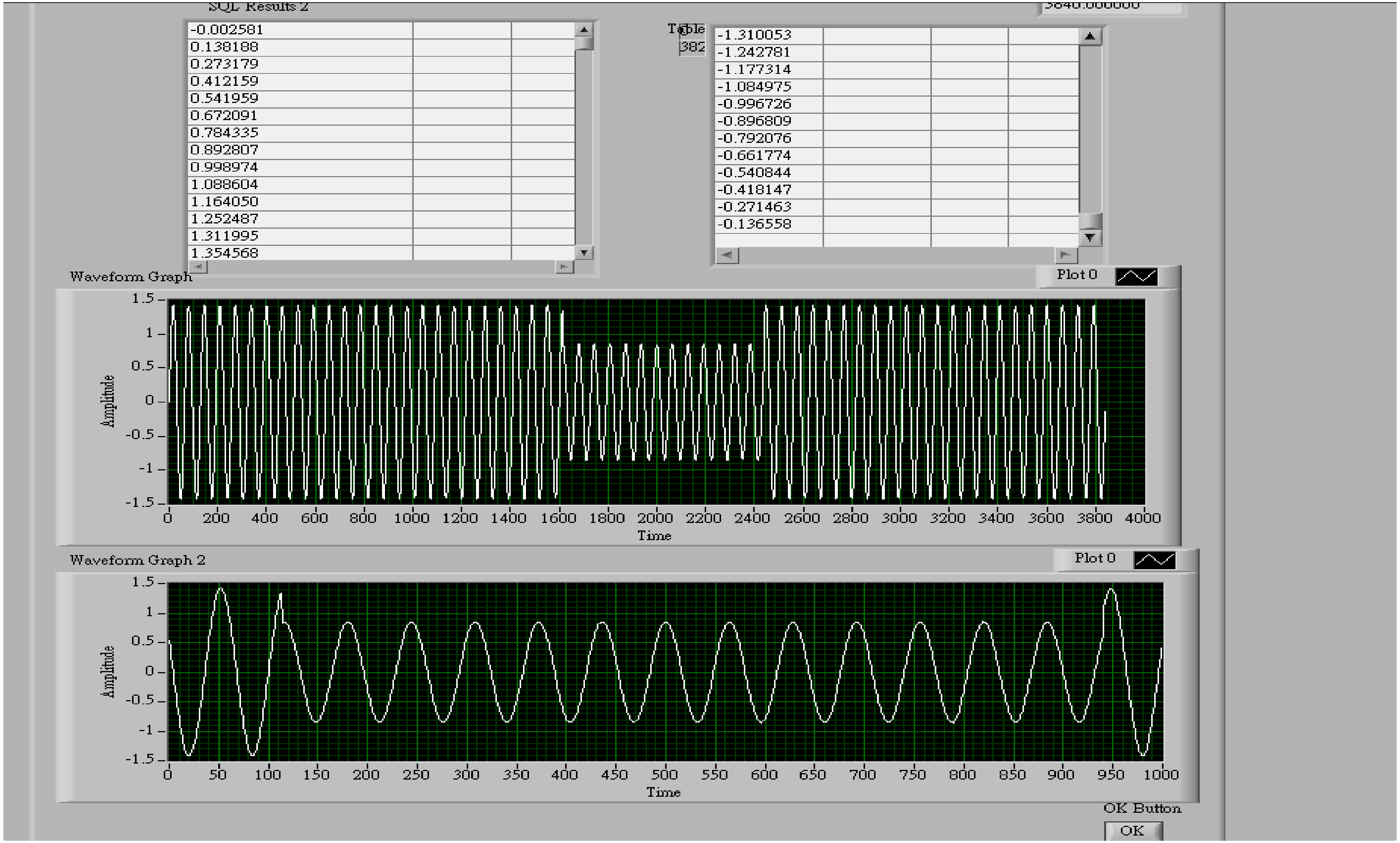
# Advanced PQ Meter Functions

| | |
|---|---|
| High Accuracy | True Four-Quadrant Metering |
| Daily/Hourly/15 Minute Interval Meter Reads | Communication to Field Network/In-Home Devices |
| Voltage Sag/Swell Recording | Waveform Capture |
| Human-Machine Interface | Harmonic Metering |
| Flicker Assessment | Connect/Disconnect Switch |
| K-Factor Calculation | Synchronized Phasor Measurements |
| Secure and Encrypted Data Transmissions | Predictive Demand |
| Interoperability | Tamper/Theft Detection |
| Configurable Settings and Internal Clock | Support for Home Area Network, Distribution Automation, and Demand Response |
| Time-of-Use Metering | Remote Upgradeability of Firmware |

