Fault Studies and Protection

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Fault (Symmetric or Unsymmetric) on a Balanced Network

1st - Motivation

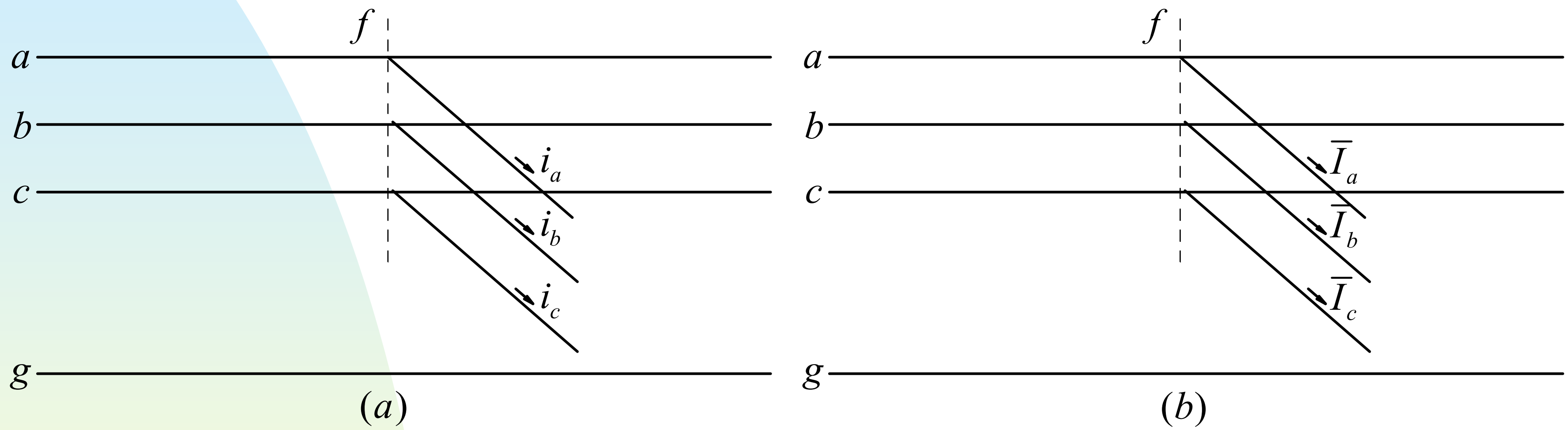


Fig. 13-1 Fault in power system.

1. Single line to ground fault (over 80% of faults, due to tree falling on line, line breakage etc.).
2. Line to line fault (lines touching in heavy winds, ice, debris falling across two lines).
3. Double line to ground fault (two lines falling due to falling trees).
4. Three-phase to ground fault (complete tower collapse, debris across all three lines).

(First three faults are asymmetric faults. Number four is a symmetric fault.)

Symmetric Faults

Faulted systems with generators and motors may be solved by two methods:

- By use of subtransient and transient voltages (for very small systems).
- By Thevenin's Theorem using superposition (more practical for large systems).
  - -Find the system admittance matrix
  - -Invert to create the system impedance matrix
  - -main diagonal is the Thev. Equivalent impedance at that bus, $I_f = V_f/Z_{kk}$

Symmetrical Components

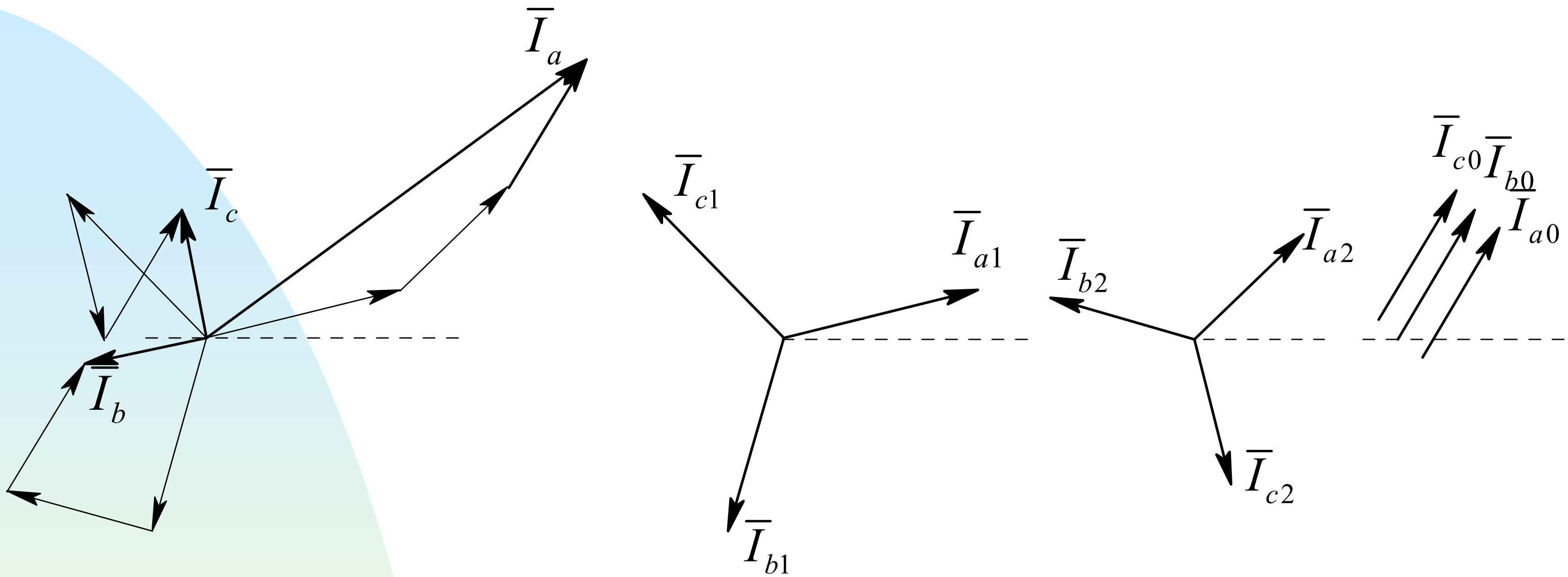


Fig. 13-2 Sequence components.

