*Session L3*

# The FREEDM System: components, main functions, system control

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# Topics for this tutorial

## Lecture L3

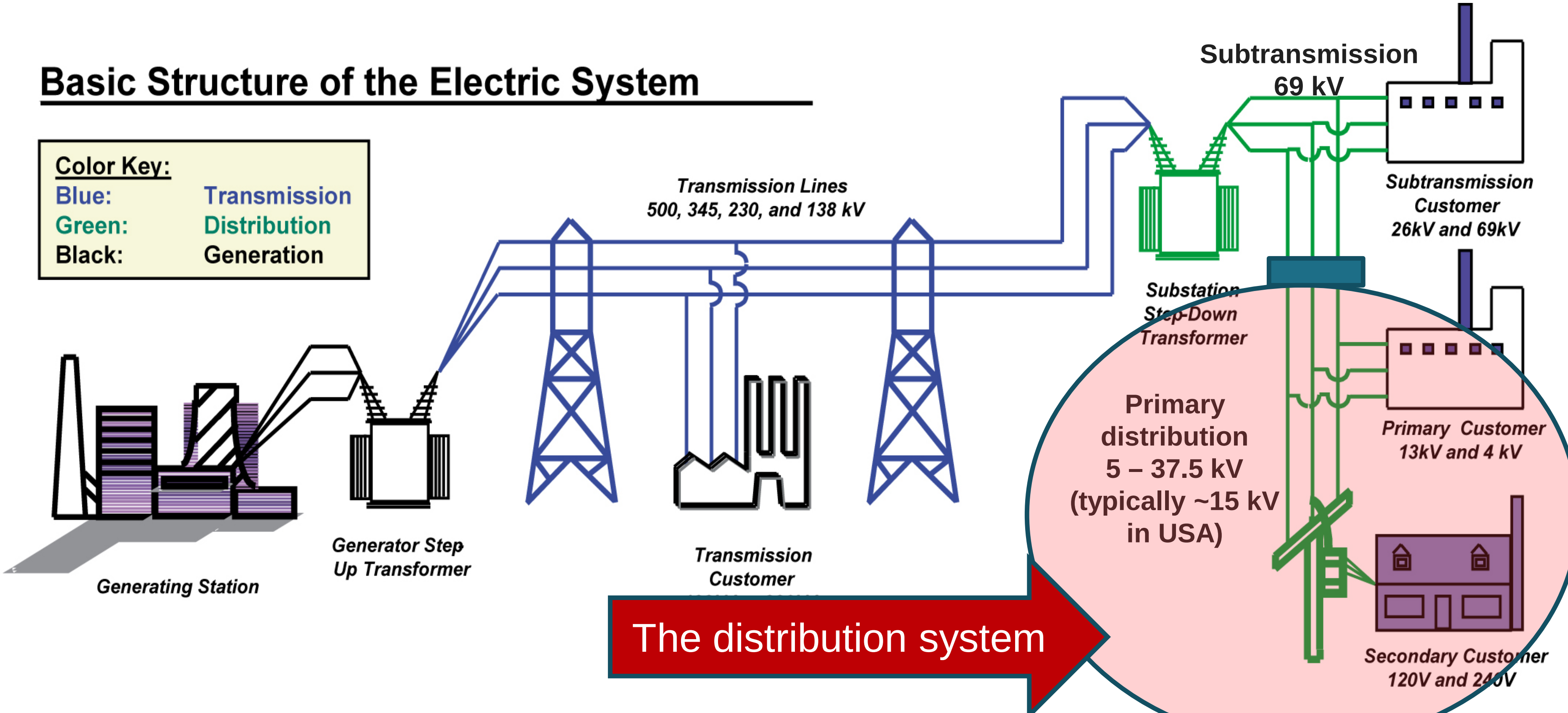
A. **Traditional distribution systems, strengths, weaknesses**

B. Overview of the FREEDM system

C. Description of two key FREEDM components: the solid state transformer (SST) and the fault interruption device (FID)

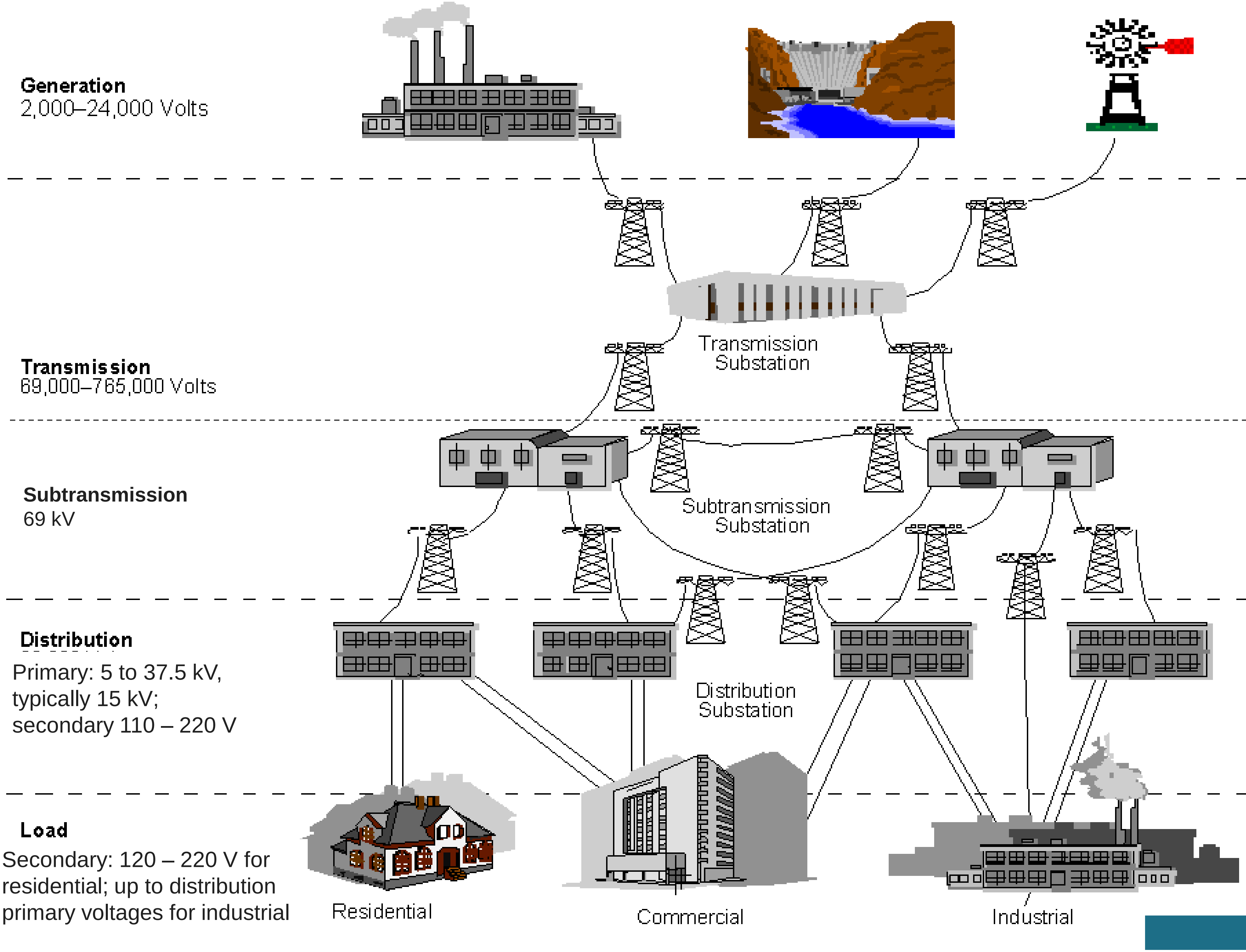
D. Some features of the distribution system of the future: pricing, cost / benefit, reliability