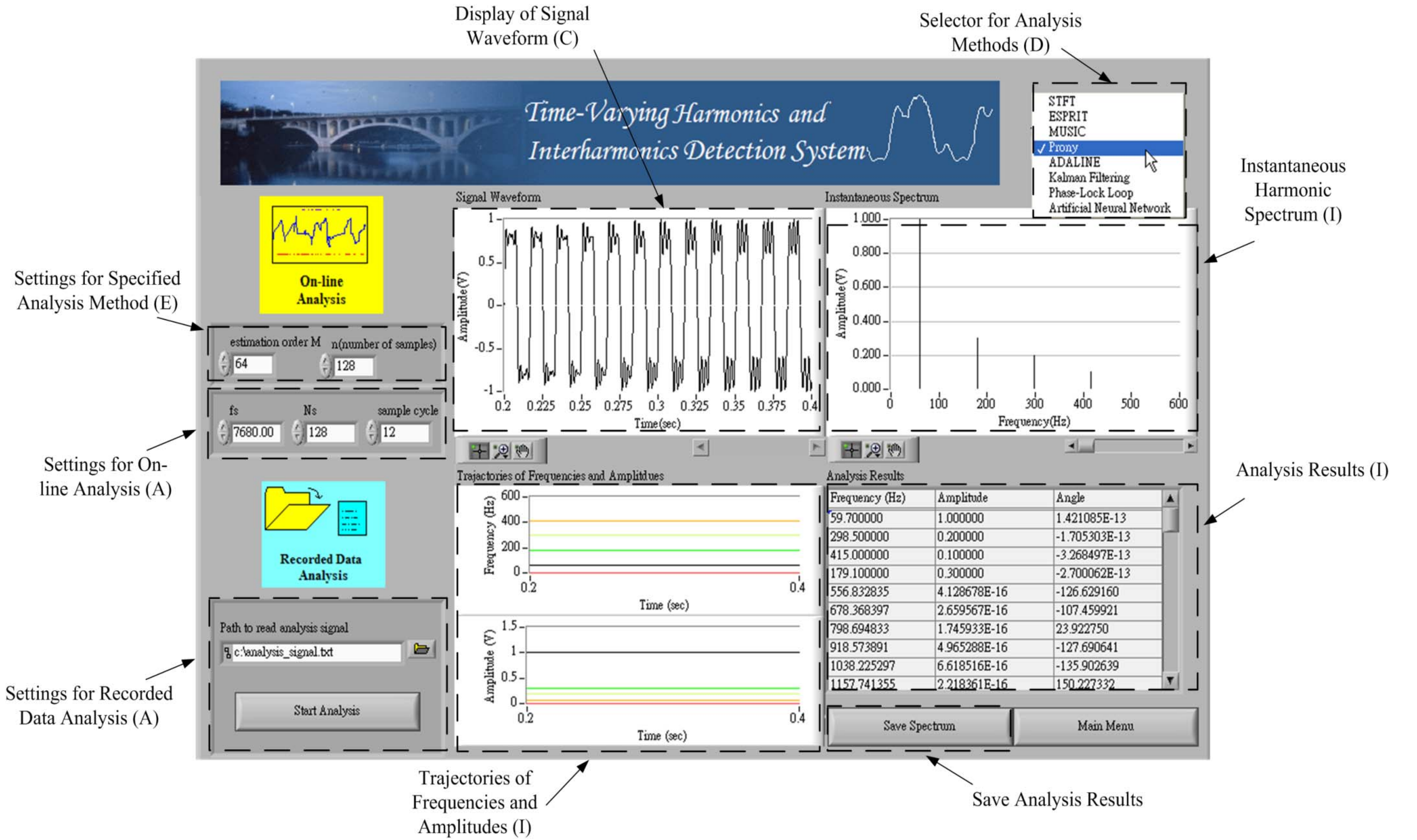
# PQ Database Design & Implementation



# Waveform Capture and Data Storage



# Visualization and Decision Support

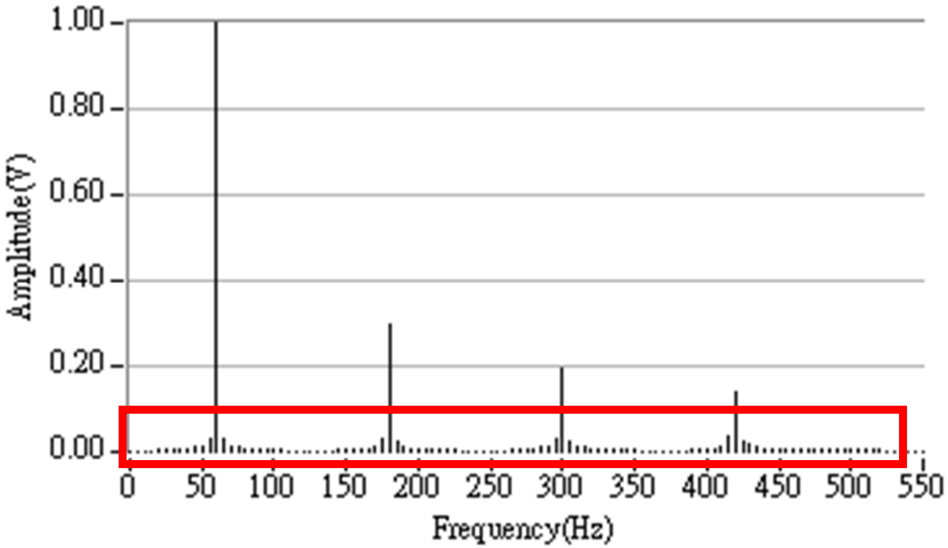



GUI of the integrated virtual instrument for on-line and recorded data PQ analyses

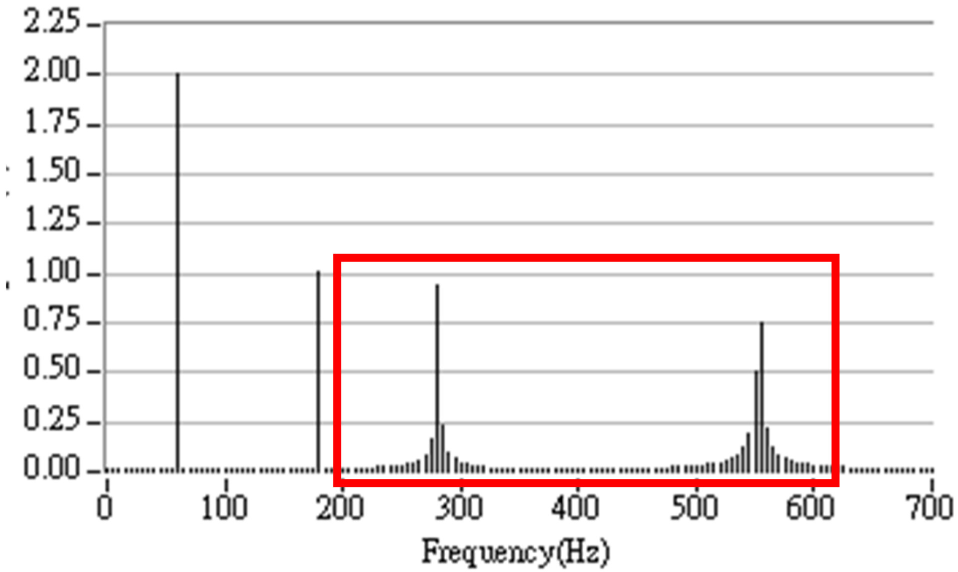
# Measurement of Harmonics/Interharmonics

$$v(t) = \sin(59.85 \times 2\pi t) + 0.3\sin(179.55 \times 2\pi t) + 0.2\sin(299.25 \times 2\pi t) + 0.15\sin(418.95 \times 2\pi t)$$

$$v(t) = 2\sin(60 \times 2\pi t) + \sin(180 \times 2\pi t) + \sin(281 \times 2\pi t) + \sin(553 \times 2\pi t)$$

