Arrowhead Station Special Equipment Operation

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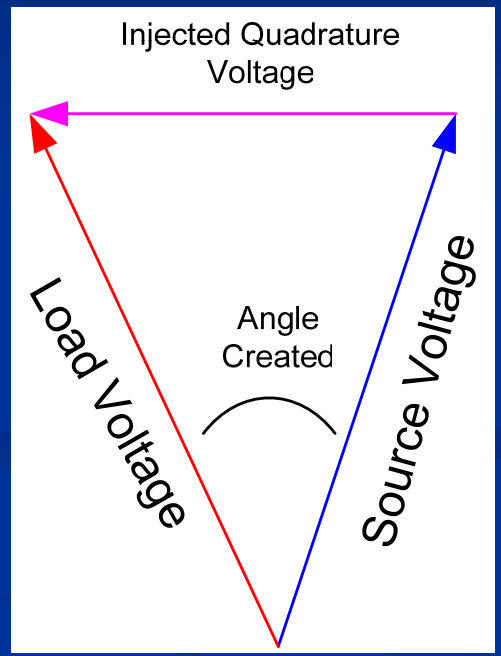
Arrowhead - Equipment Operation

- Non-Standard Equipment at Arrowhead 345 kV
  - Phase Shifting Transformer (8TR)
  - Voltage Regulating Auto transformer (9TR)
  - Shunt Caps with fast & slow controls (30K/31K)

Phase Shifting Transformer

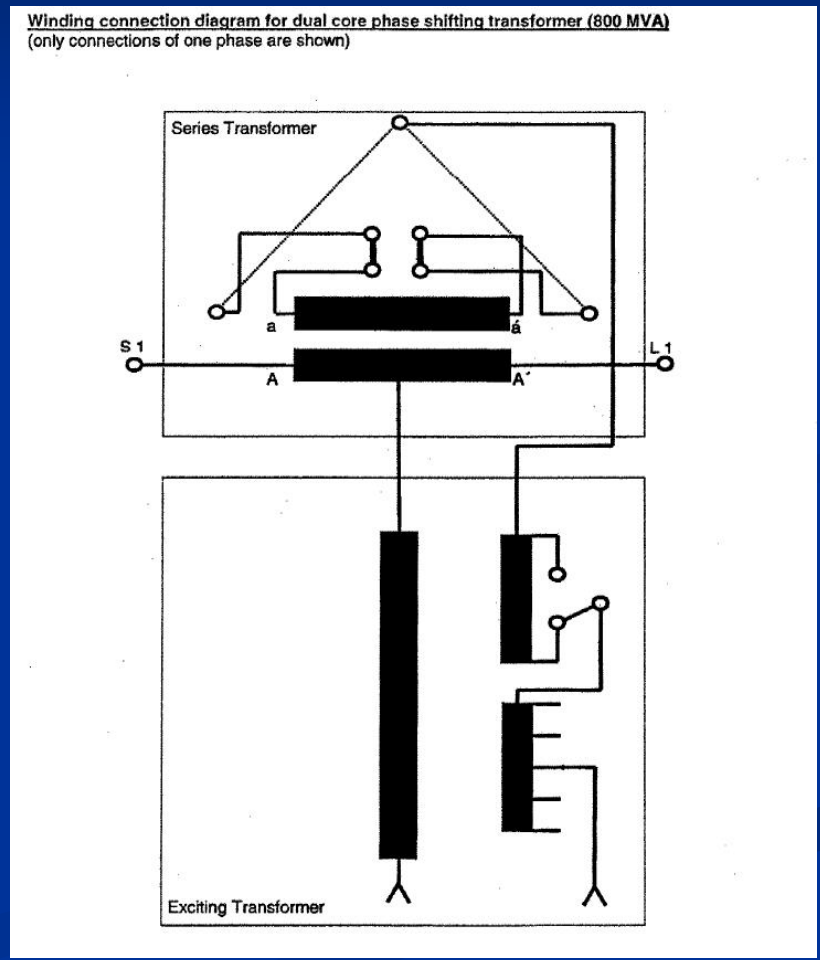
Phase Shifting Transformer

- Principle of Operation
  - Source Terminal = Sending End (MN)
  - Load Terminal = Receiving End (WI)
  - Control power flow on the line by changing angle across the line
  - Inject voltage 90 degrees out of phase from the line to ground voltages (quadrature) to create phase difference between Source and Load terminals
  - This additional angle adds to, or subtracts from, the natural system angle to increase or decrease the power flow
    - As angle increases, power flow increases
      P = (V1 * V2 * Sin (Angle)) / 2



