REACTIVE POWER

TCIPG READING GROUP, OCTOBER 3, 2014

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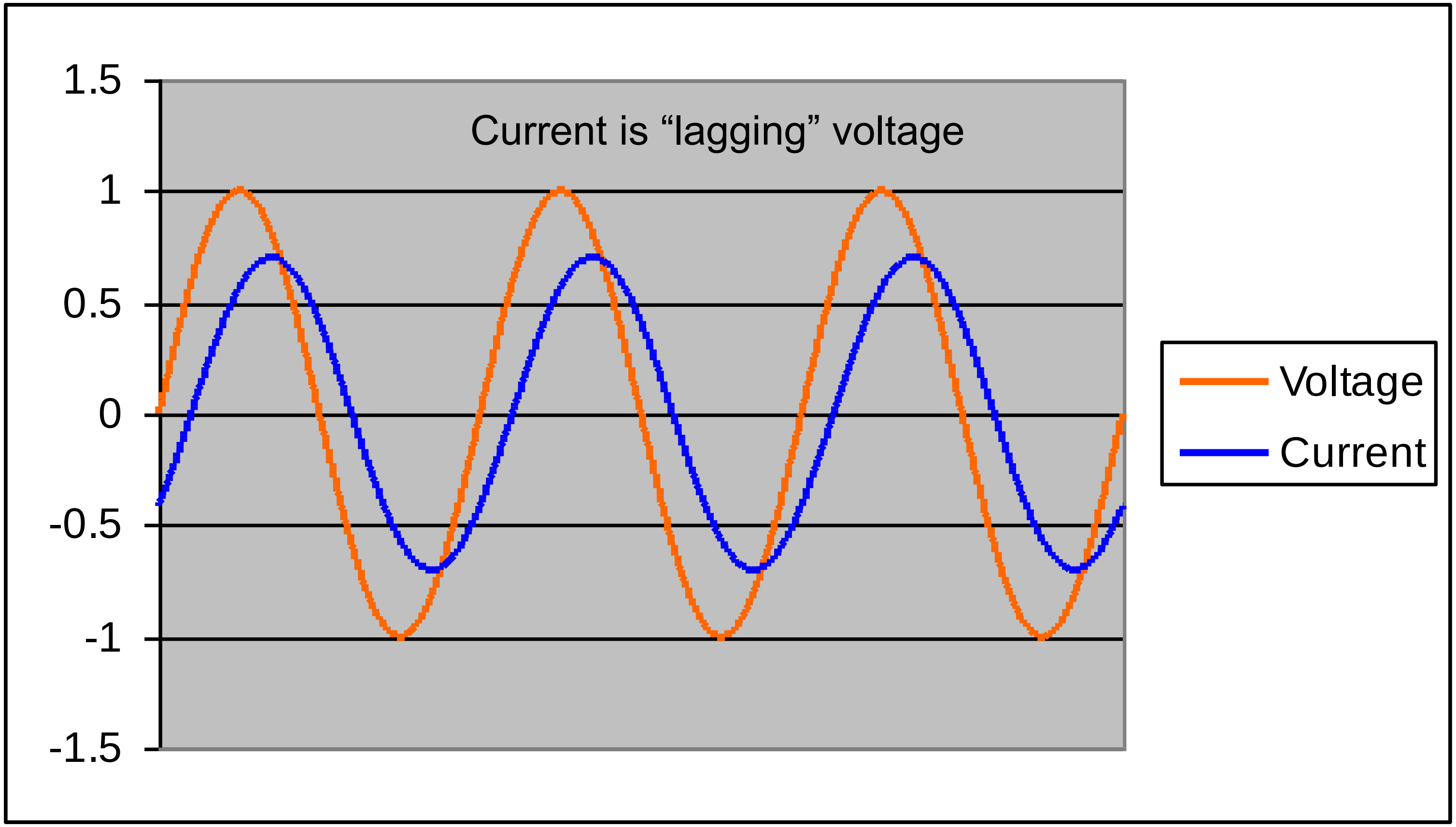
WHAT IS REACTIVE POWER?