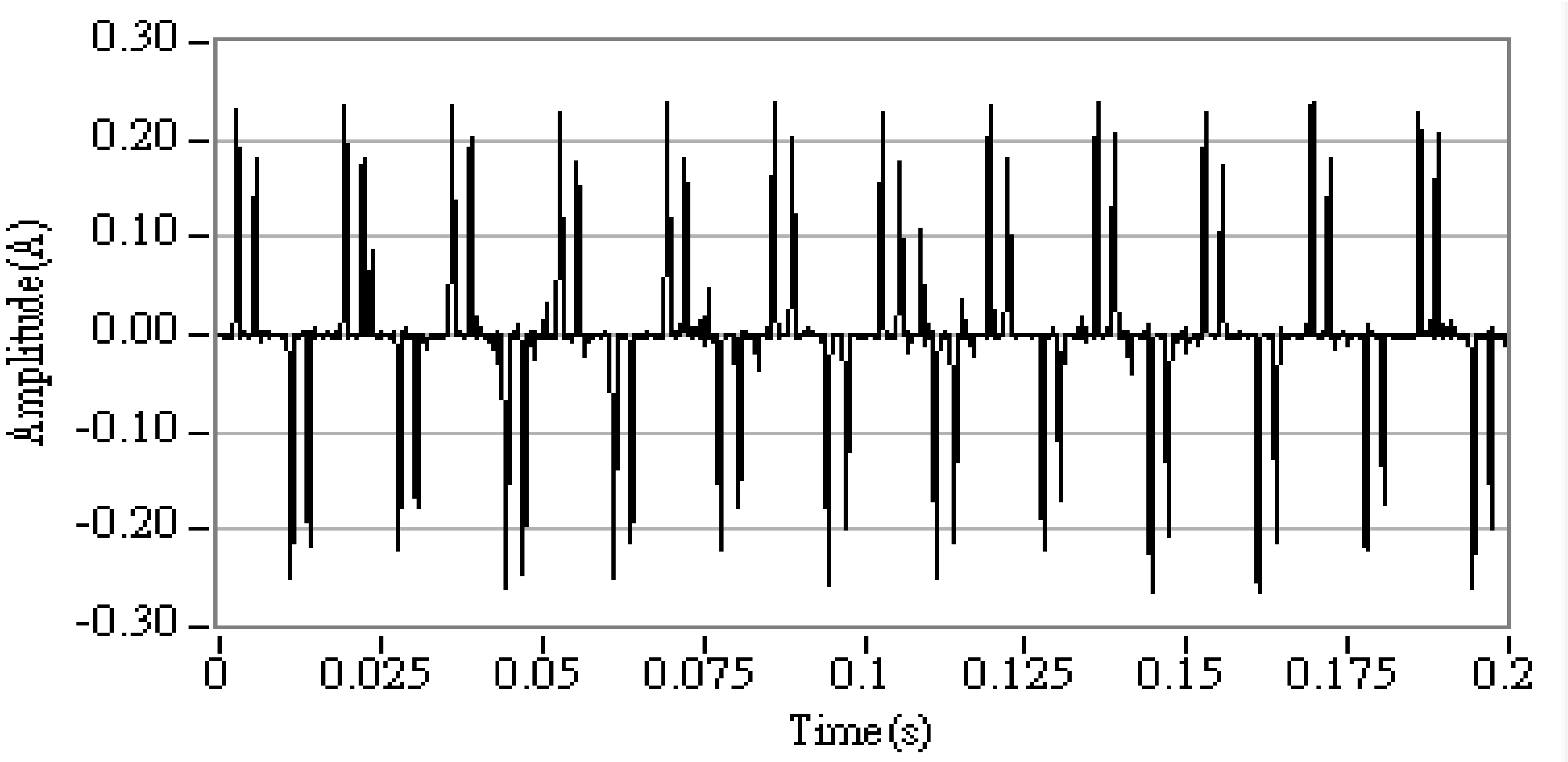



**Spectral Leakage**




**Picket-Fence Effect**

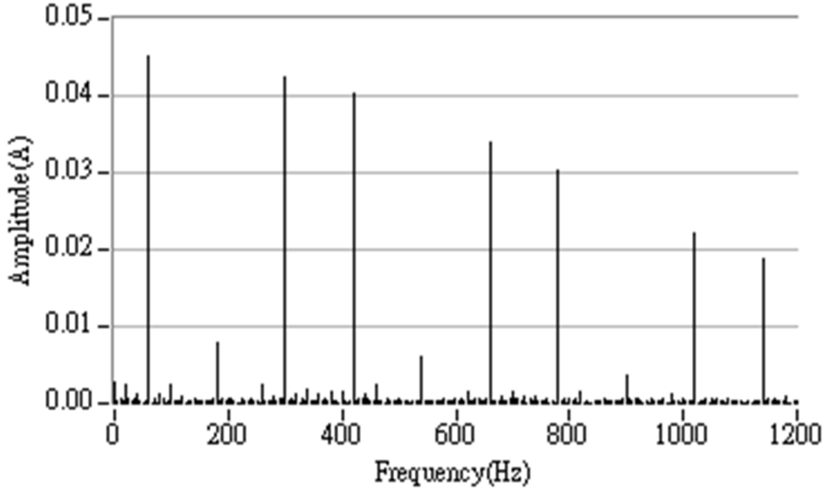
# Case Studies *(Case 1)*



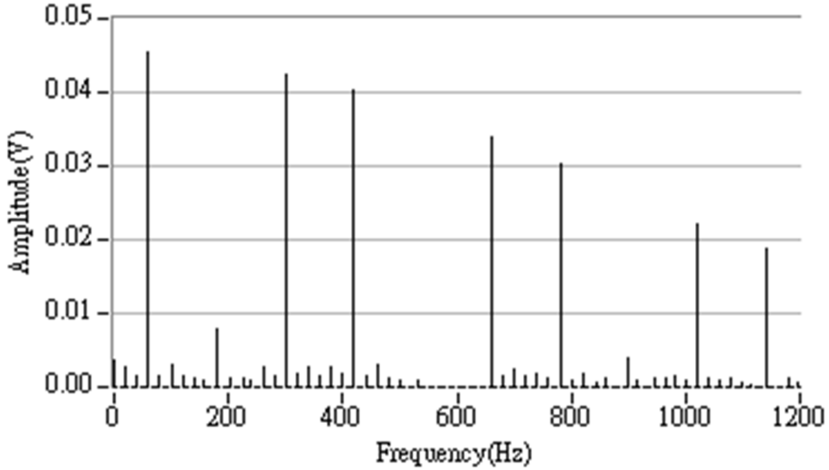

**Measured Adjustable Speed Motor Drive input current waveforms**

# Case Studies *(cont.)*

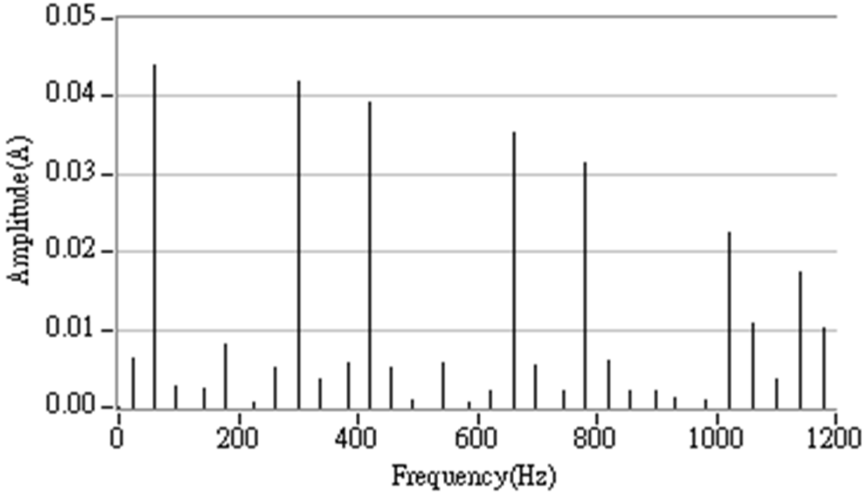
FFT without corrections




IEC grouping method

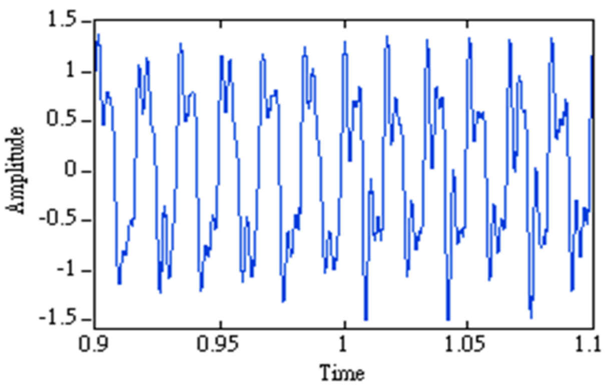



New method

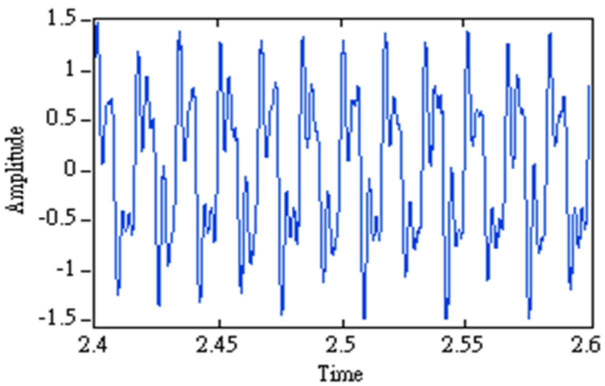


# Case Studies *(Case 2)*

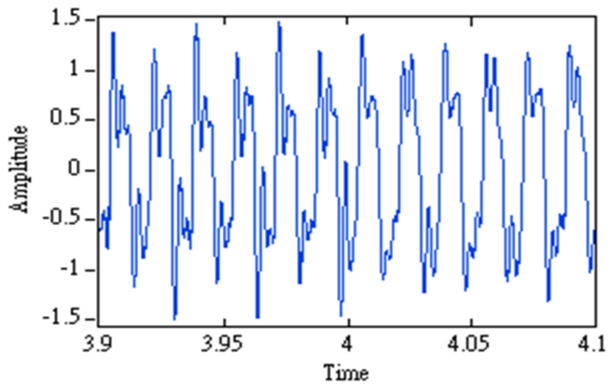
New Method for Time-Varying Harmonics Tracking