# Overview: the role of the distribution system




The entire electric power system consists of three major subsystems

– Generation system
– Transmission system (and the subtransmission system)
– **Distribution system**



Generation
2,000–24,000 Volts
Transmission
69,000–765,000 Volts
Transmission Substation
Subtransmission
69 kV
Subtransmission Substation
Distribution
Primary: 5 to 37.5 kV, typically 15 kV; secondary 110 – 220 V
Distribution Substation
Load
Secondary: 120 – 220 V for residential; up to distribution primary voltages for industrial
Residential
Commercial
Industrial

# Some characteristics of conventional distribution systems

- The primary distribution system is usually three phase, in the 15 kV class, and often rated 1 to 10 MVA
- The length of the distribution primary is generally 1 to 10 miles
- The system is usually ‘radial’ – this means that there is one source (at the substation) and many loads spread out ‘downstream’
- The radial system has branches off of the main circuits, and these are usually single phase. These are called ‘laterals’
- Loads are served at lower voltage than the 15 kV three phase: this is accomplished using distribution transformers.
- The loads are often classified into commercial, industrial, and residential. In the US nationwide, about 15% are commercial, 65% are industrial, and 20% are residential (by annual energy served)
- Many of these distribution systems were built over 40 years ago
- “Distribution secondaries” are the low voltage circuits (e.g., 120, 220 V, single phase or three phase) which serve loads

# Conventional contemporary distribution systems

**Strengths**

- **Many years of experience with this design**
- Large scale manufacturing of needed components
- **Generally acceptable reliability and cost**
- Reasonable safety record

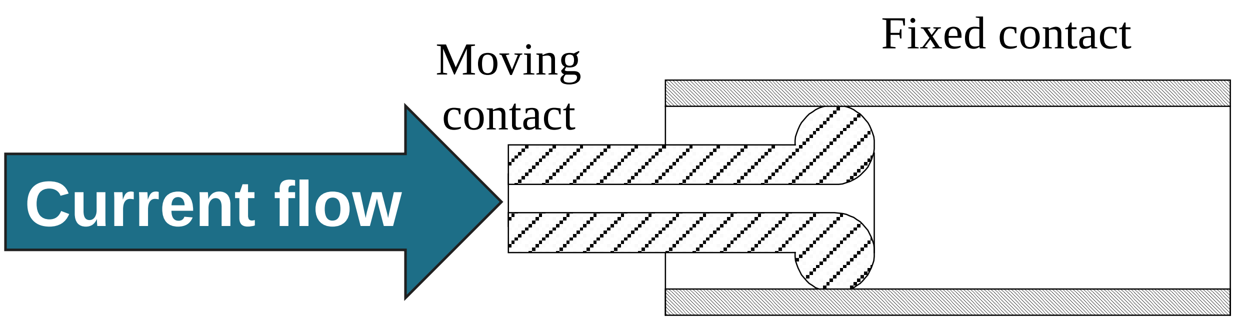
**Weaknesses**

- **Does not accept renewable resources** (e.g., solar photovoltaic) very well – especially at high penetration
- Active power loss in the primaries and distribution transformers is in the 4% range
- **No control capability**
- Requires voltage regulators and shunt capacitors to support voltage
- Little (or no) instrumentation in the system (except the watt-hour meter)
- Much of the system is operated **manually**

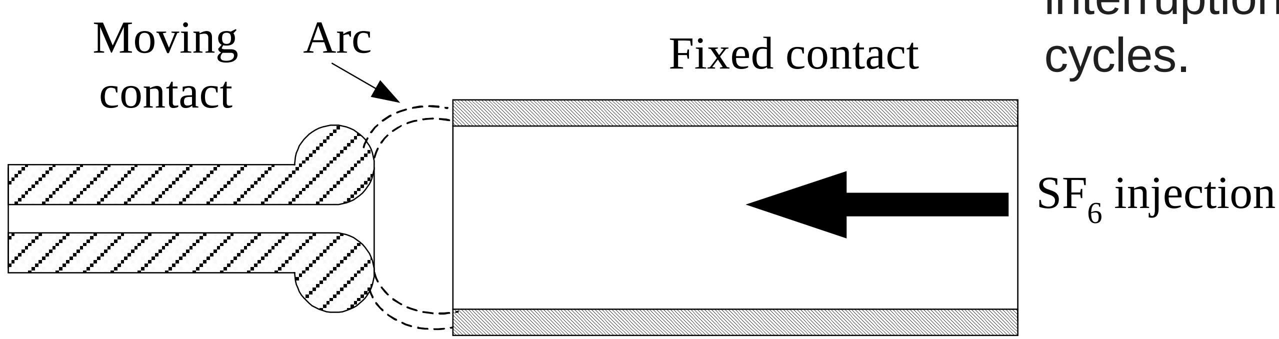
# A substation transformer


The distribution primaries are energized by substation transformers, typical rating: 69 kV / 13.8 kV, 160 MVA, 16 distribution circuits energized.