It’s all in the phase shift between voltage and current, referenced as volt-amperes reactive (var)

RELATIONSHIP TO PHASORS (TRANSIENTS)

Voltage across and current into a box in time domain:

$v(t) = V_p \cos(\omega t+\theta_v)$ $(\omega=2\pi f)$

$i(t) = I_p \cos(\omega t+\theta_i)$

Resistor v = iR (Ohm’s Law)

Voltage and current are “in phase”

Inductor v = Ldi/dt (Faraday’s Law)

If v is cos, i is sin (the current “lags” by 90°)

Capacitor i = Cdv/dt (Gauss’s Law)

If v is cos, i is -sin (the current “leads” by 90°)

RELATIONSHIP TO PHASORS (STEADY STATE)

Frequency domain:

(Phasors and impedances, $\omega=2\pi f$, complex numbers)

$V = V_p/\text{sqrt}2$ angle θ_v (RMS magnitude, cos ref)

$I = I_p/\text{sqrt}2$ angle θ_i (RMS magnitude, cos ref)

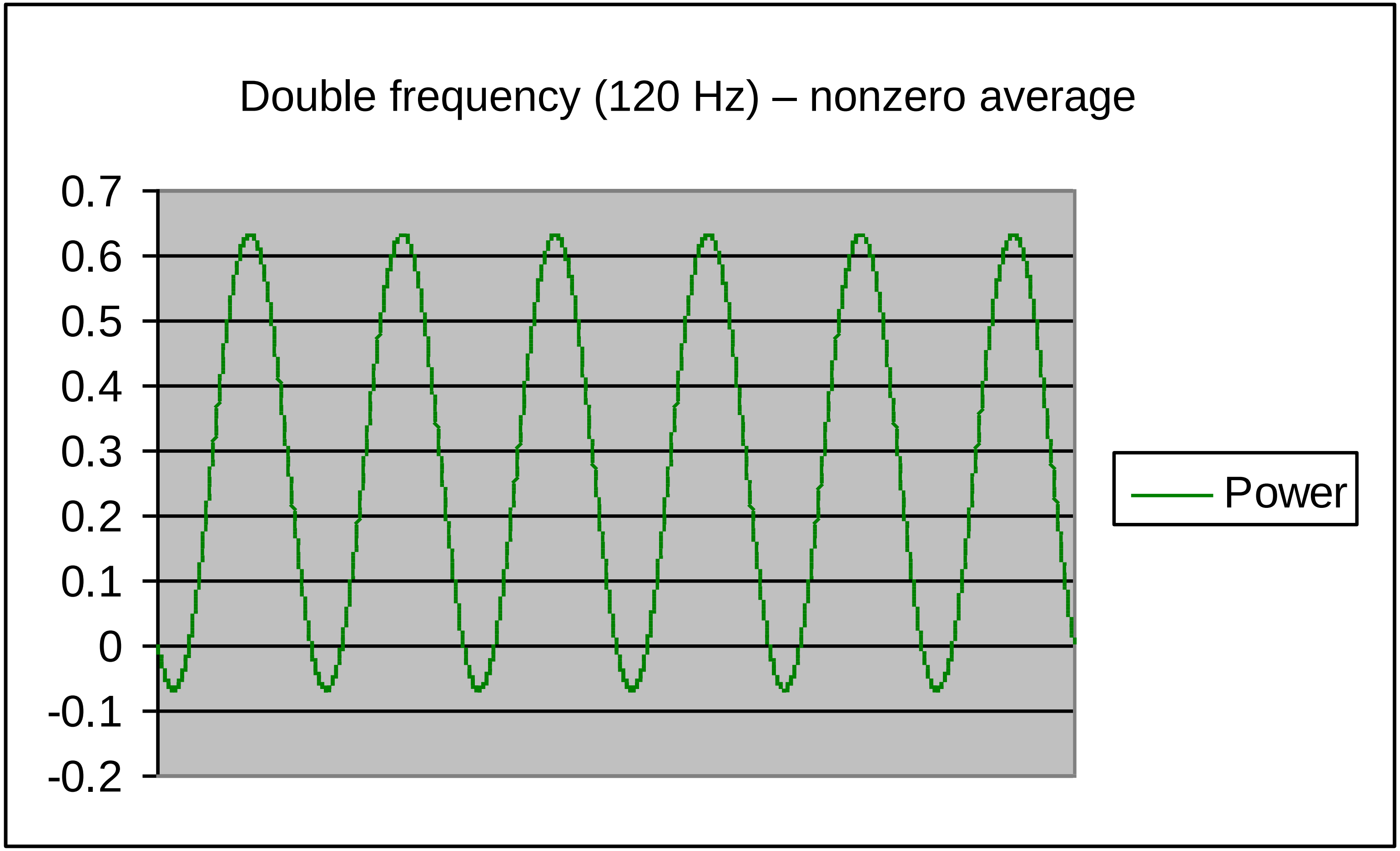
Inductor $X = \omega L$ (reactance)