Phase Shifting Transformer

- 800 MVA – Two core WYE type phase shifter
  - Two tanks / Two cores
  - Series transformer – carries full load through series windings (A – A'). Quadrature voltage to create phase angle shift is injected through this winding (a – a')
  - Exciter Winding – Tapped from center point of series winding to ground. Used to develop the voltage to inject in the series winding to create phase shift



Phase Shifting Transformer

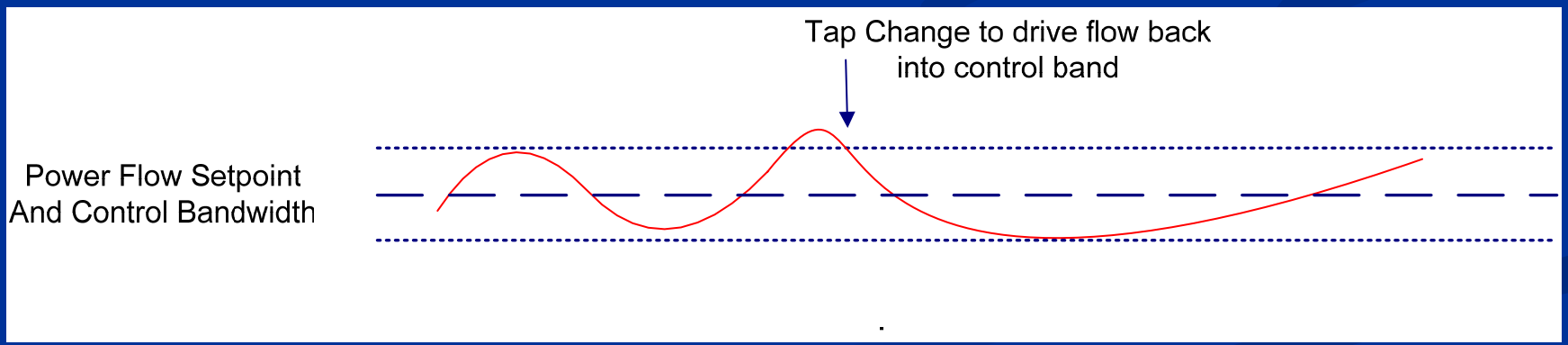
- Complex electrical & mechanical device
  - Numerous moving parts
    - LTC, ARS switch etc
  - Two tanks interconnected via high voltage throat connections
    - Series tank/winding
    - Exciter tank/Winding/LTC
  - Numerous complex protection systems

Phase Shifting Transformer

- Intended design/utilization
  - Designed to help reduce flow on AHD-STLK following the loss of King – Eau Claire – Arpin
  - Balance flows after contingency and regain some operating margin on AHD-STLK
  - Day to day operation will be in automatic control mode, however, the control band will be extremely wide
  - Post contingency re-adjustment system adjusts taps following large change in power flow

Phase Shifter Operation

- Traditional phase shifter control uses set-point and bandwidth to control flow within desired range
- Typically power would be controlled with about a +/- 10 – 50 MW control band