# $SF_6$ circuit breaker concept




**Switch Closed**

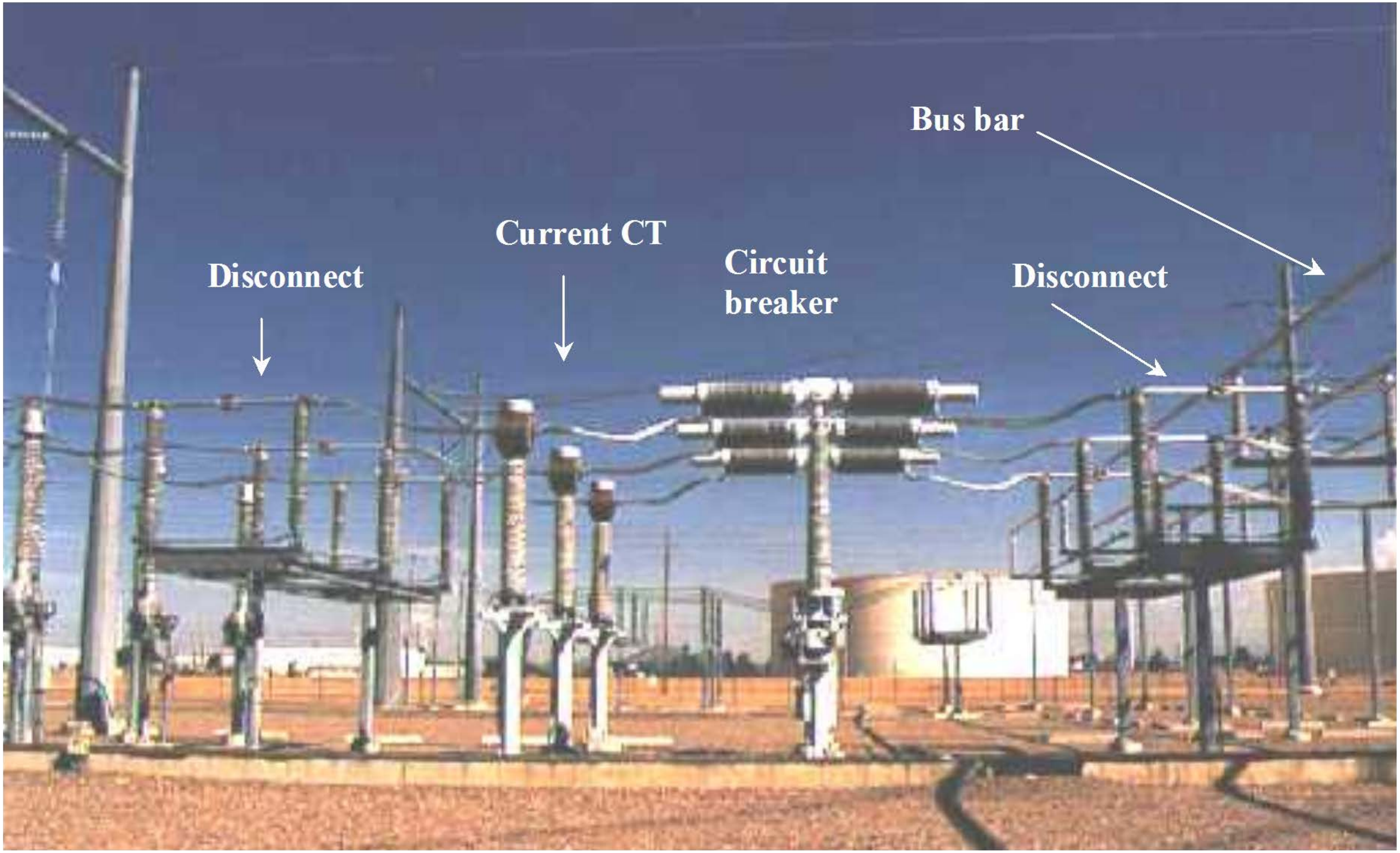



**Switch Opens**

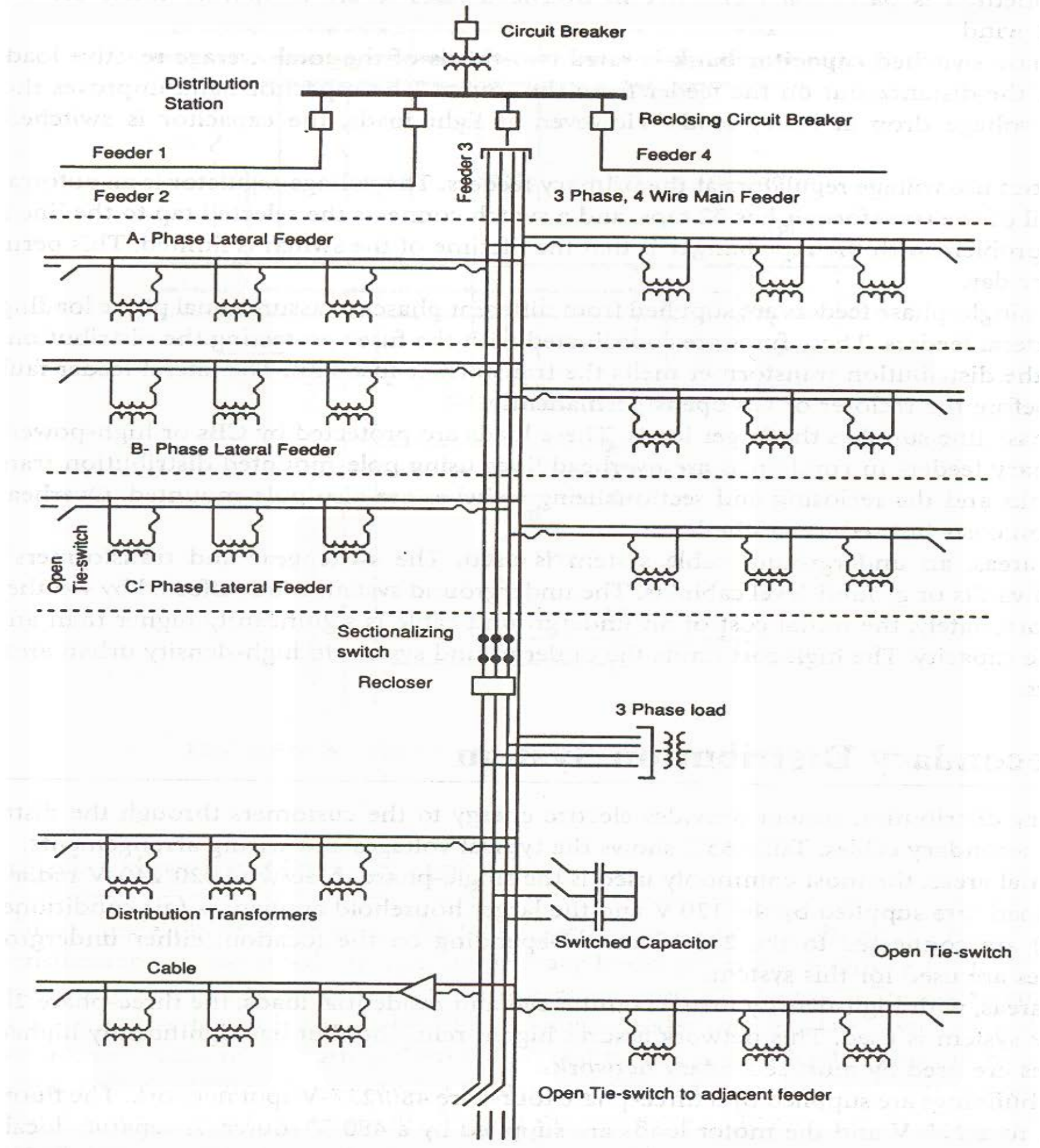
These circuit breakers are switches that can interrupt full fault current (very high currents). In a typical distribution system, there is only one circuit breaker – and this is at the substation at the root of the distribution primary feeder. A typical interruption current is about 800 A. These are three phase units. Typical interruption time: about 5 cycles.