$t$ = 1 sec

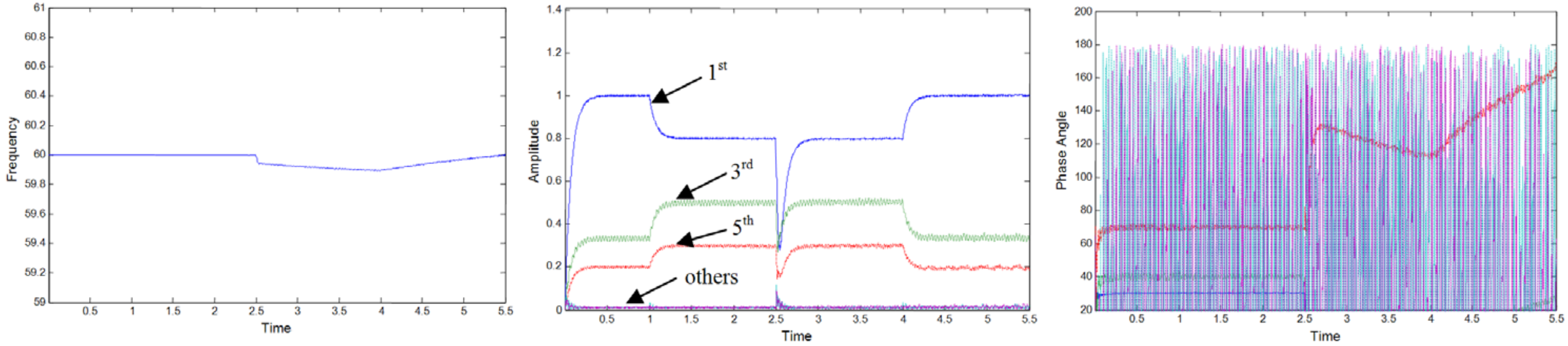



$t$ = 2.5 sec

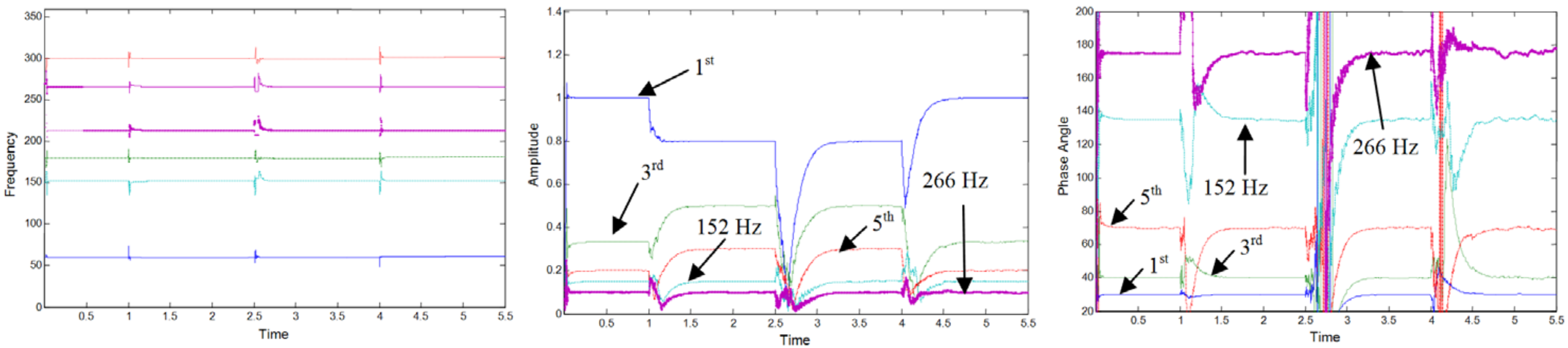



$t$ = 4 sec

# Case Studies *(cont.)*




**Traditional method**



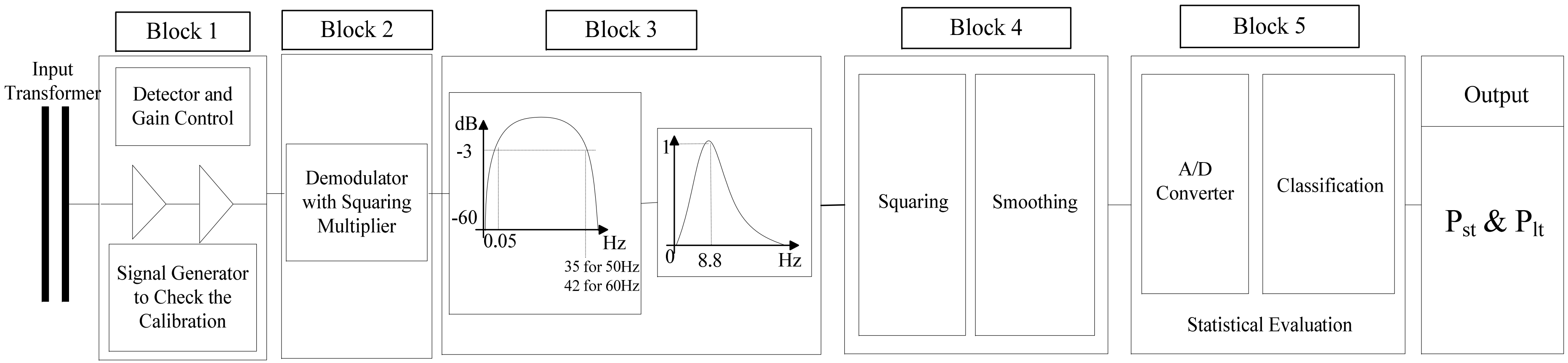

**New method**

# Measurement of Flicker

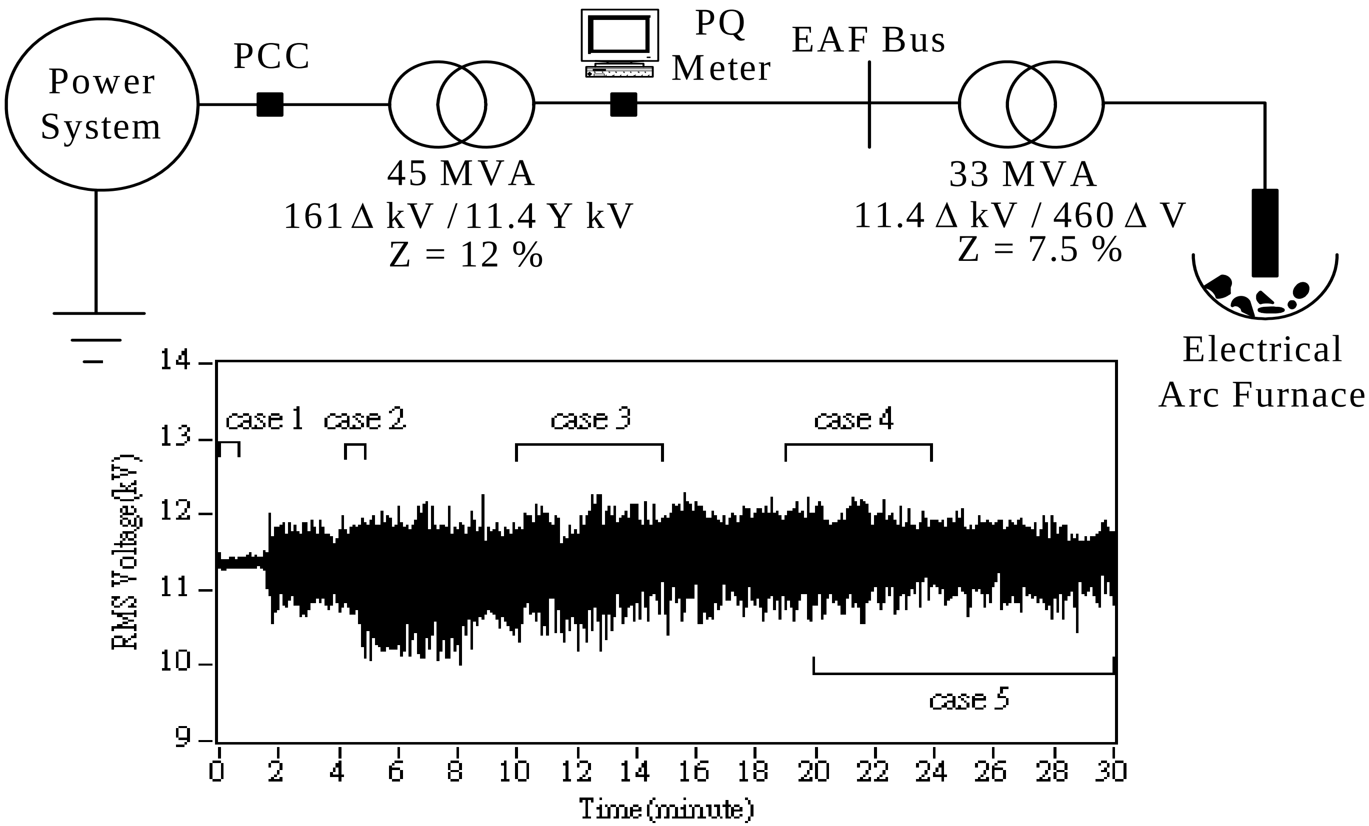
- IEC Flickermeter
- Squaring Demodulation Method
- Discrete Wavelet Synchronous Detection Method
- ADALINE Detection Method
- EPLL Detection Method
- New Approach for Implementation of IEC Flickermeter

# Measurement of Flicker *(cont.)*

- International Electrotechnical Commission (IEC) Standard 61000-4-15 provides both functional and design specifications for flicker measurement and the flickermeter architecture is described by the block diagram as follows.