Asymmetrical faults cause unbalanced currents and voltages, therefore we use Symmetrical Components to determine the currents and voltages after a fault.

Symmetrical Components are a means of representing three unbalanced phasors by resolving them into three balanced systems of phasors. These three balanced systems are called sequence networks. (positive, negative and zero)

Sequence Networks: Per-Phase Representation of a Balanced Three-phase representation

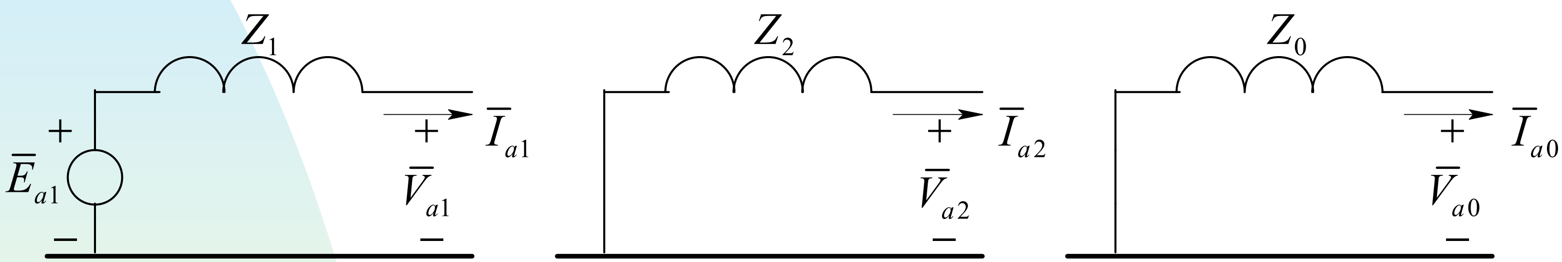


Fig. 13-3 Sequence networks.

Single-Line to Ground (SLF) Fault through a Fault Impedance

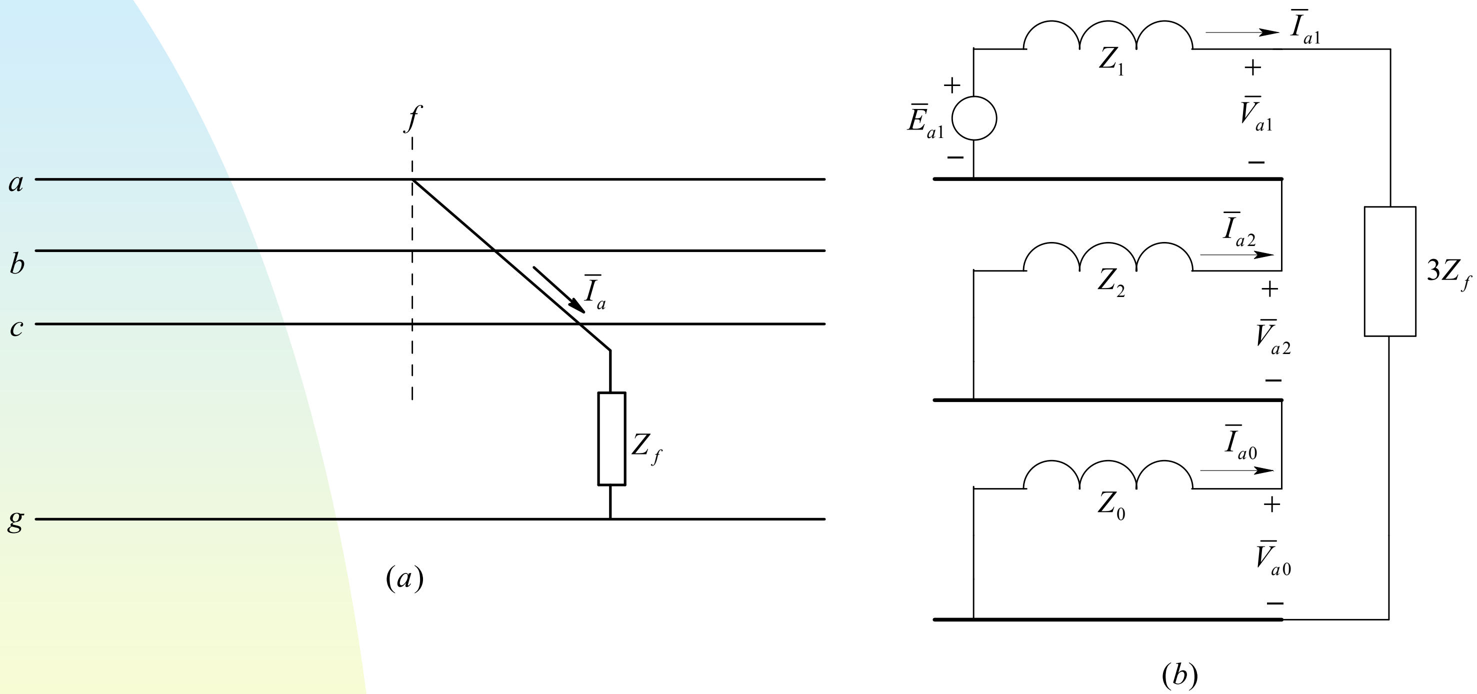


Fig. 13-5 Single line to ground fault.