# 69 kV substation

## this is the usual voltage for the subtransmission system



# A typical classical 'legacy' radial distribution system

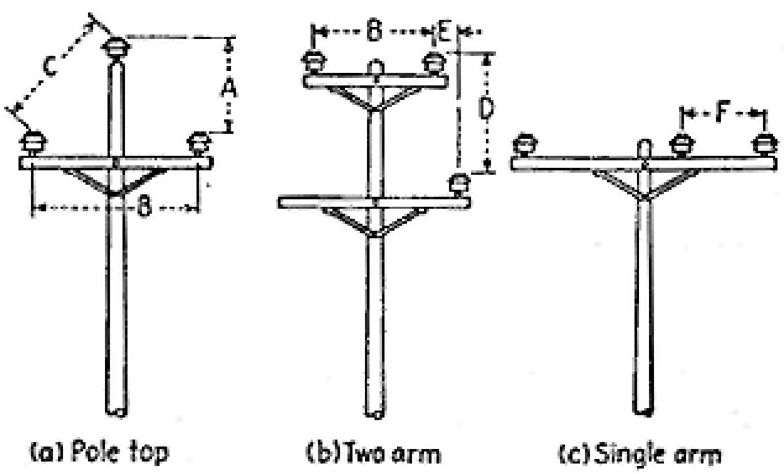


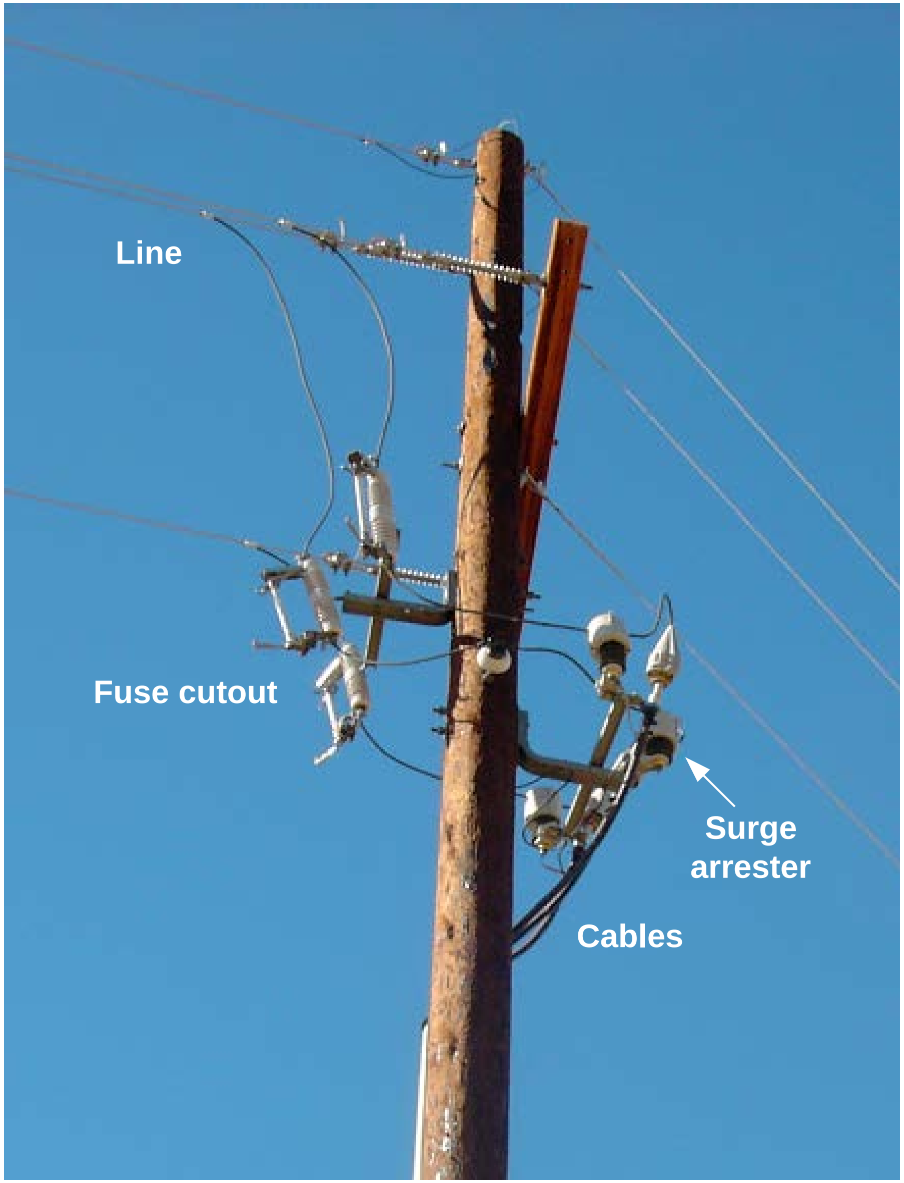
# Distribution lines

**Overhead distribution line (e.g., 4.2-45 kV)**

- Wood tower with cross arm. The wood is treated against rotting. (creosote).
- Simple concrete block foundation or no foundation.
- Small porcelain or plastic post insulators.
- The insulators shaft is grounded on important lines to eliminate leakage current causing wood tower burning.
- Simple rod grounding.
- Shield conductor is seldom used.

Typical distribution line

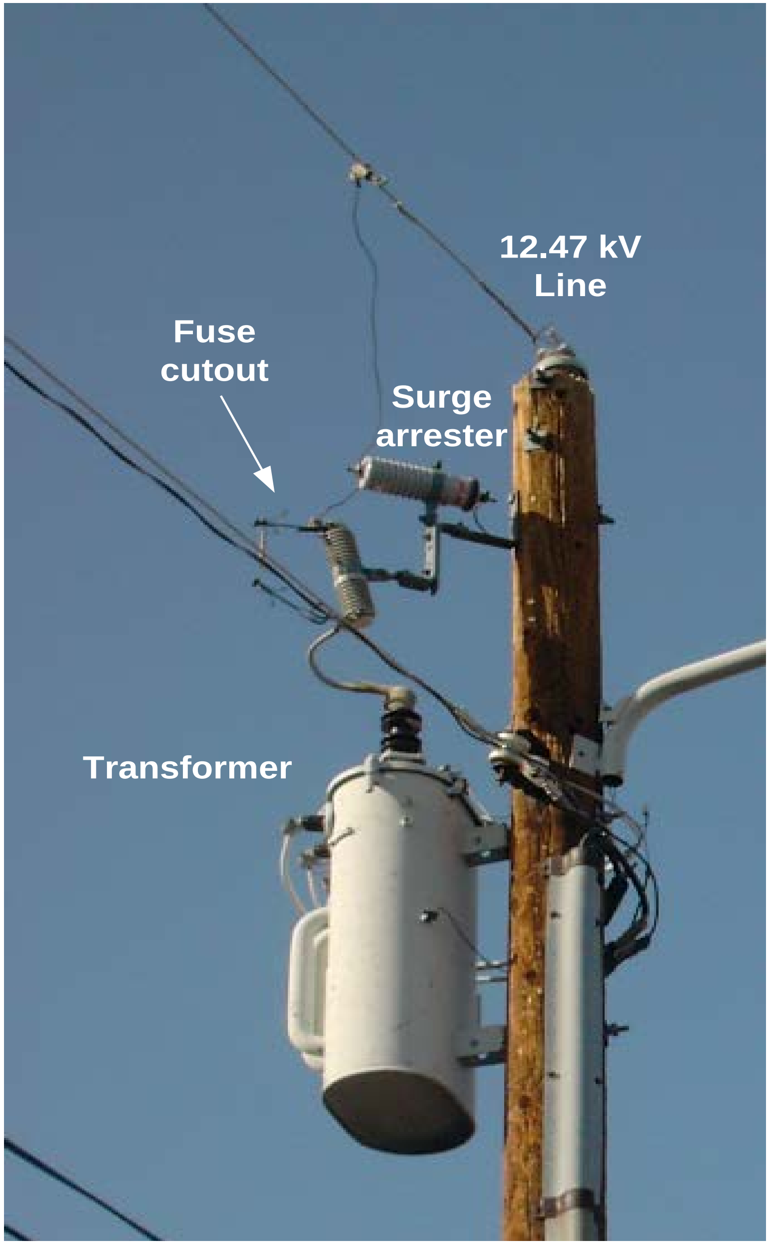





# Cable and distribution line junction

Underground circuits and service drops are desired – but may be costly and may have undesirable maintenance characteristics.

Fuses are used for protection.  An opened fuse is generally visible from ground level.