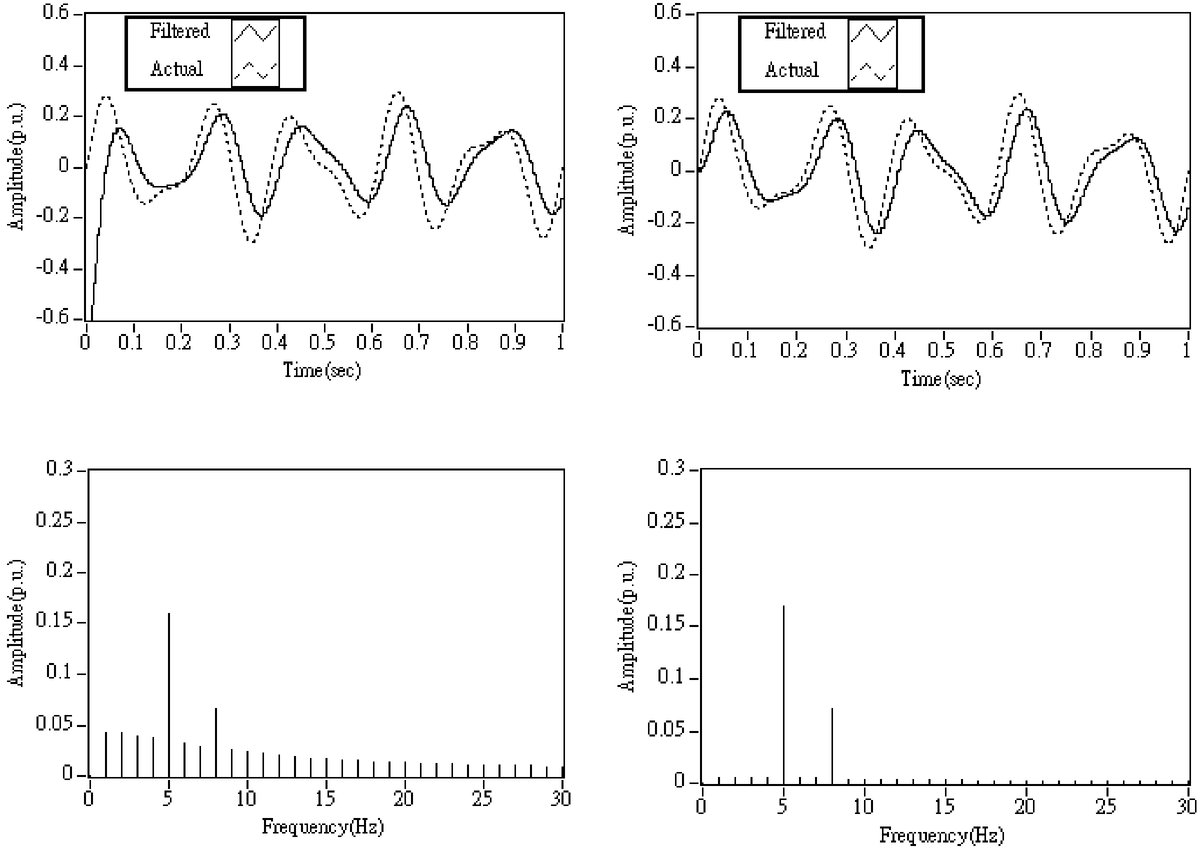


# Case Studies *(Case 3)*

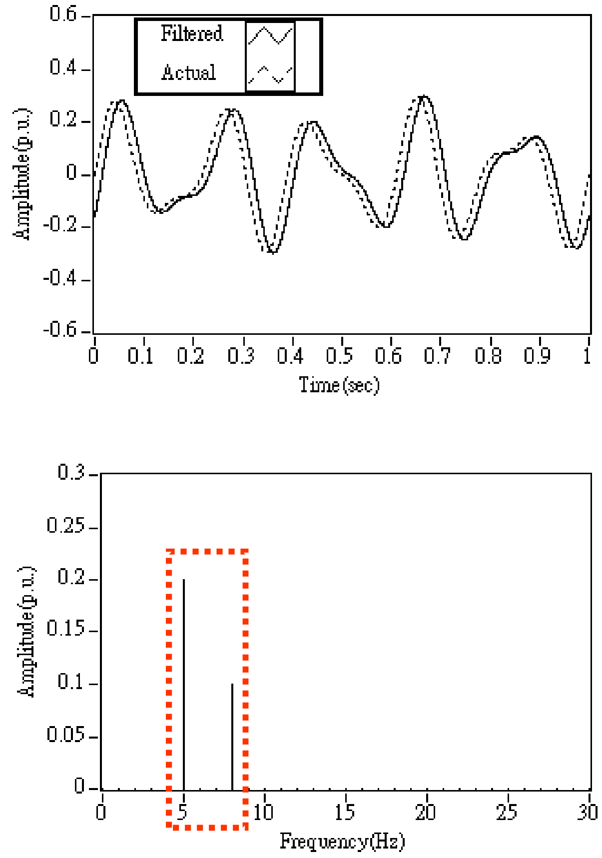



| Pst | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| IEC 61000-4-15 | 1.1325 | 6.5320 | 8.8694 | 9.2112 | 6.3733 |
| Proposed Method | 1.1102 | 6.3912 | 8.9557 | 9.1165 | 6.4136 |
| Relative Error (%) | 1.9691 | 2.1555 | 0.9730 | 1.0281 | 0.6323 |