Double-Line to Ground Fault

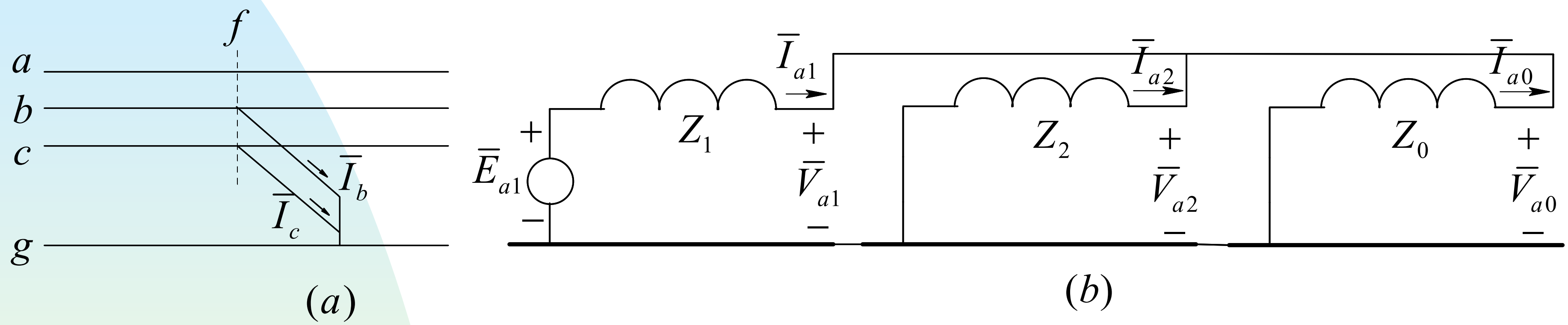


Fig. 13-6 Double line to ground fault.

Line-Line Fault (ground not involved)

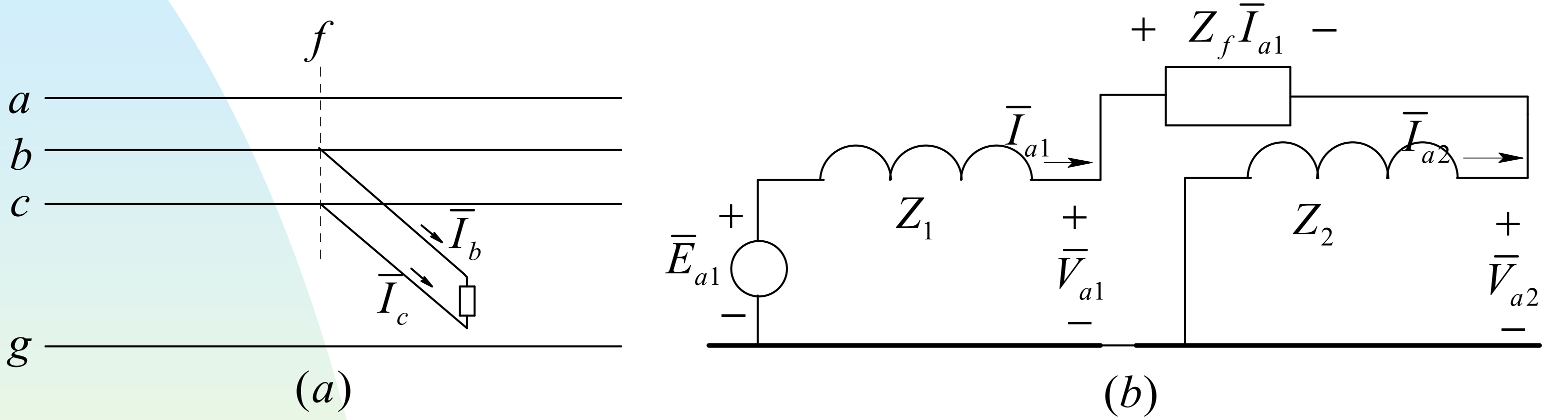


Fig. 13-7 Double line fault (ground not involved).

Path for Zero-Sequence Currents

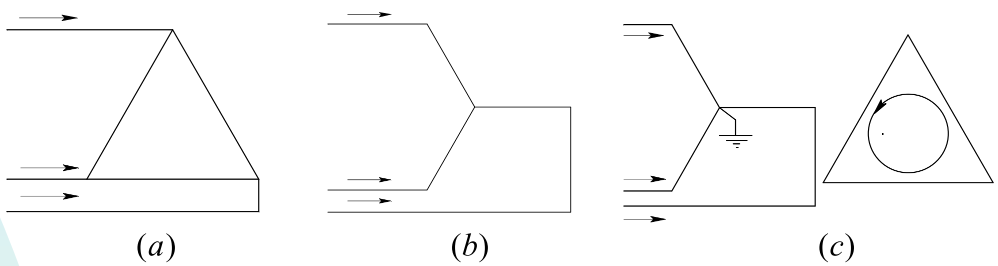
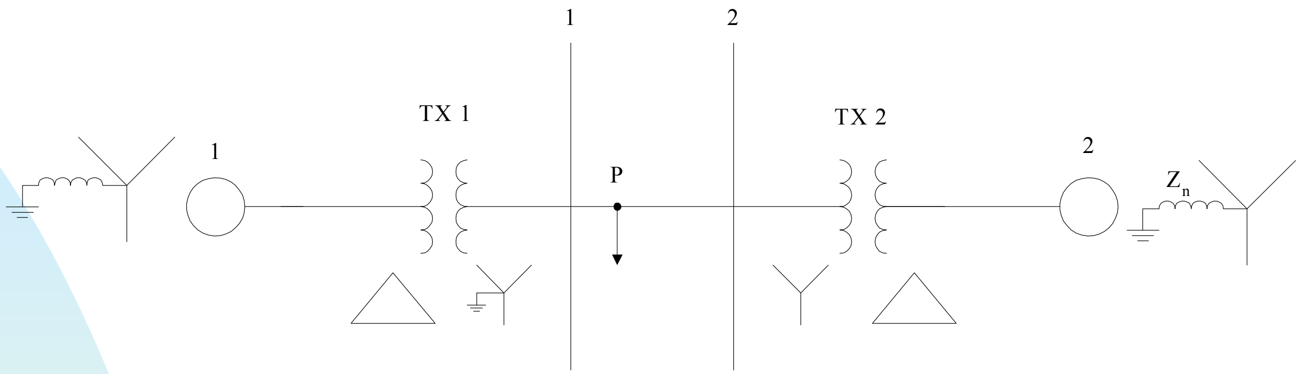


Fig. 13-8 Path for zero-sequence currents in transformers.