Capacitor $X = -1/\omega C$ (reactance)

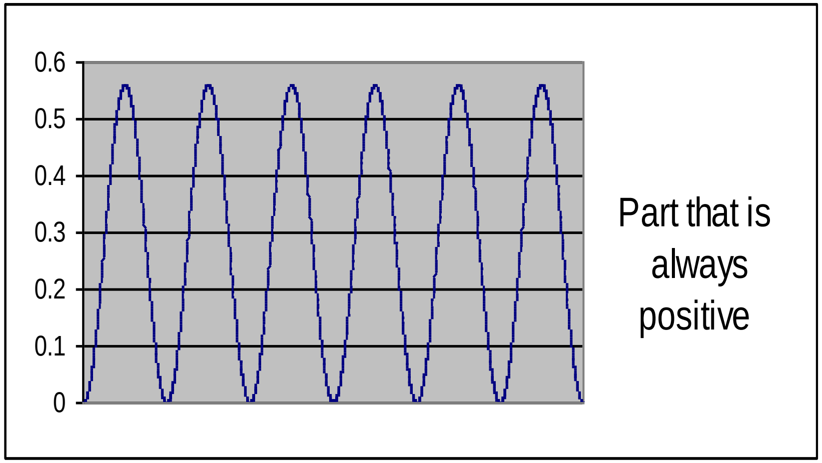
Add ***Resistor*** R and you get $Z=R+jX$ (impedance)

Ohm's Law $V = ZI$

INSTANTANEOUS POWER (ONE PHASE)

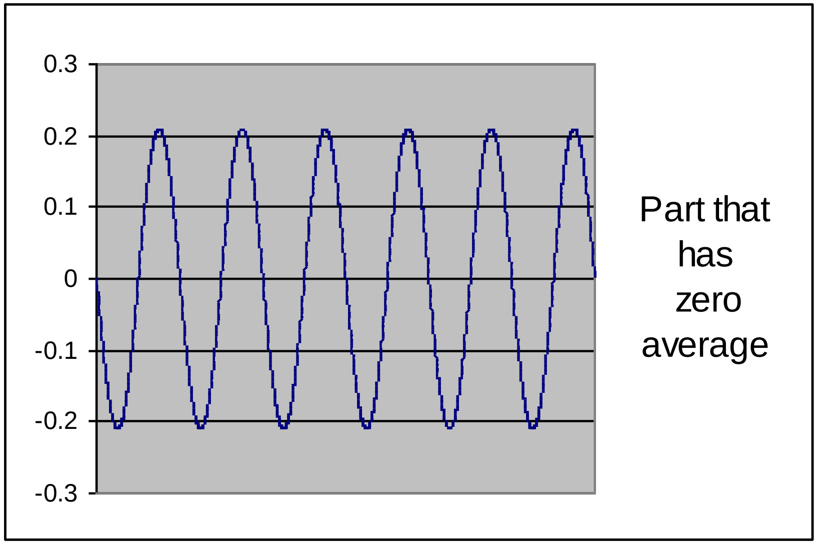


DECOMPOSED INTO TWO TERMS



P (1-cos(2ωt))

P = .275 PU Watts



- Q sin(2ωt))