# Case Studies *(cont.)*

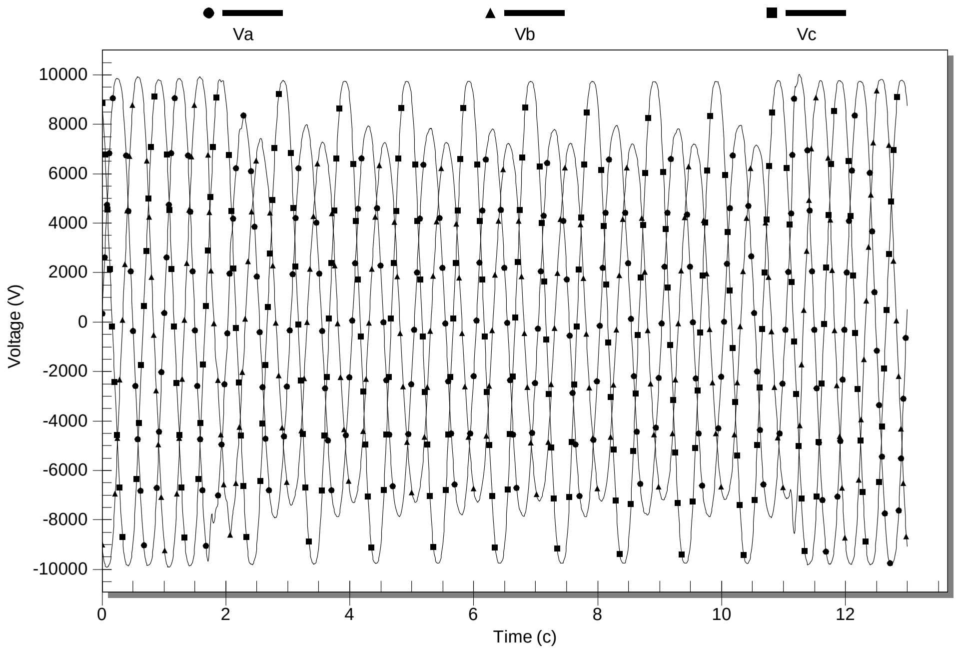



Other methods



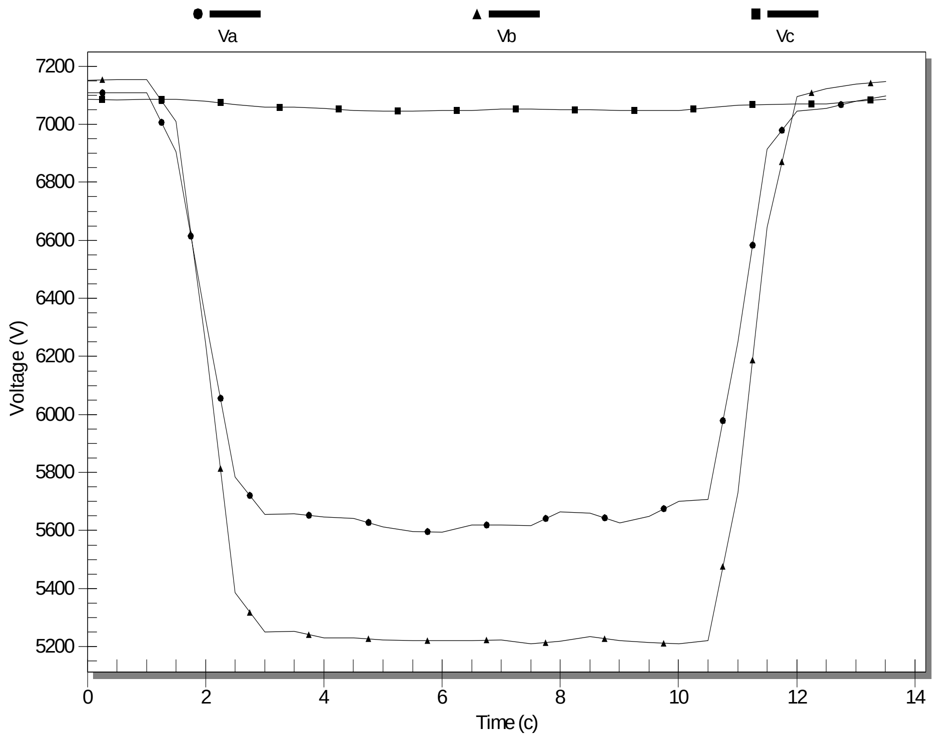

New method

# Analysis of Sags/Swells/Interruptions




**Three-Phase Voltage Sag Waveform**

**Three-Phase Voltage RMS Voltage Sag**



# Analysis of Sags/Swells/ Interruptions *(cont.)*

## IEEE Std. 1159 - 1995

| Categories | | Typical duration | Typical voltage magnitude |
|---|---|---|---|
| Short duration variations | Instantaneous Sag | 0.5 - 30 cycles | 0.1 - 0.9 pu |
| | Instantaneous Swell | 0.5 - 30 cycles | 1.1 - 1.8 pu |
| | Momentary Interruption | 0.5 cycles - 3 sec | < 0.1 pu |
| | Momentary Sag | 30 cycles - 3 sec | 0.1 - 0.9 pu |
| | Momentary Swell | 30 cycles - 3 sec | 1.1 - 1.4 pu |
| | Temporary Interruption | 3 sec - 1 min | < 0.1 pu |
| | Temporary Sag | 3 sec - 1 min | 0.1 - 0.9 pu |
| | Temporary Swell | 3 sec - 1 min | 1.1 - 1.2 pu |
| Long duration variations | Interruption, sustained | > 1 min | 0.0 pu |
| | Undervoltages | > 1 min | 0.8 - 0.9 pu |
| | Overvoltages | > 1 min | 1.1 - 1.2 pu |

# Analysis of Sags/Swells/Interruptions *(cont.)*

Several parameters of power quality events are necessary to be identified:

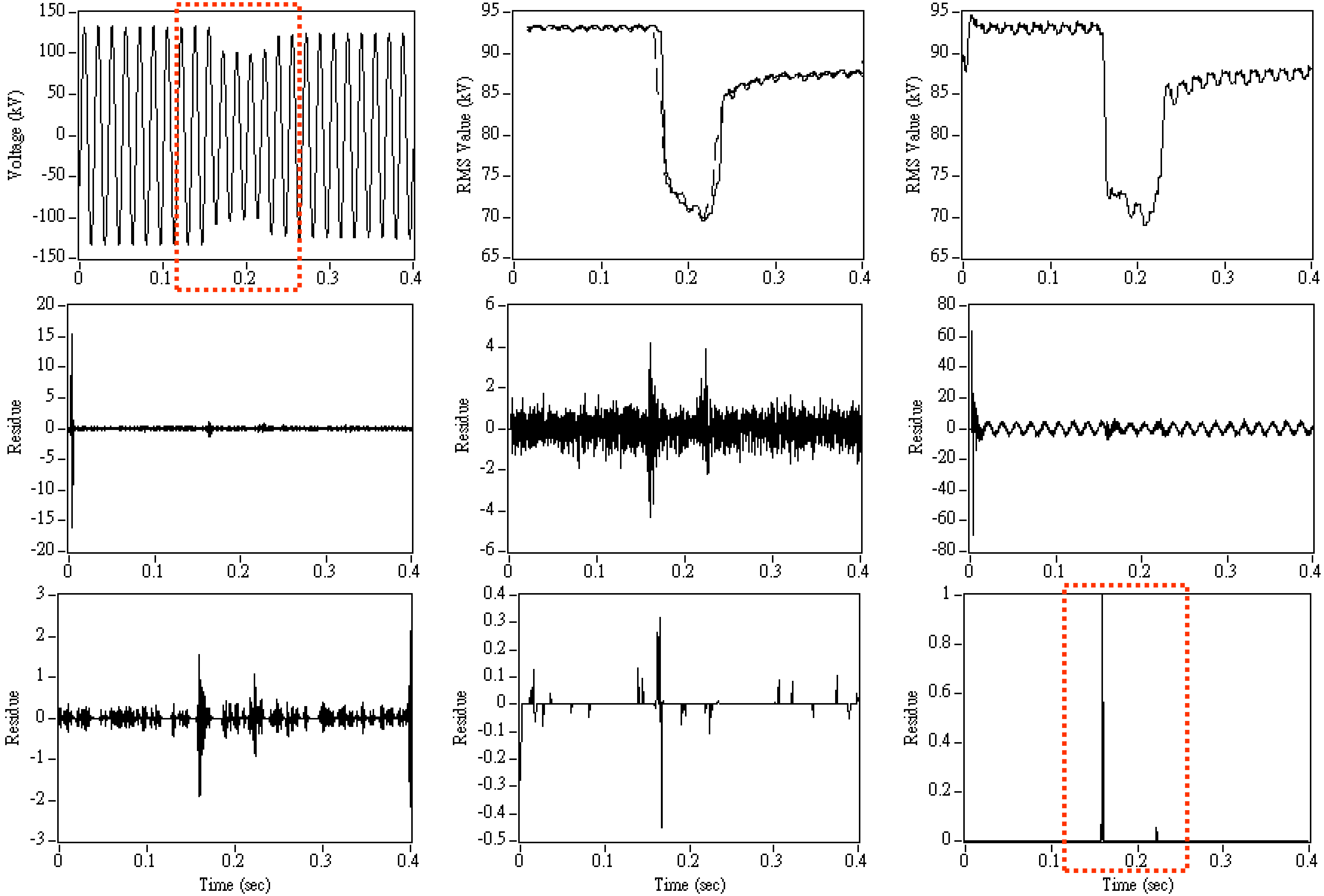
- Starting-time localization of events
- Ending-time localization of events
- Duration of events
- Classification of events
- Variation of events