One-Line Diagram of a Simple System



- Example: Double Line to Ground Fault at point "P" (subtransient fault study)

- Bases of 100MVA, 345kV
- Machines 1, 2: 100MVA, 20kV,
- Transformers: 100MVA, 345kV Y/20kV Δ,
- Transmission Line: (2-3.5 times)

Find the subtransient current to ground (I_n) for a double line to ground fault at bus 1 (assume that phases b and c are involved in the fault).

Example: Double Line to Ground Fault

First, where do we want to go: $I_f = I_n = 3I_{a0}$, we need to find I_{a0}

$$V_{a0} = -I_{a0} Z_0 \Rightarrow I_{a0} = -\frac{V_{a0}}{Z_0}$$

$$V_{a1} = V_{a2} = V_{a0}$$

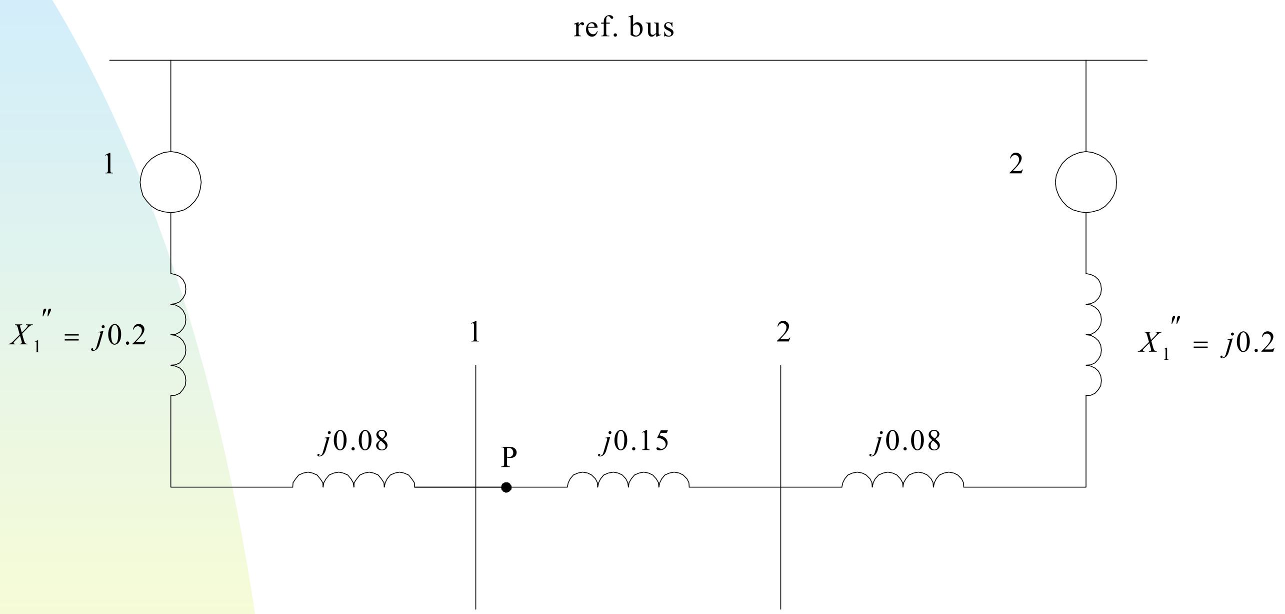
$$V_{a1} = V_f - Z_1 I_{a1}$$

$$I_{a1} = \frac{V_f}{Z_1 + \left(\frac{Z_2 Z_0}{Z_2 + Z_0} \right)}$$

(so we want to find the 2x2 bus imp. matrix for each of the three seq. networks)

Example: Double Line to Ground Fault

- Positive Sequence Network



- Negative Sequence Network

(omit gen. sources, admittance matrix will be identical to pos. seq.)

Example: Double Line to Ground Fault

$$Y_{11-2} = Y_{11-1} = \sum Y's$$

$$= \frac{1}{j0.28} + \frac{1}{j0.15} = -j10.24$$

$$Y_{22-2} = Y_{22-1} = \frac{1}{j0.28} + \frac{1}{j0.15} = -j10.24$$

- (-Y between buses)

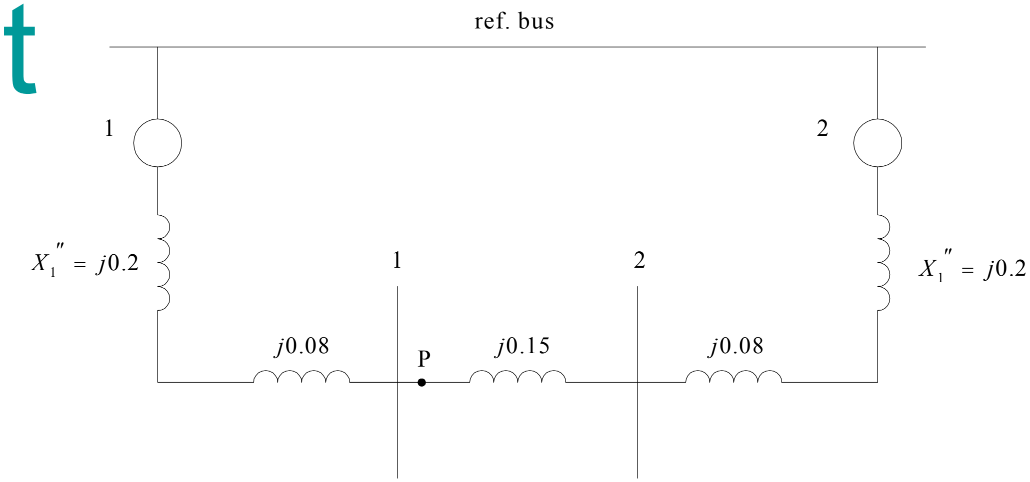
$$Y_{12-1} = Y_{12-2} = \frac{1}{-j0.15} = j6.67$$