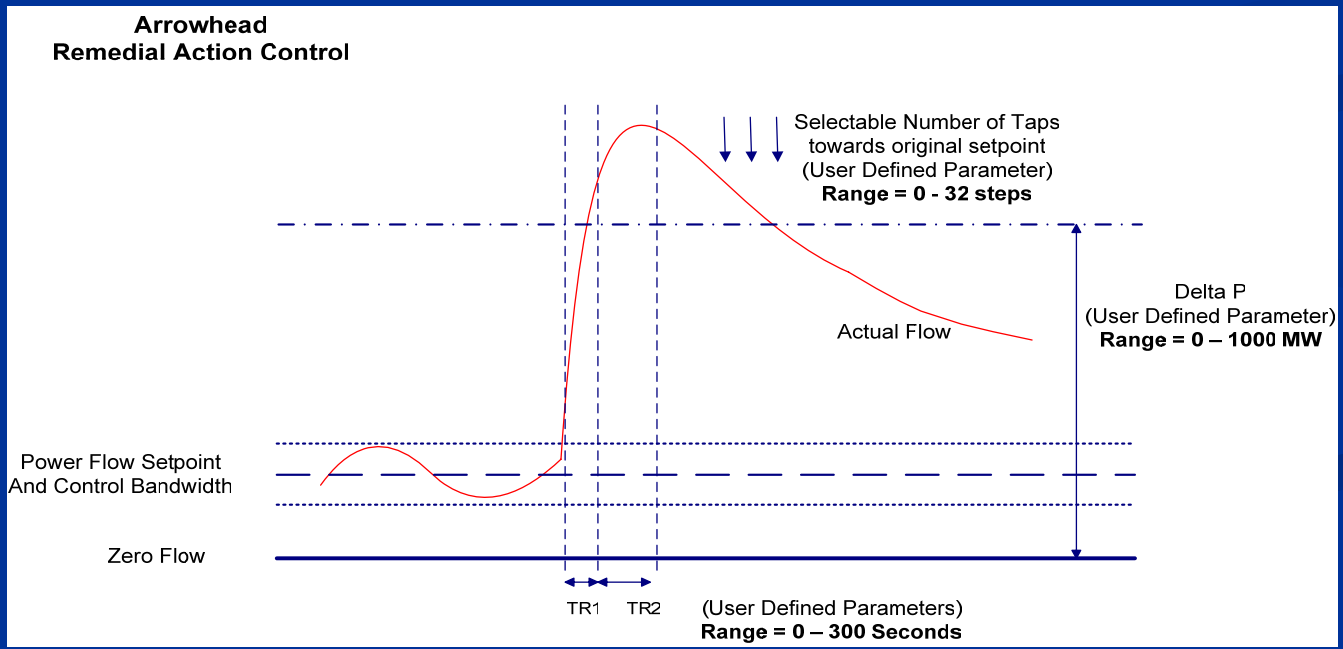


Phase Shifter Operation

- Arrowhead PST will utilize a very wide control band
  - Preliminary estimate 0 – 670 MW
    - Set point = 335 MW
    - Bandwidth = 335 MW
  - Under normal conditions, flow will be allowed to range from 0 - 650 MW without PST action
    - Preserves PST control capability for post contingency
    - If flow cannot be maintained below 650 MW, phase shifter automatic adjustment will keep flow below 670 MW