# Analysis of Sags/Swells/Interruptions *(cont.)*

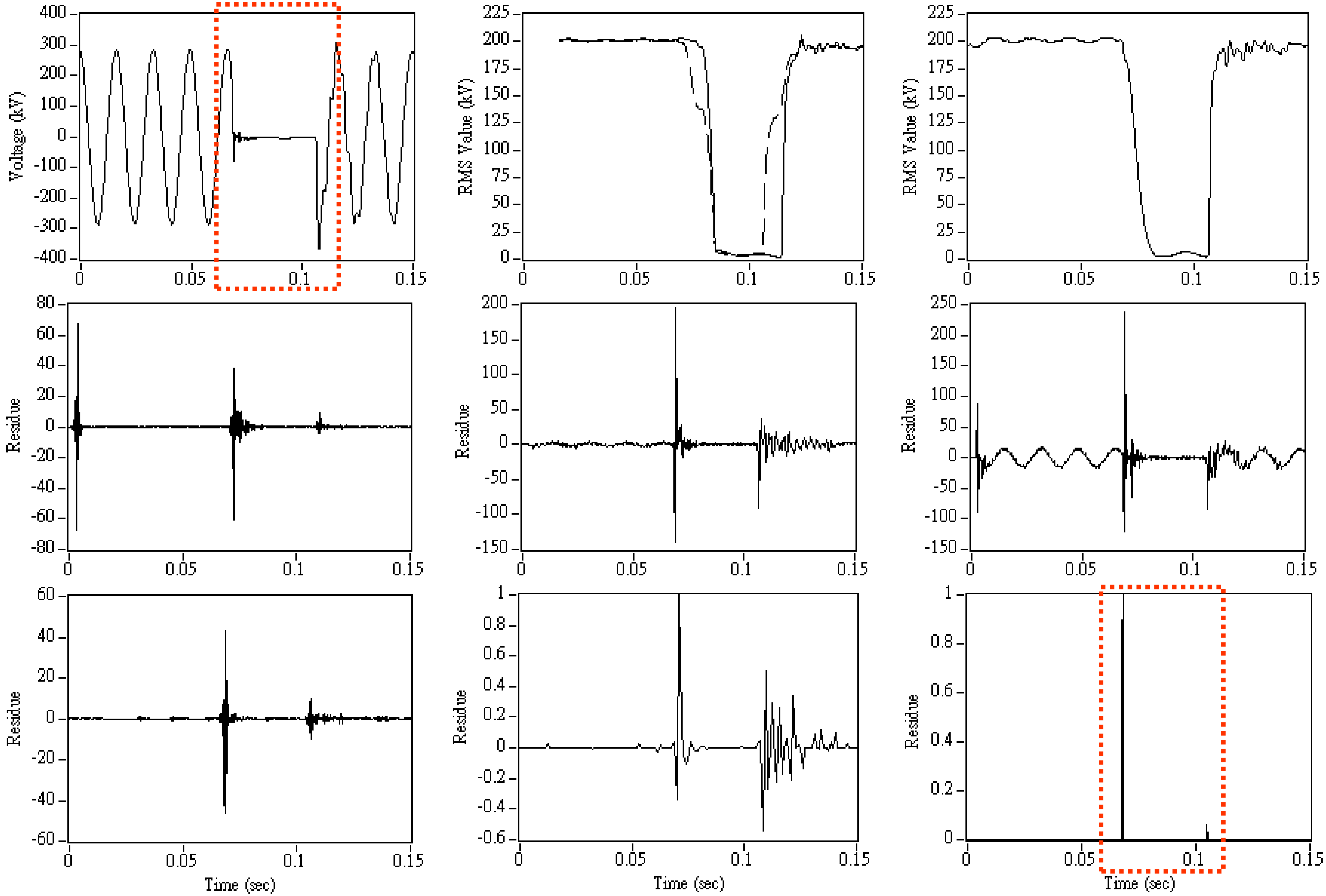
Commonly seen approaches:

- Direct Estimation of RMS Value
- ADALINE Detection Method
- High-pass Filtering
- Autoregressive (AR), Moving-Average (MA), and ARMA Models
- Wavelet Analysis
  - Squaring Method
  - Shrinkage Method
  - Inter-scale Dependency
- New Approach