Q = 0.205 PU VARS

COMPLEX POWER

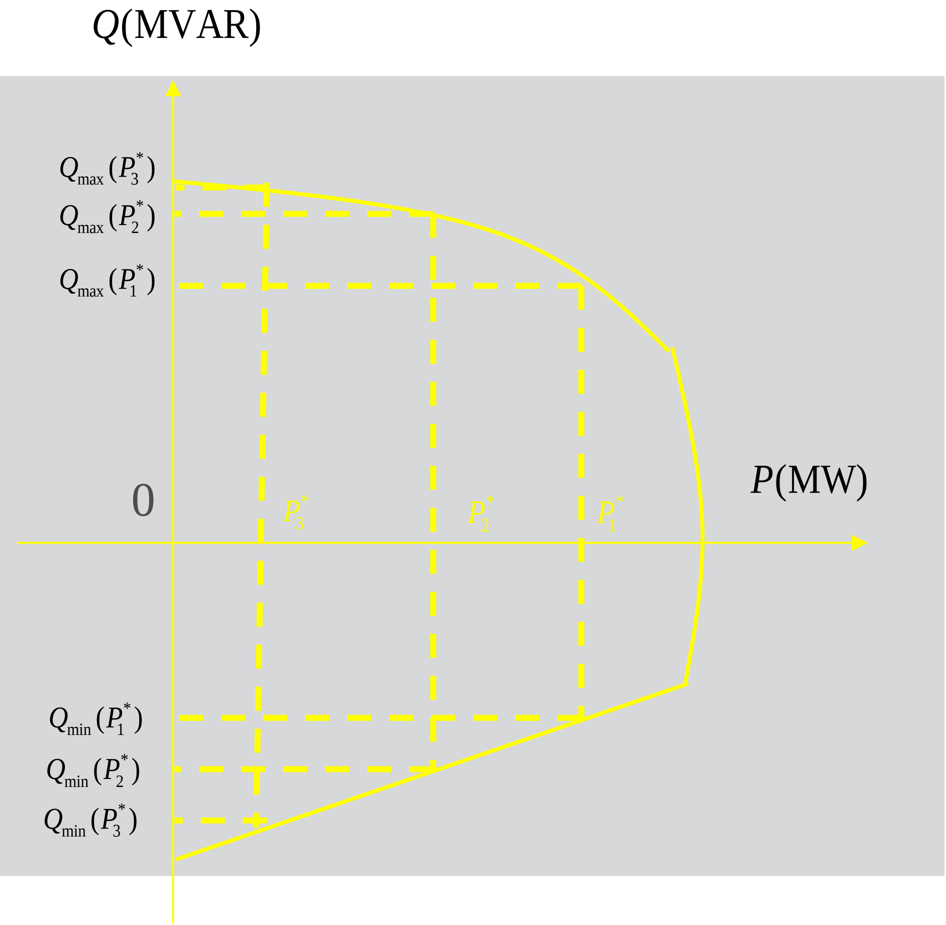
$S = V I^*$ (* is conjugate)

$= P + jQ$

Magnitude of S is called “Apparent” power

$= \mathrm{SQRT}(P^2 + Q^2)$

PQ capability curve



- A relationship between MW and MVAR limits
- Thermal issues
- Stability issues

WORDS FROM CARSON TAYLOR

“A power system at a given operating state and subject to a given disturbance undergoes voltage collapse if post-disturbance equilibrium voltages are below acceptable limits. Voltage collapse may be total (blackout) or partial.”

WORDS FROM PRABHA KUNDUR

> “Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage.”

MORE WORDS FROM PRABHA KUNDUR

“The main factor causing instability is the inability of the power system to meet the demand for reactive power. The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through the inductive reactance associated with the transmission network.”

MORE WORDS FROM PRABHA KUNDUR

“Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant portion of the power system.”

“A criterion for voltage stability: inject VARS at bus k and the voltage at bus k goes up (V-Q sensitivity is positive).”

SCENARIO (LACHS AND KUNDUR)

- Generating units near load centers out of service. Heavily loaded lines and low VAR reserves.
- Loss of a heavily loaded line. Increases other line loadings and VAR losses - voltage reduction.
- Load consumption would temporarily lower to stabilize. AVRs would act to restore generator voltages, but increased VAR flow would lower voltages elsewhere.
- The ULTCs at load centers would increase distribution voltages and so the load would go back up, and EHV voltages would go back down.
- Generators would hit VAR limits.