# Consumer service drop

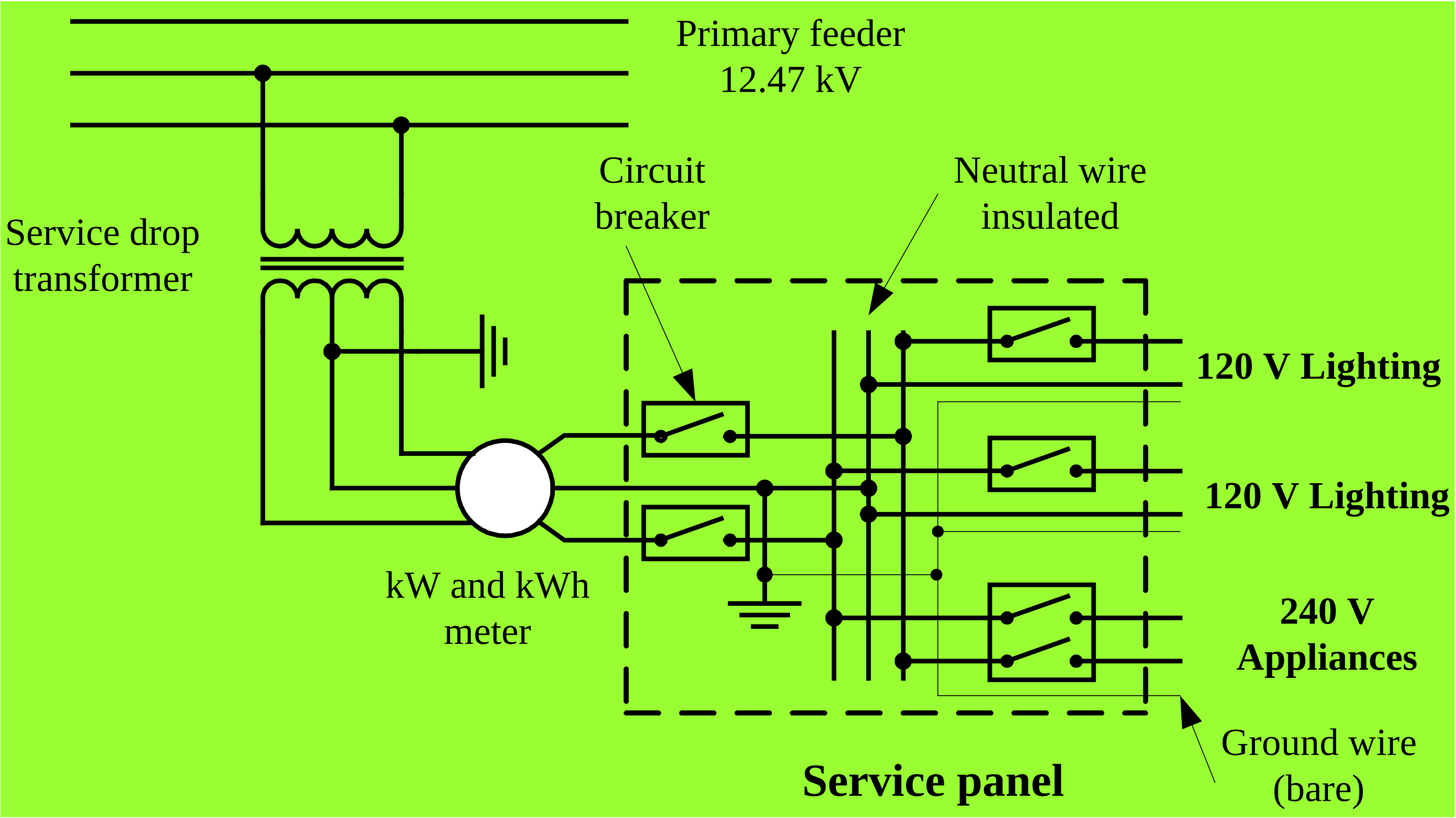
Conventional magnetic transformers often serve 5 to 15 residences. Commercial and industrial customers usually have a single distribution transformer. Surge arresters are used to comply with Basic Impulse Level (BIL) requirements (about 60 kV for most US systems). A typical distribution transformer that serves five residences is rated 50 kVA. A typical distribution transformer for a commercial customer like K-Mart is about 1000 kVA.

# Distribution line


# Residential distribution transformer

typically 25 to 100 kVA

# Typical residential connection in the USA



# Residential metering


## Residential watt-hour meter

Caution:

Power = watts

Energy = watt-hours

Most US residential electrical meters are read ‘manually’ by a meter reader. These can only measure energy used in a given interval.

Smart meters are rapidly being deployed. These may be read remotely, and they also give energy use in 15 minute intervals.

# Why change the traditional design?

The **SMART GRID** initiative requires that the customer may have renewable generation resources – solar photovoltaic

The **SMART GRID** initiative requires that operators have greater control capability in distribution systems

Also:
Use newer technologies to improve system performance and reliability

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# Cost to benefit analysis

- Much of the electric power business is cost / benefit driven
- Regulated electric utilities need to derive monetary benefits that offset expenditures and investments
- Meanwhile the utility companies need to achieve their ‘renewable portfolio goals’ – these are targets for renewable electric energy production
- Some targets for recovering investments in United States business ventures are sooner than 10 years.
- There are many uncertain / approximate factors that are difficult to evaluate in dollar terms.

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# Reliable operation of the grid

Maintaining reliability is a complex enterprise that requires trained and skilled operators, sophisticated computers and communications, and careful planning and design.

There is a cost / benefit associated with power system reliability. Would you pay double your present electric bill if you were guaranteed zero outages? Or would you elect to pay half your bill if you could be interrupted for up to an hour per month? The issue is unresolved.

The North American Electric Reliability Corporation (NERC) and its ten Regional Reliability Councils / Corporations have developed system operating and planning standards for ensuring the reliability of a transmission grid that are based on seven key concepts:

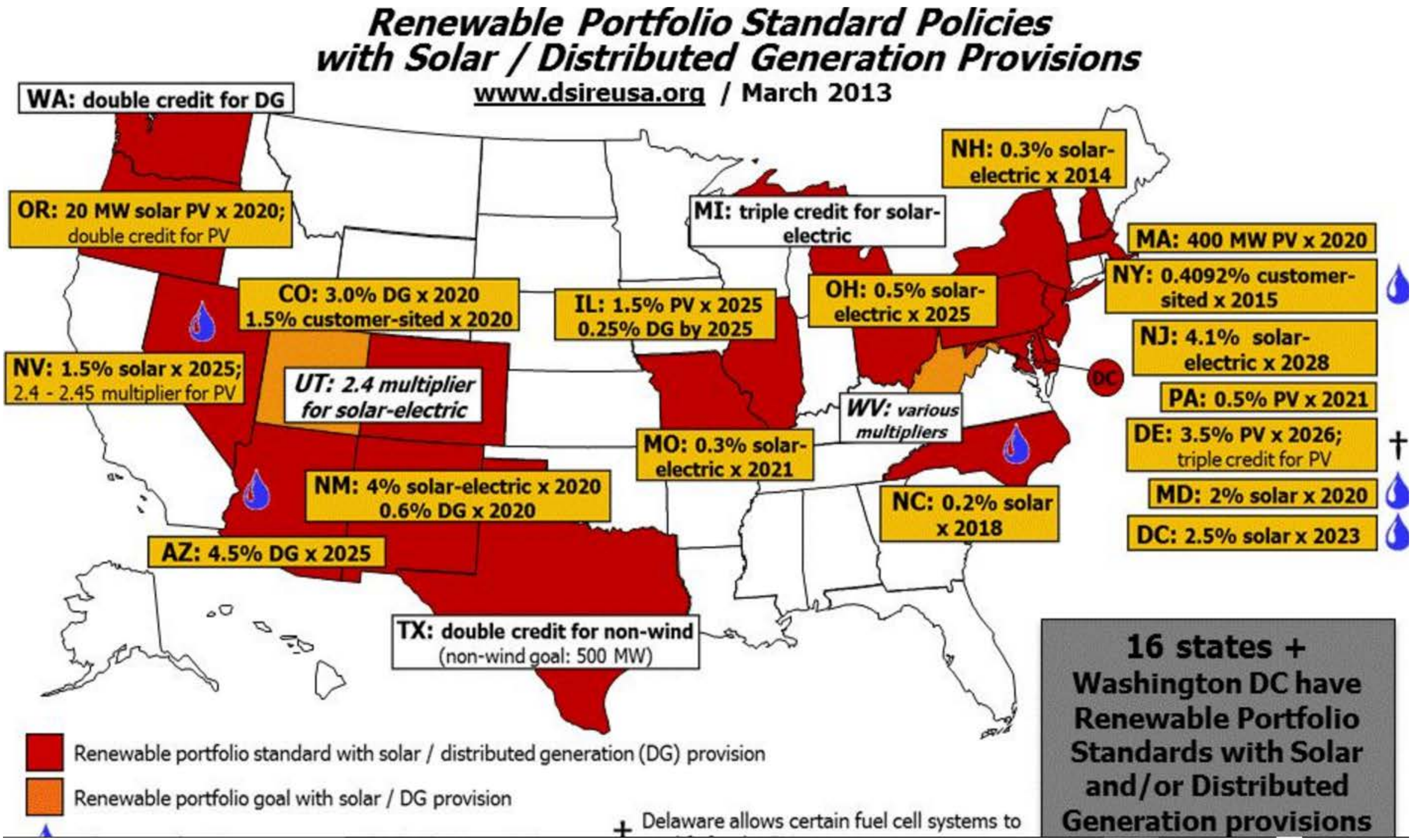
# Reliable operation of the grid

1. Balance power generation and demand continuously
2. Balance reactive power supply and demand to maintain scheduled voltages
3. Monitor flows over transmission lines and other facilities to ensure that thermal (heating) limits are not exceeded
4. Keep the system in a stable condition
5. Operate the system so that it remains in a reliable condition even if a contingency occurs, such as the loss of a key generator or transmission facility (the "*N*-1 criterion")
6. Plan, design, and maintain the system to operate reliably
7. Prepare for emergencies.

## Balance of power

- Production by the generators must be scheduled or "dispatched" to meet constantly changing demands
- Typically on an hourly basis, and then fine-tuned throughout the hour.
- Automatic generation controls used to continuously match generation to actual demand.
- Demand is somewhat predictable (daily demand curve), highest during the afternoon and evening and lowest in the middle of the night, and higher on weekdays when most businesses are open.

# The renewable portfolio standards



# A sampling of residential electric energy costs costs worldwide

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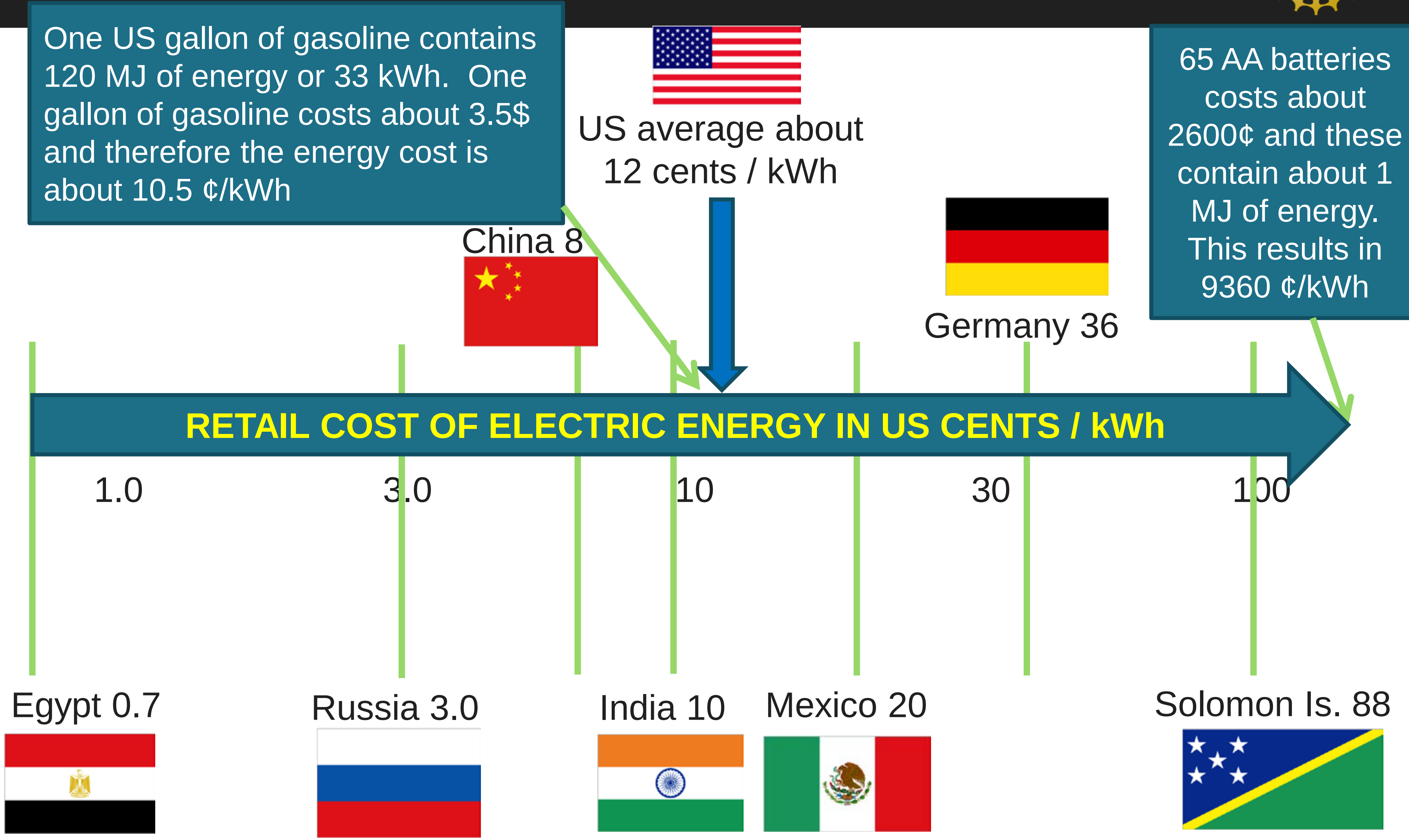



Data shown are all in US cents per kWh

# The FREEDM benefits

**Accommodate High Penetration of Distributed Generation**
- Effective Volt / Var Control
- Plug and Play
- ES + DGI

**High Reliability and PQ**
- Looped Primary
- Fault Locating, Isolation, Service Restoration
- Fast Protection with FID
- Regulate Service voltage