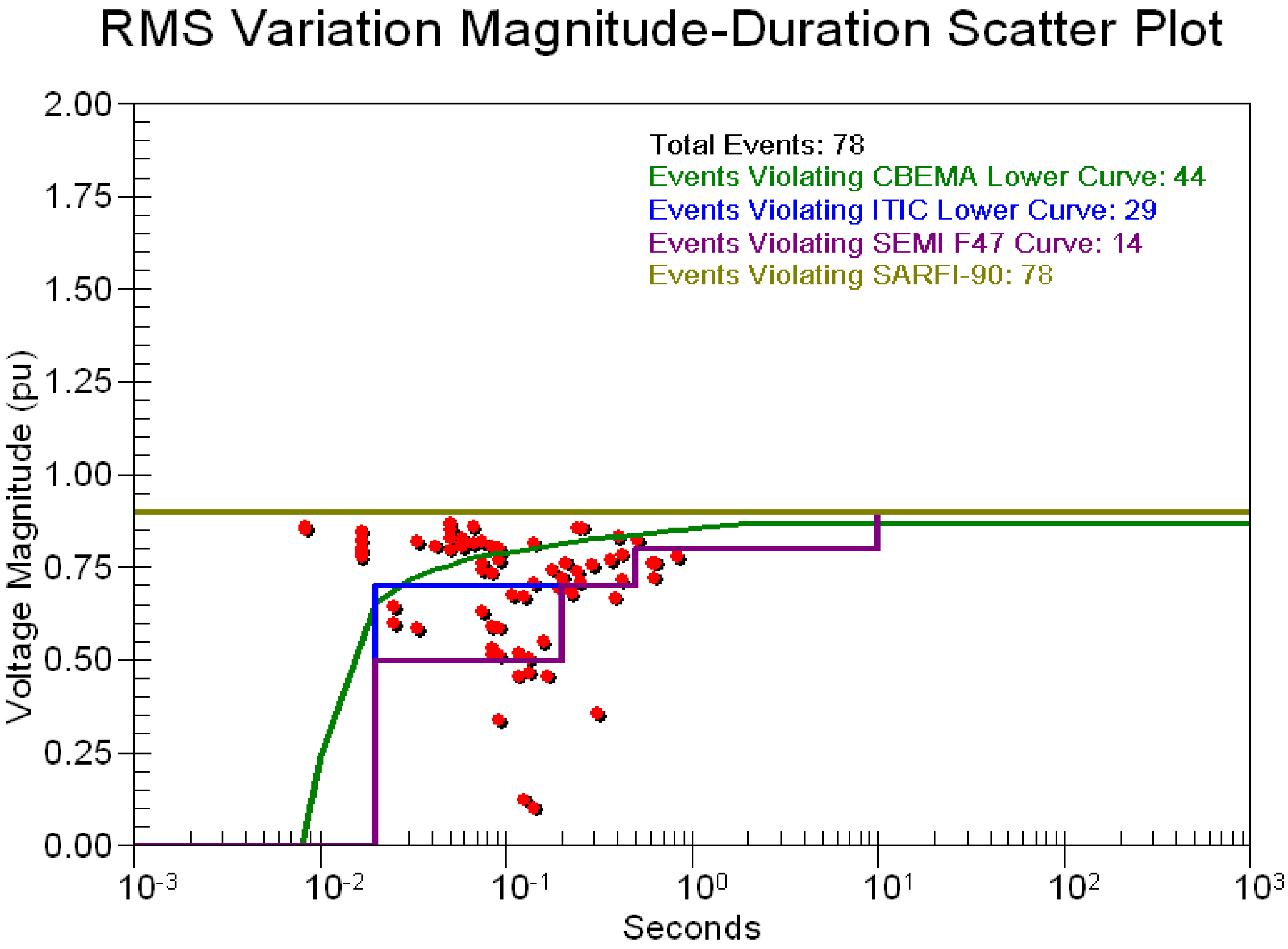
# Case Studies *(Case 4)*



# Case Studies *(Case 5)*



# Case Studies *(cont.)*

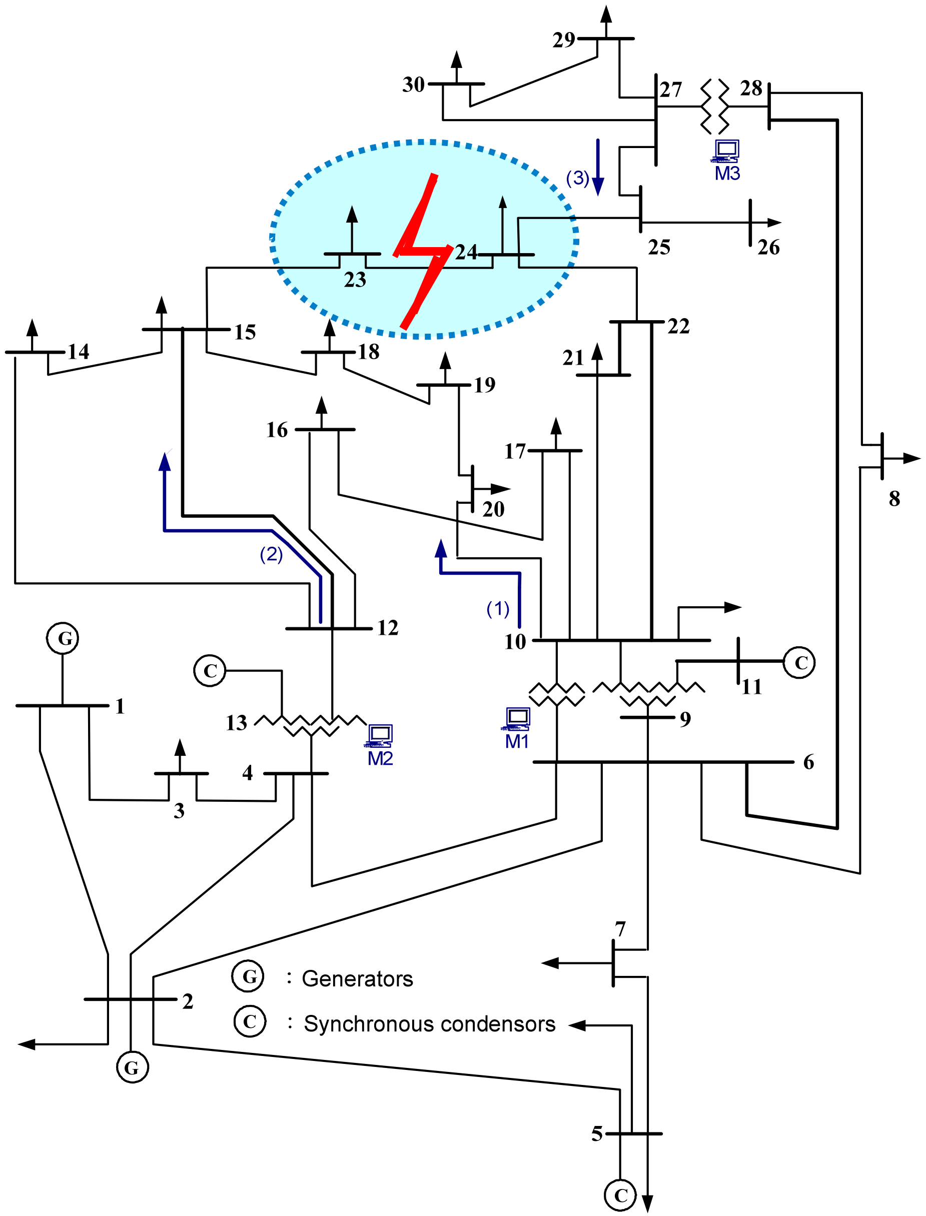


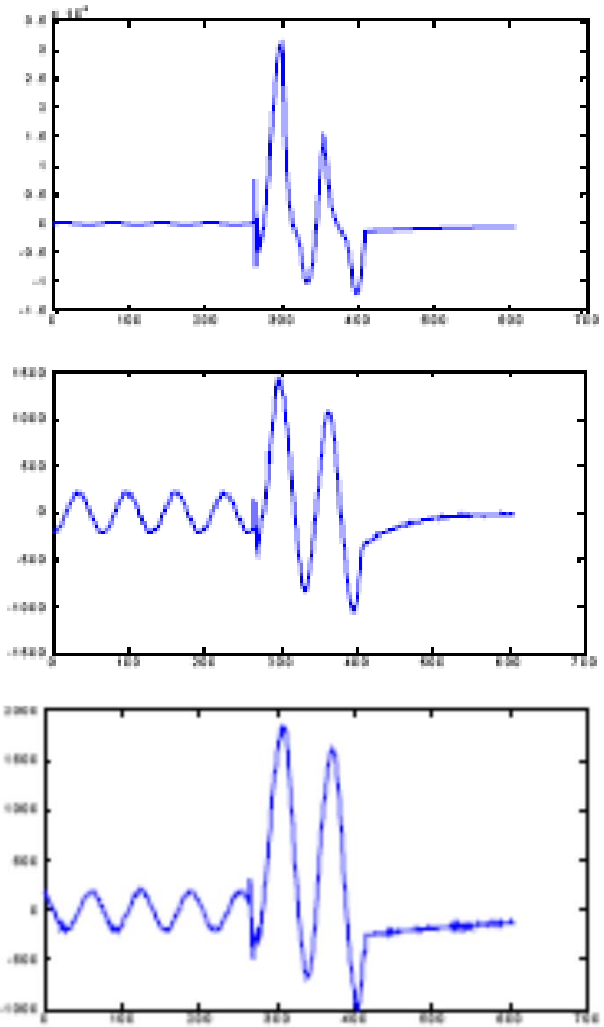

**Scatter plot with recorded voltage sags indicated**

# More PQ Measurement Issues

| More Smart Grid PQ Measurement Issues |
| --- |
| (1) Smart Meter with Advanced PQ Analysis Functions |
| (2) Wide Area Monitoring Scheme with PQ Disturbance Identification and Remedy |
| (3) Integration of Measured PQ Data and Database Design |
| (4) Tracking PQ Disturbances and Real-time PQ Analysis |
| (5) Deployment of Advanced PQ Meters in Power Network |
| (6) Embedding Advanced PQ Monitoring Functions in Substation/Feeder Automations |
| (7) Commutation Protocols for PQ Monitoring |
| (8) PQ-related Standards Development |
| (9) Measurement and Analysis of PHEV-related PQ Impacts on Distribution System |

# Smart PQ Disturbance Source Location Tracking/Identification



# Conclusions

- Future measurement devices under Smart Grid shall include functions for
  - Power Quality
  - Energy metering
  - Asset condition monitoring
  - Operational status monitoring
- Improved communications between different measuring devices are essential
- Data management of PQ assessment will be a challenge
- Better understanding of PQ emissions and network asset conditions
- Optimization of asset usage by customers
- Need effective metrics for assessment of PQ measuring progress


# *Thank You!*

wchang@ee.ccu.edu.tw

http://140.123.111.49/teacher/main33.htm