15 YEARS OF INTERESTING STUFF

- Proceedings: Bulk Power System Voltage Phenomena - Voltage Stability and Security, Potosi, MO, Sep 19-24, 1988

- Proceedings NSF Workshop on Bulk Power System Voltage Phenomena Voltage Stability and Security, Deep Creek Lake, MD, Aug. 4-7, 1991

- Proceedings of the Bulk Power System Voltage Phenomena - III Seminar on Voltage Stability, Security & Control, Davos, Switzerland, August 22-26, 1994

15 YEARS OF INTERESTING STUFF

- Proceedings of the Symposium on "Bulk Power System Dynamics and Control IV - Restructuring", Santorini, Greece, August 24-28, 1998
- Proceedings Bulk Power Systems Dynamics and Control V - Security and Reliability in a Changing Environment, Onomichi, Japan, August 26-31, 2001
- Proceedings Bulk Power Systems Dynamics and Control VI, Cortina, Italy, August 22-27, 2004

COMMON INTERPRETATION

- “Static” voltage collapse has become synonymous with maximum power transfer and the ability to solve a load flow problem.

- “Dynamic” voltage collapse involves detailed load models, control and other dynamics.

Voltage Collapse Animation (DC)

Created by Chad Thompson and Pete Sauer of The University of Illinois at Urbana-Champaign

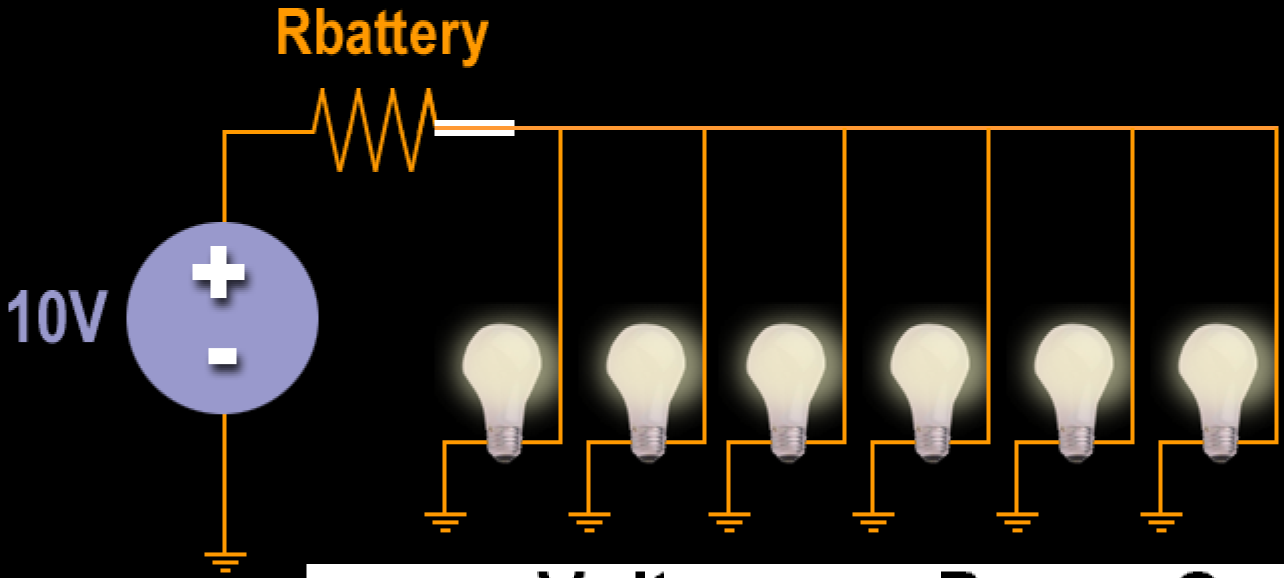
Based on a previous animation by Bob Thomas of Cornell University

- Suppose a control system is designed to switch lights on in a room in order to bring a room brightness to 30 Watts (equivalent to a certain level of lumens).

- This animation will switch lights on in sequence as you advance the slides in order to reach the 30 Watt level. The control system would continue to switch lights in as it tries to obtain a total power output of 30 Watts.

- If the voltage source supplying the light bulbs was ideal (no internal resistance), this would be possible. But, this animation shows that adding load to a source with internal resistance changes the voltage available to the load and eventually results in voltages so low that the addition of another light bulb actually lowers the total power and therefore overall brightness.