$$Y_{bus-1} = Y_{bus-2} = \begin{vmatrix} -j10.24 & j6.67 \\ j6.67 & -j10.24 \end{vmatrix}$$

$$Z_{bus-1} = Z_{bus-2} = [Y_{bus}]^{-1} = \begin{vmatrix} j0.17 & j0.11 \\ j0.11 & j0.17 \end{vmatrix}$$

Example: Double Line to Ground Fault

- Zero Sequence Network



- Note that since j0.08 is connected at bus 2 and is not connected to any other bus, it is not included in Y_{22-0}.

$$Y_{11-0} = \frac{1}{j0.08} + \frac{1}{j0.5} = -j14.50$$

$$Y_{12-0} = Y_{21-0} = -\frac{1}{j0.5} = j2.0$$

$$\Rightarrow Y_{bus-0} = \begin{vmatrix} -j14.50 & j2.0 \\ j2.0 & -j2.0 \end{vmatrix}$$

$$Y_{22-0} = \frac{1}{j0.5} = -j2.0$$

$$Z_{bus-0} = Y_{bus-0}^{-1} = \begin{vmatrix} j0.08 & j0.08 \\ j0.08 & j0.58 \end{vmatrix}$$

Example: Double Line to Ground Fault

$$I_{a1} = \frac{V_f}{Z_{11-1} + \left(\frac{Z_{11-2}Z_{11-0}}{Z_{11-2} + Z_{11-0}}\right)} = \frac{1}{\left(j0.17 + \frac{(j0.17)(j0.08)}{j0.17 + j0.08}\right)} = -j4.456\,pu$$

$$\Rightarrow V_{a1} = V_{a2} = V_{a0} = V_f - Z_{11-1}I_{a1} = 1 - (j0.17)(-j4.456) = 0.2425\,pu$$

$$I_{a0} = \frac{-V_{a0}}{Z_{11-0}} = \frac{-0.2425}{j0.08} = j3.031\,pu$$

$$I_n = 3I_{a0} = j9.093\,pu$$

(can immediately see that it is about 9 times nominal)

$$I_{base} = \frac{100{,}000}{\sqrt{3} * 345} = 167.3A$$

(k's in numerator and denominator cancel)

$$I_n = 167.3(9.093) = 1521A$$

(virtually purely inductive)

Protection in Power System

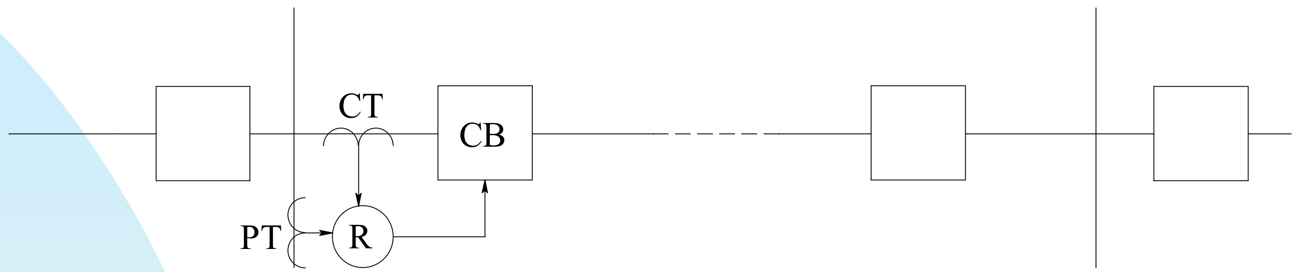


Fig. 13-14 Protection equipment.

- The protection system has the following design criteria.
- reliable
- selective – avoid unnecessary tripping, we isolate the smallest possible portion of the system
- fast – to minimize fault duration. Any intentional time delays, i.e., if used as a back up protection system, should be precise
- economical – maximum protection for minimum cost
- simple – minimize protection equipment and cost

Protection in Power System

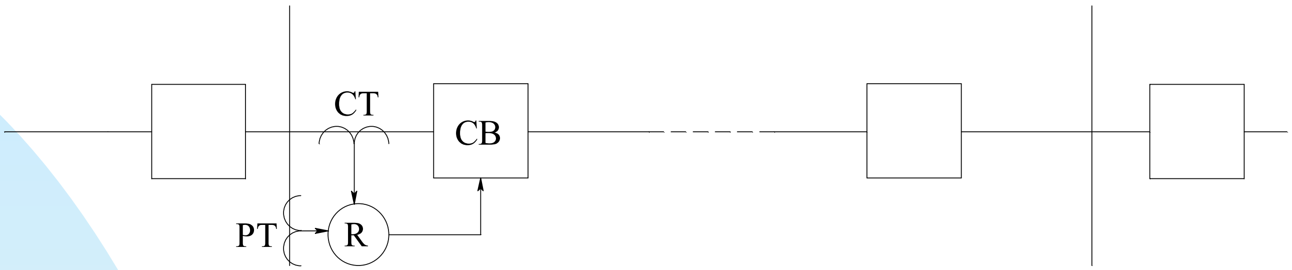


Fig. 13-14 Protection equipment.