**Real Time Monitoring and Control**
- Enhanced System Monitoring and Control
- CVR

**Resiliency**
- Microgrid at Node, Feeder Section, Whole Feeder

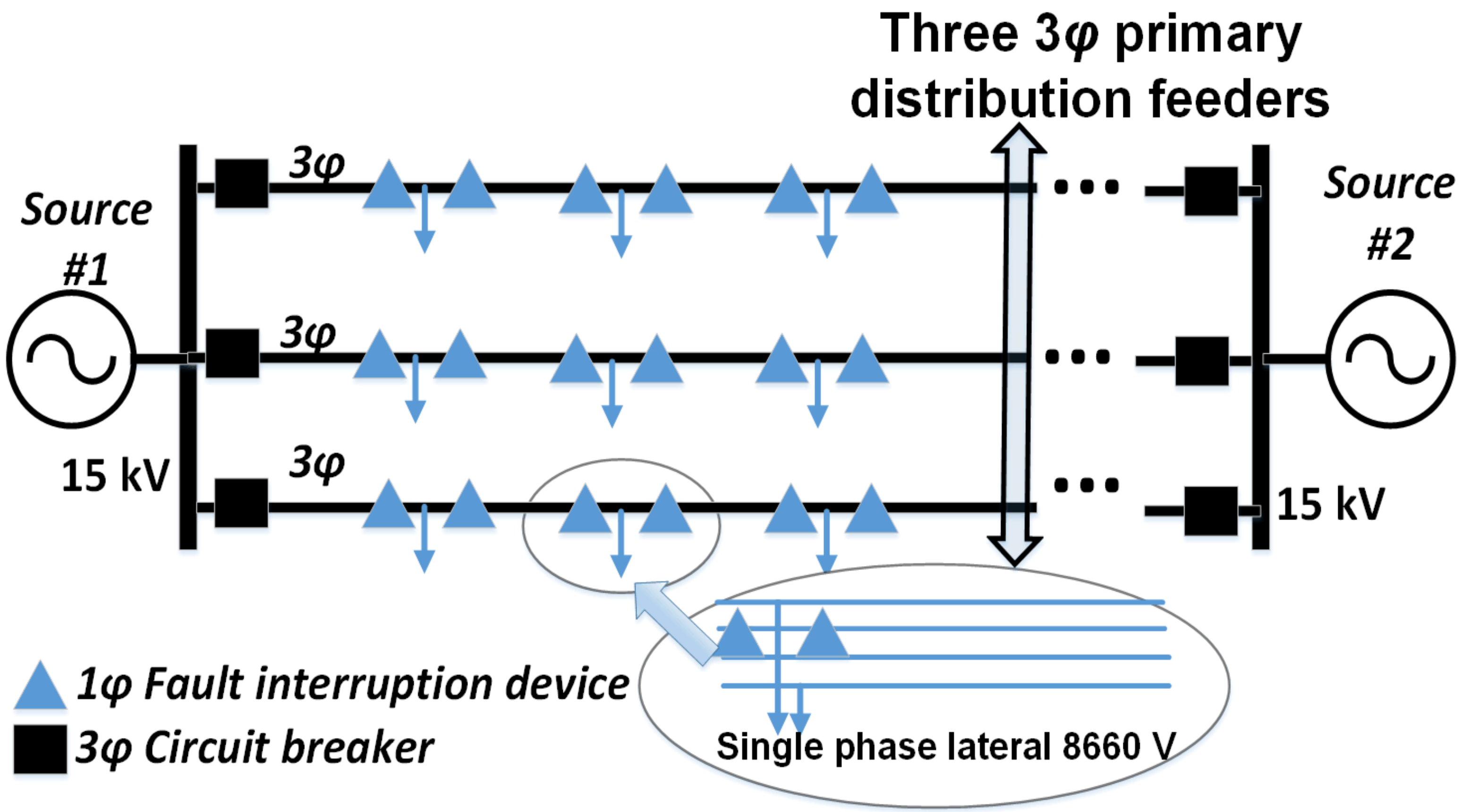
**Customer Participation**
- DGI- Price Signals DLMP

**Motivate New Business**
- Transactive Energy

# FREEDM features - benefits

| FREEDM System Features/Functions | Benefit | Type | | | |
|---|---|---|---|---|---|
| | | Economic | Reliability & PQ | Societal | Security |
| **Accommodate High Penetration**<br>- **Effective Volt / Var Control**<br>- **Plug and Play**<br>• **ES + DGI** | - mitigate voltage issues<br>- reduce power loss<br>- simplify DER integration<br>- Mitigate variability of power | • | | • | • |
| **High Reliability and PQ**<br>• **Looped Primary**<br>• **Fault Locating, Isolation, Service Restoration**<br>- **Fast Protection with FID**<br>- **Regulate Service voltage** | VH reliability<br>Minimize fault impact on comp.<br>VH PQ | | • | | |
| **Real Time Monitoring and Control**<br>- **Enhanced System Monitoring and Control**<br>- **CVR** | - Advanced DSM<br>-Reduced O&M<br>-optimal capacity use<br>- Load management: peak demand and energy reduction | • | | | |
| **Resiliency**<br>• **Microgrid at Node, Feeder Section, Whole Feeder** | | | • | • | |
| **Customer Participation**<br>• **DGI- Price Signals DLMP** | • Customer DSM<br>- Peak demand reduction<br>- Economic efficiency | • | | | |
| **Motivate New Business** | | | • | • | |

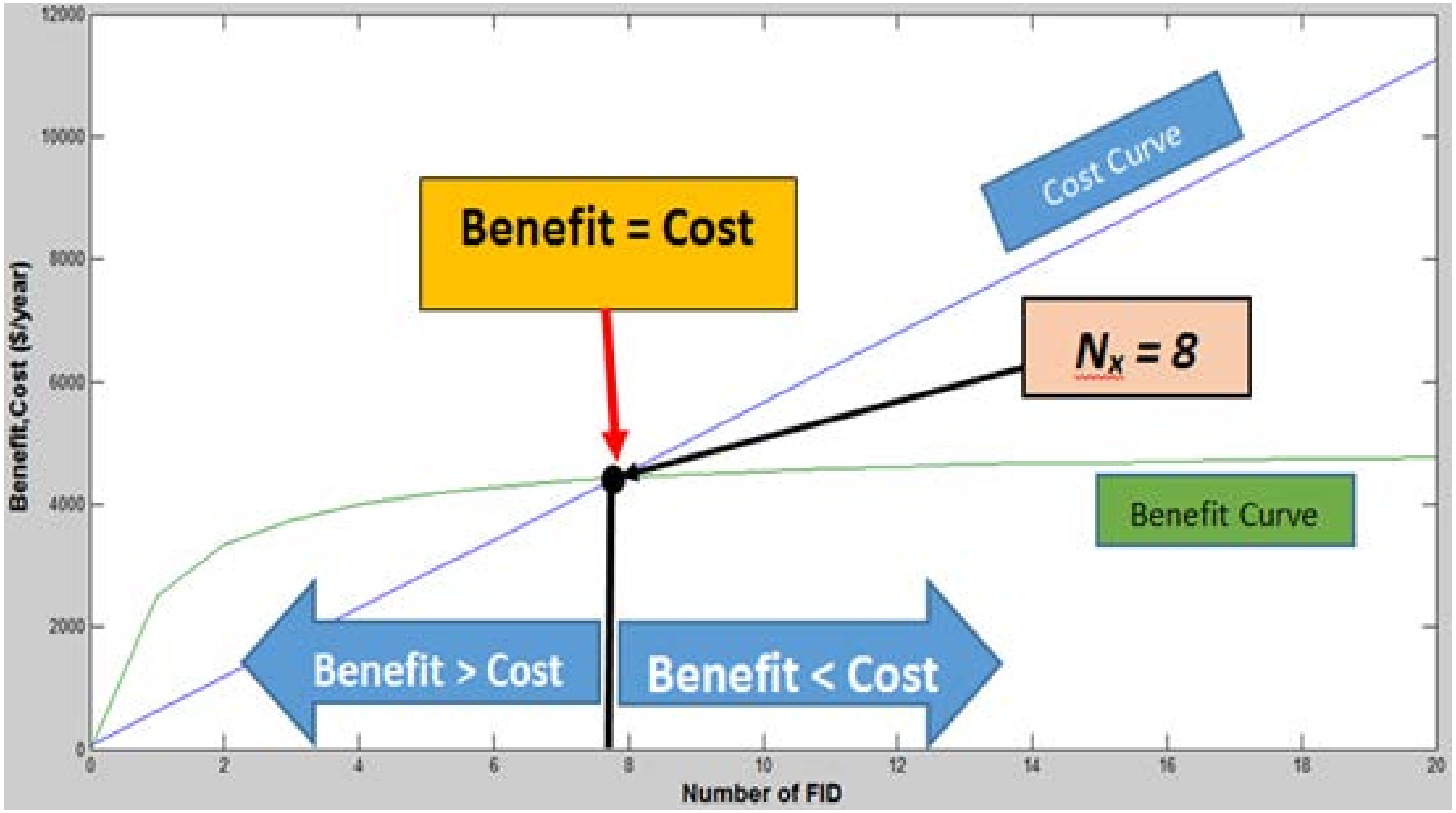
# Alternative deployments of the FREEDM system