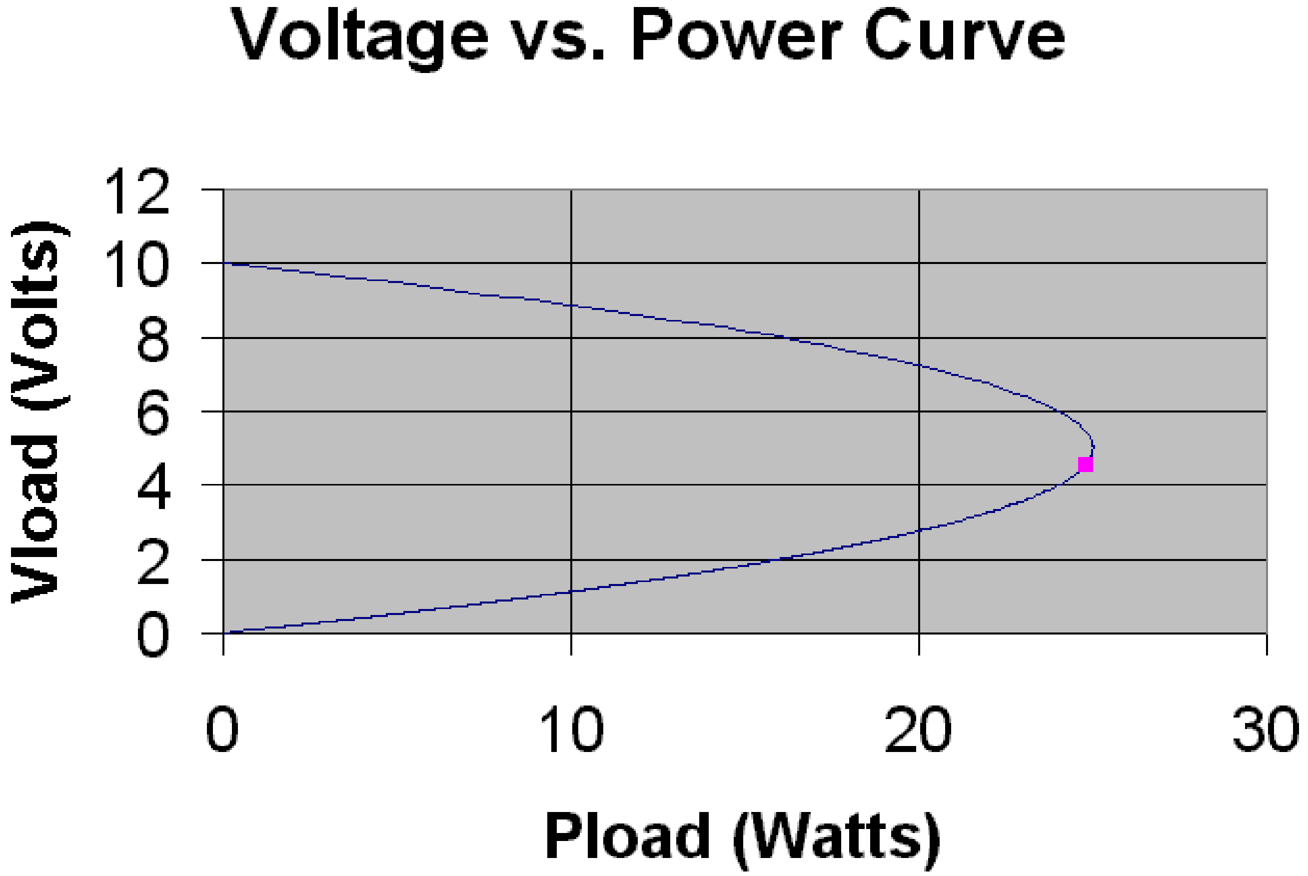
- The control system would continue to add more light bulbs to try and achieve 30 Watts of total power – but it would not be able to do so – as it adds more light bulbs, the room would get darker and darker and the voltage would continue to drop - this can be interpreted as a voltage collapse.