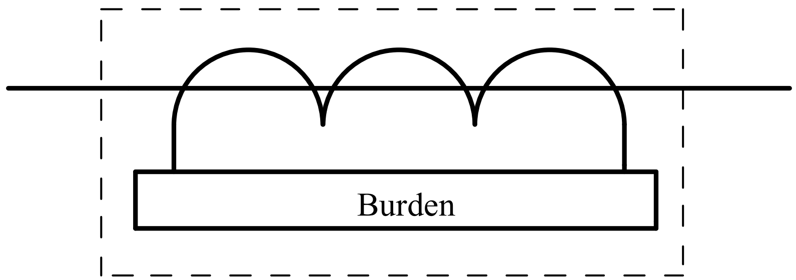
- Instrument Transformers: Convert power system voltages and currents to low levels (115V, 5A) for relay operation, for safety and economy (allows smaller relays), and provides isolation from the power system.

- Relays: sense the fault and cause circuit breaker contacts to open.

- Circuit Breakers (CB's): mechanical switch capable of interrupting fault currents and possibly reclosing.

Current Transformers (CT)

(a)



(b)

Fig. 13-15 Current Transformer (CT) [5].

Differential Relays

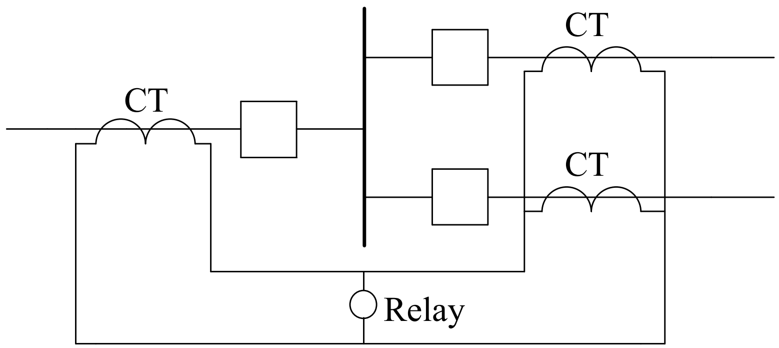


Fig. 13-17 Differential relay.

Used to protect generators, transformers and buses etc.

- Same concept as a ground fault interrupter (GFI), where the relay trips when the current at two locations should be the same but is different due to a fault.

Directional Over-Current Relays

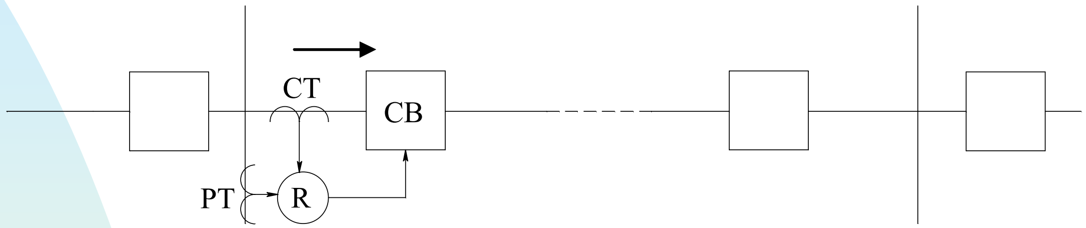


Fig. 13-18 Directional over-current Relay.

When I’ > I_p (specified pickup value), the trip coil of the CB is energized causing the CB to open.

Impedance (Distance) Relays

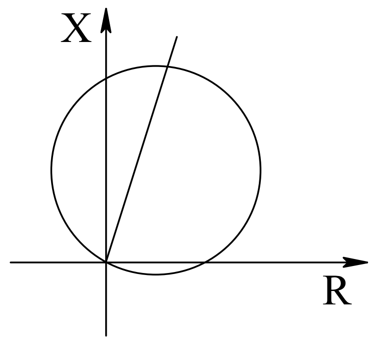


Fig. 13-20 Impedance (distance) relay.

Use the voltage to current ratio, or impedance ratio.
During a fault, we have an increase in current and a decrease in voltage at the fault point.

The closer the fault is to the protection system, the larger the current and smaller the voltage, so the smaller the V/I ratio, or smaller Z, therefore called “distance relay”

Microwave Terminal for Pilot Relays

Fig. 13-21 Microwave terminal [5].

For Transmission Lines, compares the terminal quantities (V or I) via a communication channel rather than by a direct wire interconnection of relays.

-power line carrier
-fiber optic cable
-microwave
-GPS (satellite)
-pilot wires (e.g. telephone)

Zones of Protection

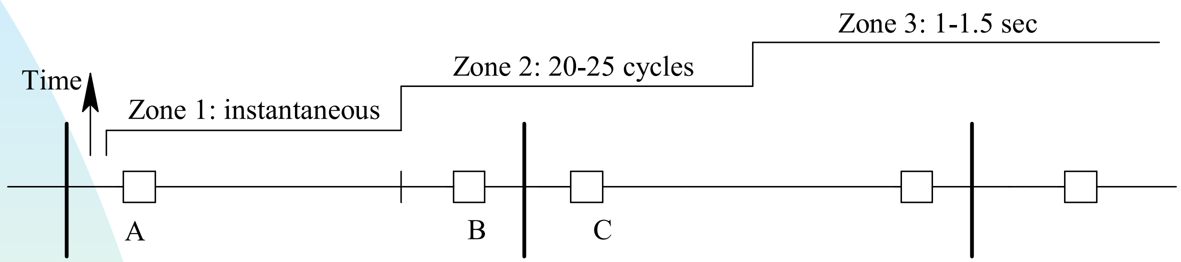


Fig. 13-22 Zones of protection.