There are a number of alternative circuit configurations for the deployment of FREEDM. This diagram shows one such configuration. The various alternatives should vbe compared for their cost / benefit characteristics

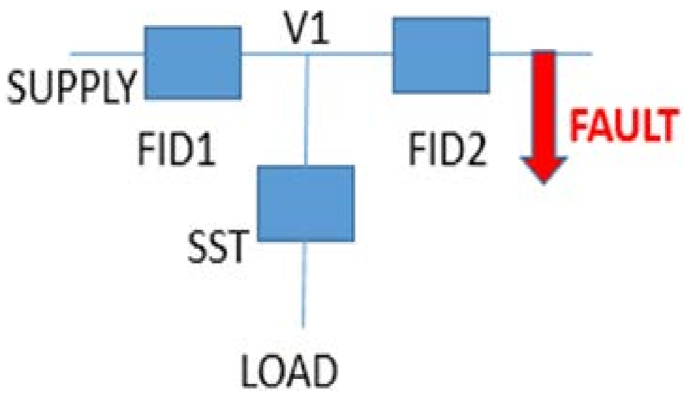
# Tradeoffs in the use of fault interruption devices

The use of FIDs has been recommended because these electronic FIDs allow the high speed interruption of faults, thereby allowing loads to operate normally and within CBEMA / ITIC requirements. A typical configuration of the FREEDM system is illustrated with the cost of the FIDs shown. The benefit is the benefit obtained by avoiding outages (i.e., > one-half cycle duration low voltage events). Three alternative configurations of the FREEDM system were studied, and results tabulated both by testing and via system theoretic analysis.



# Energy storage to alleviate the number of FIDs

A fault in a distribution system must be cleared so that the system voltage does not drop to a low value and becomes inconsistent with the CBEMA / ITIC curves. In general, a circuit breaker takes ~6 cycles to clear a fault. An FID clears the fault quickly but the associated cost is high. The concept studied to alleviate the cost of the FIDs is to use an energy storage device of the order of 5 kWh in the solid state transformer (SST) to serve the load during a fault. This then allows the avoidance of the FID but attainment of the CBEMA / ITIC requirements.




- FID2 opens in about 100 μs
- Voltage V1 is 'low' for shorter than ½ cycle
- The load is **NOT** 'lost' as per CBEMA / ITIC

A substantial savings is attainable through the avoidance of electronic FIDs through the use of a 5 kWh class energy storage element (e.g., a battery) as a DC input to the FREEDM SST. This conclusion is obtained using the system average interruption duration and system average interruption frequency indices (SAIDI and SAIFI).

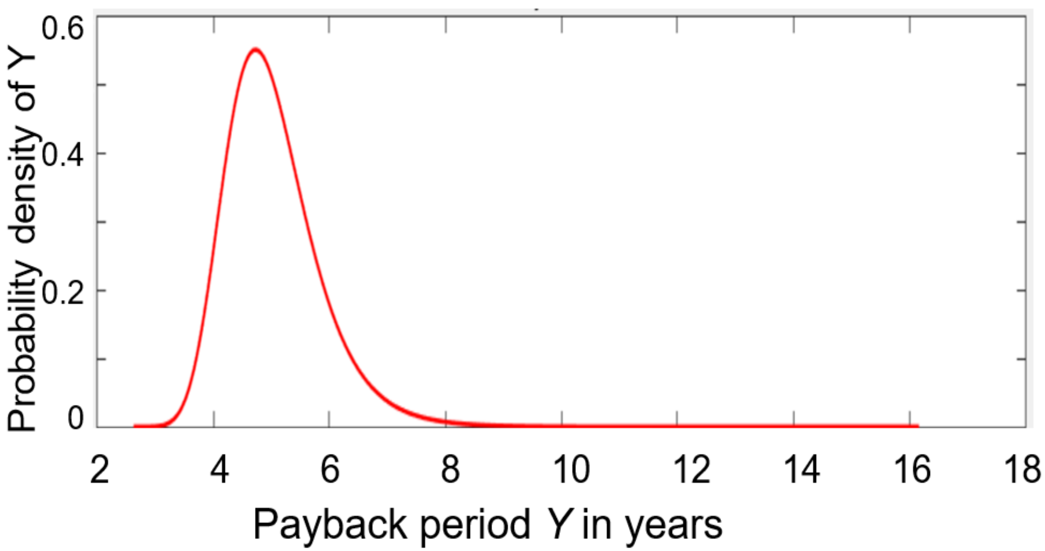
# Costs of the FREEDM system

## an example calculation of the cost of a 1ϕ SST

| SST Actual Construction Cost<br>Rating: 20 kVA | | |
|---|---|---|
| **Conservative Design** | | |
| Rectifier | | 8,282 |
| DC → DC converter | | 6,549 |
| DC → AC converter | | 2,110 |
| Sensors and controllers | | 1,244 |
| Total | $ | 18,185 |
| | | |
| **Optimal Design** | | |
| Total | $ | 9,093 |

# Probabilistic formulation of the cost / benefit analysis

One useful metric in cost / benefit analysis is the calculation of the payback period. If Y = C / B, Y = payback period, C = initial investment, B = benefit per year accrued, then Y is called a 'ratio distribution' when C and B are probabilistic.




Statistics of cost and benefit in an example

| | Cost C | Benefit B |
|---|---|---|
| **Mean, μ** | 26000 $ | 5500 $/y |
| **Standard deviation, σ** | 1250 $ | 750 $/y |

Probability density function of the payback period *Y* for this example. This is found using a system theoretic approach.