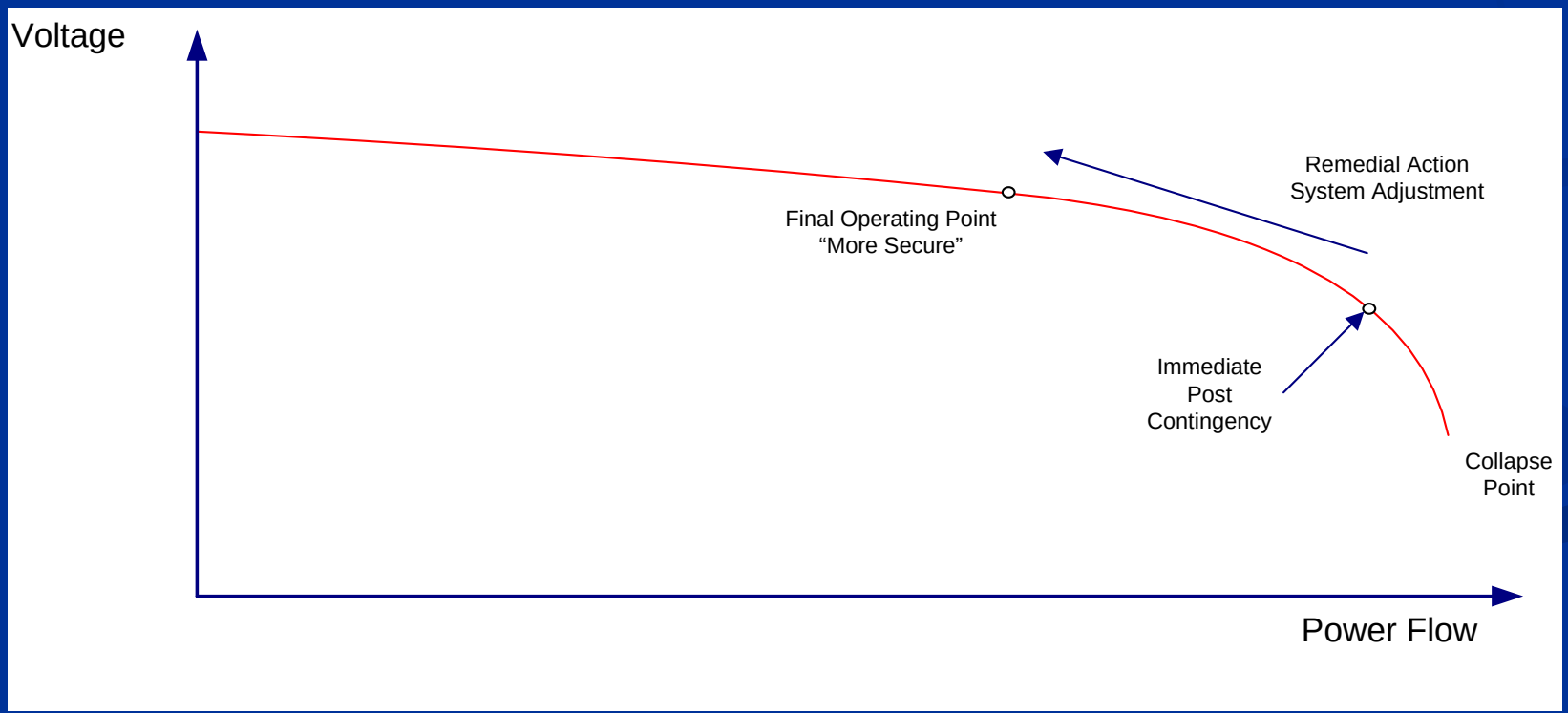
Phase Shifter Operation

- Post Contingency Re-Adjustment System (RAS)
  - Designed to detect a sudden large change in powerflow and adjust taps so as to partially counteract that increase in flow
  - If control was allowed to drive flow back to below 650 MW, other facilities become overloaded and voltage security limits are approached



Phase Shifter Operation

- Remedial Action System
  - Quickly adjusts PST taps to drive system towards a more secure operating point



Phase Shifter Controls

- Phase Shifter Controls
  - Dual, Selectable Primary and Secondary Automatic Power Flow Control (APFC)
    - Post Contingent Readjustment is critical, so redundancy is needed
    - Power flow control must be enabled for RAS to be active
  - Similar to other PST Controls in the MP System
    - Setpoint controlled via SCADA or Local control
    - Bandwidth will be a fixed parameter (entered locally or via remote pc connection)

- Automatically adjusts taps to keep power within the band defined by:
  (Setpoint + bandwith) – (Setpoint – bandwidth)
  670 MW - 0 MW

- Normal Operation
  - Phase Shifter Automatic Control ON
  - Setpoint = 335 MW
  - Bandwidth = 335 MW
  - Post contingency Control – For fast flow change > 100 MW, PST will tap back by 10 taps
    - Control trips to manual and alarms – Immediate coordination with MISO, XEL, ATC reqd.

Phase Shifter Operation

- Other facts
  - Raise = Advance = Increase flow to Wisconsin
  - Lower = Retard = Decrease flow to Wisconsin
  - 32 steps – Approx 1 degree per step
  - 10 - 15 MW per step
  - Designed for max of 35 degrees across PST – control will lock out at that value.
    - No auto or manual adjustment allowed
    - LTC step voltage would be exceeded

Arrowhead 230/345 kV Autotransformers

Arrowhead 230/345 kV Autotransformers

- 4 x 266 MVA single phase units (800 MVA – 3 phase total)
- 3 – Active, 1 – Cold standby
  - Designed for installation without need to physically move the unit
  - Universal buswork designed to allow relatively quick connection of power leads.
  - Controls and protection are swapped via wiring changes in termination cabinet or junction box
- +/- 10% LTC on the 345 kV side
- Outfitted with automatic controls

Arrowhead 230/345 kV Autotransformers

Autotransformer Operation

- Auto Transformer Controls
  - Dual, Selectable Primary and Secondary Automatic Voltage Control (AVC)
  - Similar to PST Control
    - Voltage Setpoint controlled via SCADA or Local control
    - Bandwidth will be a fixed parameter
- Automatically adjusts taps to keep voltage within the desired band
- Normal Operation
  - Initially Voltage Control in Manual Mode
    - Capacitor banks will perform bulk of the 345 kV voltage regulation
  - Voltage control philosophy will be adjusted as we gain experience with operation of the line
- Initially will operate with standby unit connected. After a few months, we will put this unit back in standby and connect primary unit for service

345 kV Capacitor Banks

345 kV Capacitor Banks

- 2 x 75 MVar capacitor banks (30K/31K)
- Breaker switched with inrush/outrush reactors
- Equipped with standard (slow) controls and Fast (high speed) insertion controls
- Arrowhead caps are to be used as the primary voltage control for Arrowhead and Stone Lake 345 kV
  - Stone Lake 345kV cap held in reserve for contingency use
- Critical that ALL 345 kV caps be maintained in AUTOMATIC mode
- Goal is to maintain Arrowhead 345kV between 352 kV and 362 kV (102% - 105%)
  - Voltage control settings / ranges may be adjusted after we have some operational history
  - This control range will aid in maintaining 230 kV voltage at nominal target level of 236 kV

345 kV Capacitor Banks

- Slow control settings
  - Caps on at 352 kV (102%), Caps off at 366 kV (106%)
  - Timing in the range of 30 – 60 seconds
  - Time staggered for coordination, First on/Last off
- Fast control settings
  - Caps on at 338 kV (98%), Caps off at 373 kV (108%)
  - Caps close in or trip after 12 cycles below/above setpoints
- Single control point for each capacitor bank controls
  - Both Normal and High speed enabled/disabled by single auto control