- We want to protect generators, transformers, lines, buses

Protective zones have the following characteristics:

- neighboring zones are overlapped (ensure all areas are protected) but overlap area is made as small as possible
- circuit breakers (CBs) are located in the overlap regions
- for a fault anywhere in a zone, all circuit breakers in that zone open to isolate the fault (with exceptions and permutations to reduce deenergized area)

Circuit Breakers

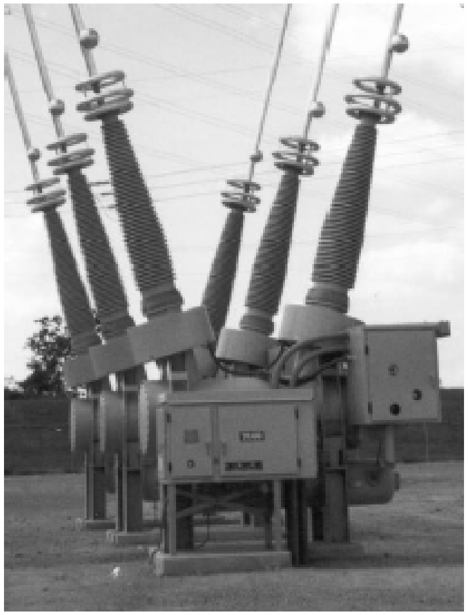


Fig. 13-25 SF_6 circuit breaker [5].

Wave Energy Opportunities and Developments

Wave Energy Technology Lead Professors:

Annette von Jouanne (EECS), Ted Brekken (EECS), Bob Paasch (ME),

Solomon Yim (CE/Ocean), Alex Yokochi (ChE)

College of Engineering, Oregon State University

Excellent Multidisciplinary Group of Undergraduate and Graduate Students

Oregon Coastal Community Contributors:

Fishermen Involved in Natural Energy (FINE)

Newport Wave Energy Team (local government, utilities, other stakeholders)

OSU's multidisciplinary Wave Energy team has been pursuing innovation in several thrust areas including:

1) Researching novel direct-drive wave energy generators

-11th prototype (10kW) successfully ocean tested with CPT Sept. 2008 (the CPT and OSU team did a tremendous job in this collaborative effort)

- Small Scale and Large Scale Prototype Dev. and Testing with CPT
  - Aug. 2009 testing in the O.H. Hinsdale TWB
  - Jan. 2010 testing in the O.H. Hinsdale LWF

2) Developed Unique Wave Energy Linear Test Bed to adv. devices

3) Northwest National Marine Renewable Energy Center (NNMREC)

Northwest National Marine Renewable Energy Center (NNMREC)

Proposing since 2004, Main Thrusts Include:

-Floating “test berth” system off the OR Coast to test wave energy technologies,

-Extensive modeling,

-Environmental impact studies,

-Community outreach and other initiatives.

Main Collaborators: OSU, UW, OWET, NREL, OSG, FINE, EPRI

USDOE annual award is $1.25M, that can be renewed for up to 5 years.

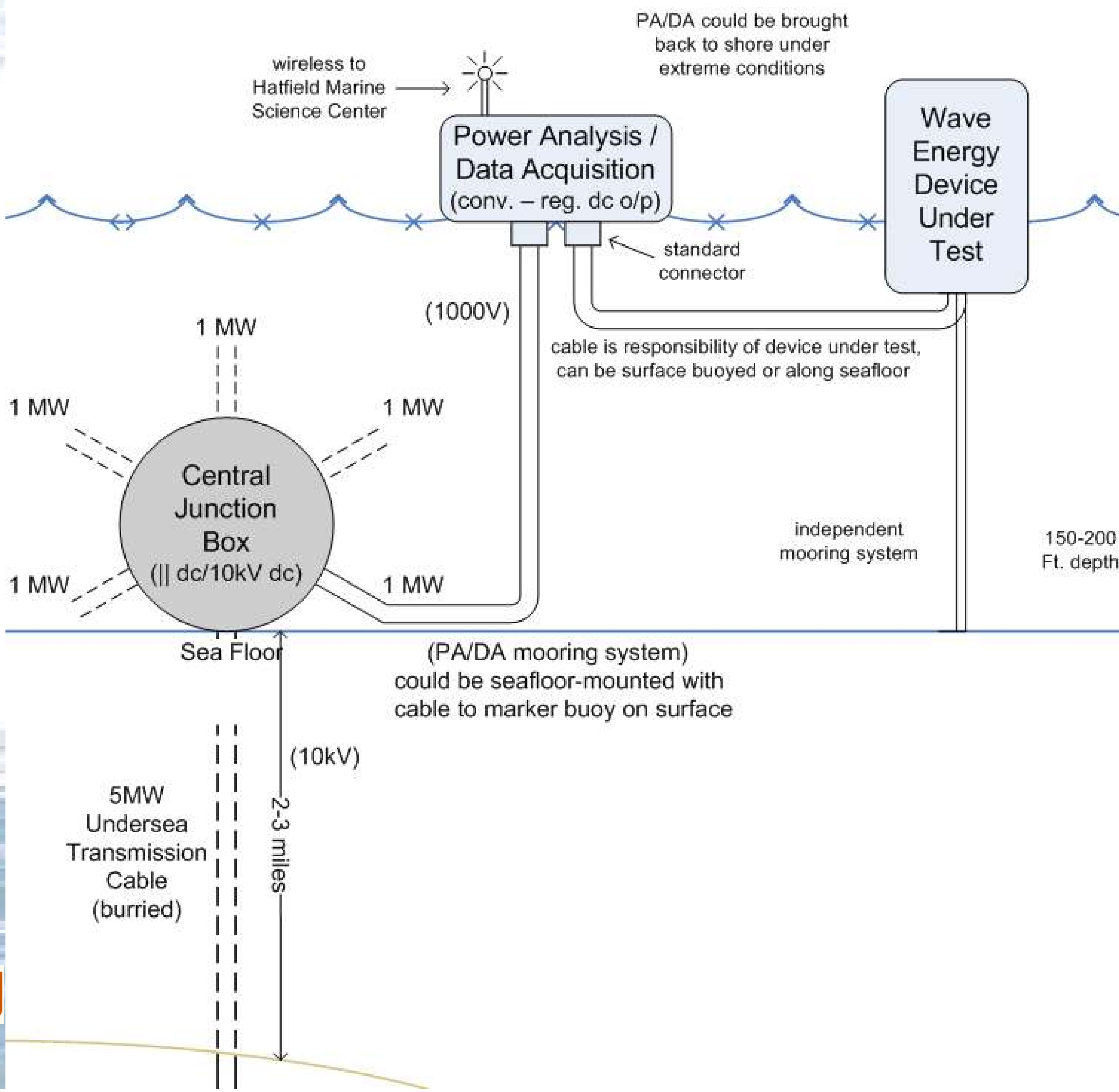
With cost share, $13.5M over 5 years.

FY09 Federal Omnibus, $2.3M, advance full scale Wave Energy ocean test berths

OSU PI’s: Drs. Bob Paasch (Dir.), Annette von Jouanne, Ted Brekken, George Boehlert, Solomon Yim, Alex Yokochi, Merrick Haller, Tuba Ozkan-Haller

NNMREC Program Manager: Meleah Ashford

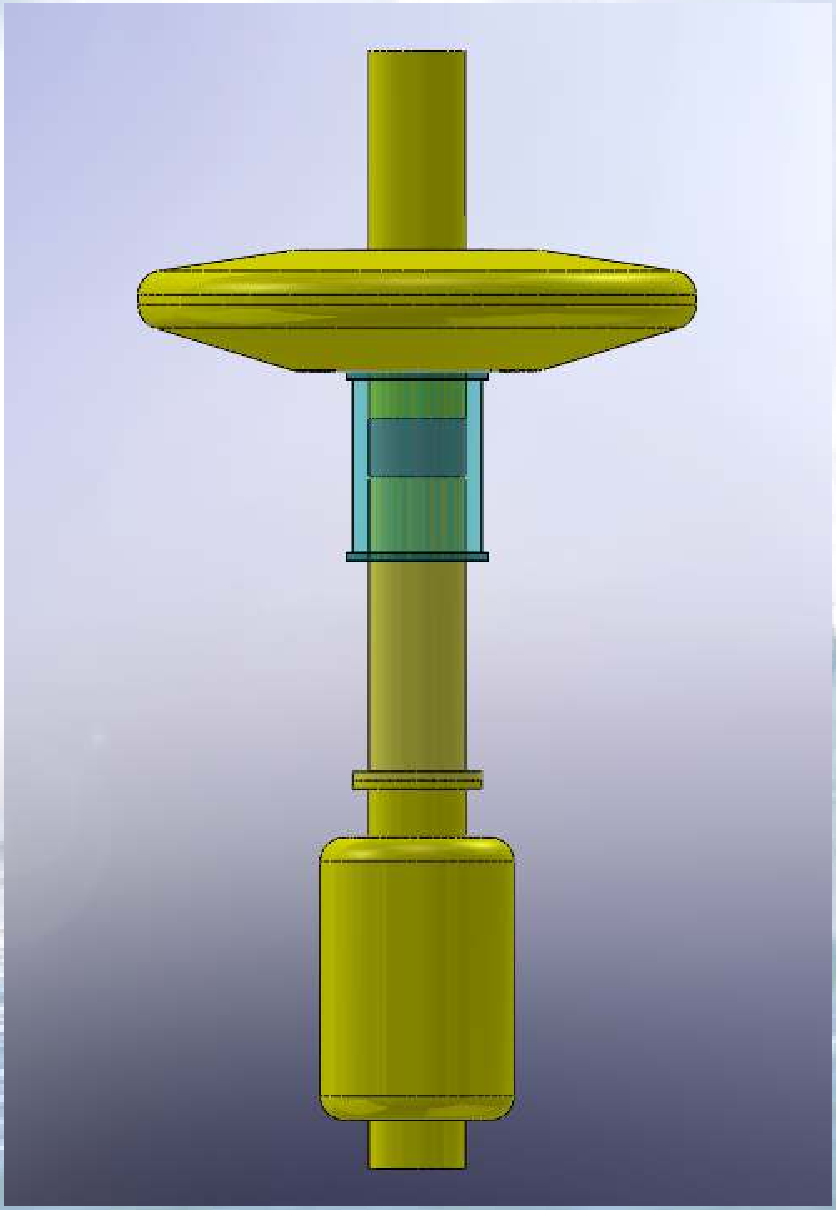
Draft Schematic of Wave Energy Center Test Berth Interconnect



NNMREC Test Berth Schedule and Cost (Estimated)

PHASE	2009	2010	2011	2012	2013
I. One Floating Test Berth (1 MW)	• $1.5M-Oregon Legislature				
II. Up to four more Floating Test Berths (1 MW ea.)		• $1.5M-Oregon Legislature • $0.5M-FY09 Federal • $3.5M Unfunded			
III. Central Junction Box		• $1M-FY09 Federal			
IV. Grid-connected Test Berth (including subsea cable to shore, substation interconnect, land-based facilities at HMSC for data analysis, communications and control)			• $4M Unfunded		
V. Demonstration Site (generating up to 5 MW)				• $10M Unfunded	

Sept. 2008 L-10 Buoy



- Oregon State University, School of Electrical Engineering and Computer Science

Sept. 2008 L-10 Buoy

Team Just Before Deployment

Sept. 2008 Deployment

Sept. 2008 Deployment