24 Watts total

Voltage drops some

Voltage drops more

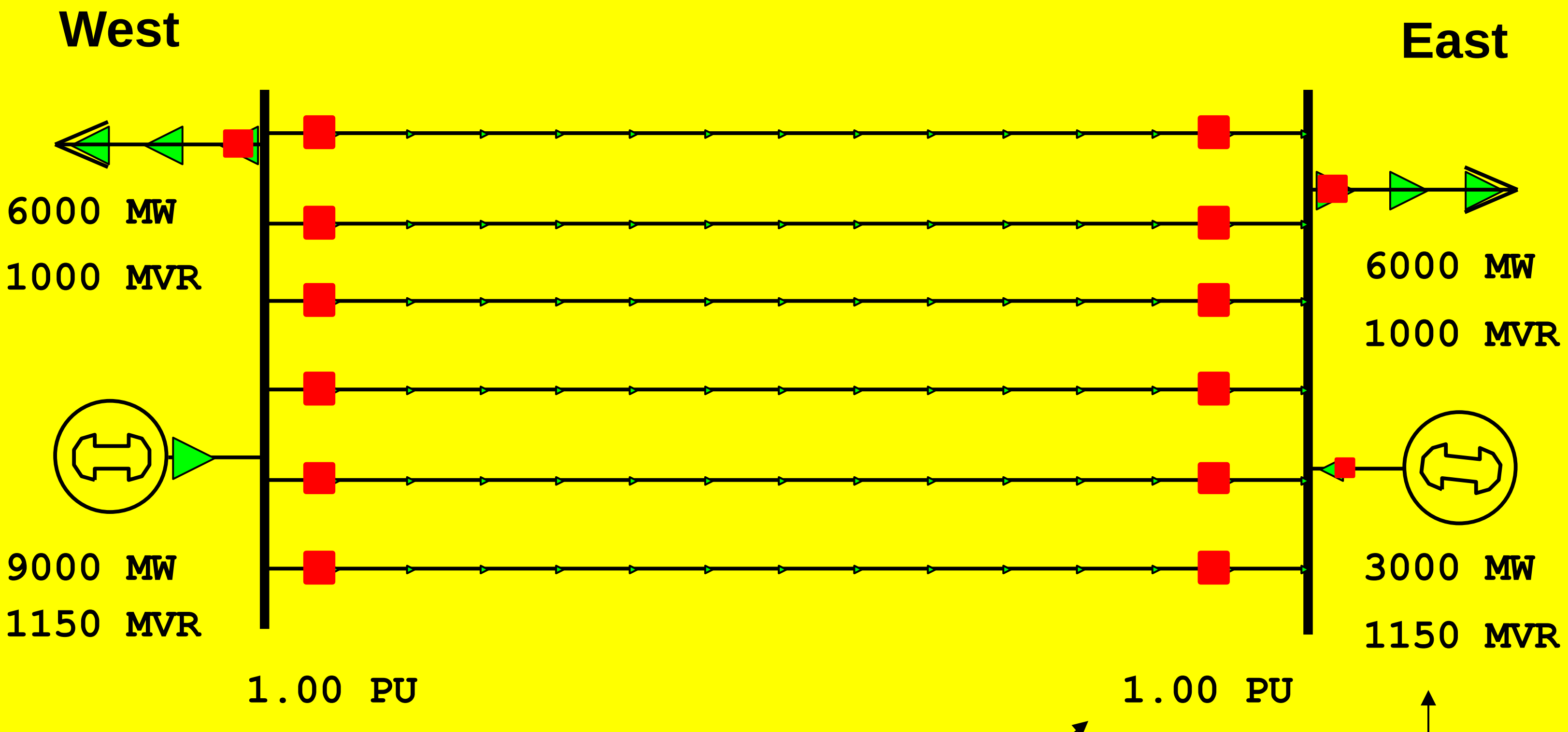


DISTRIBUTION FEEDERS

- What do switched capacitors control?
  - Voltage
  - Power factor
- How fast do they control?
  - Timer – day/night or seasons
  - Continuous

Case 1: All Lines In-Service

3,000 MW transfer – 500 MW per line



Voltage is 100% of rated voltage.
(300 MVARs required by lines).

East generator is below 1,200 MVAR limit.

Case 2: One Line Out

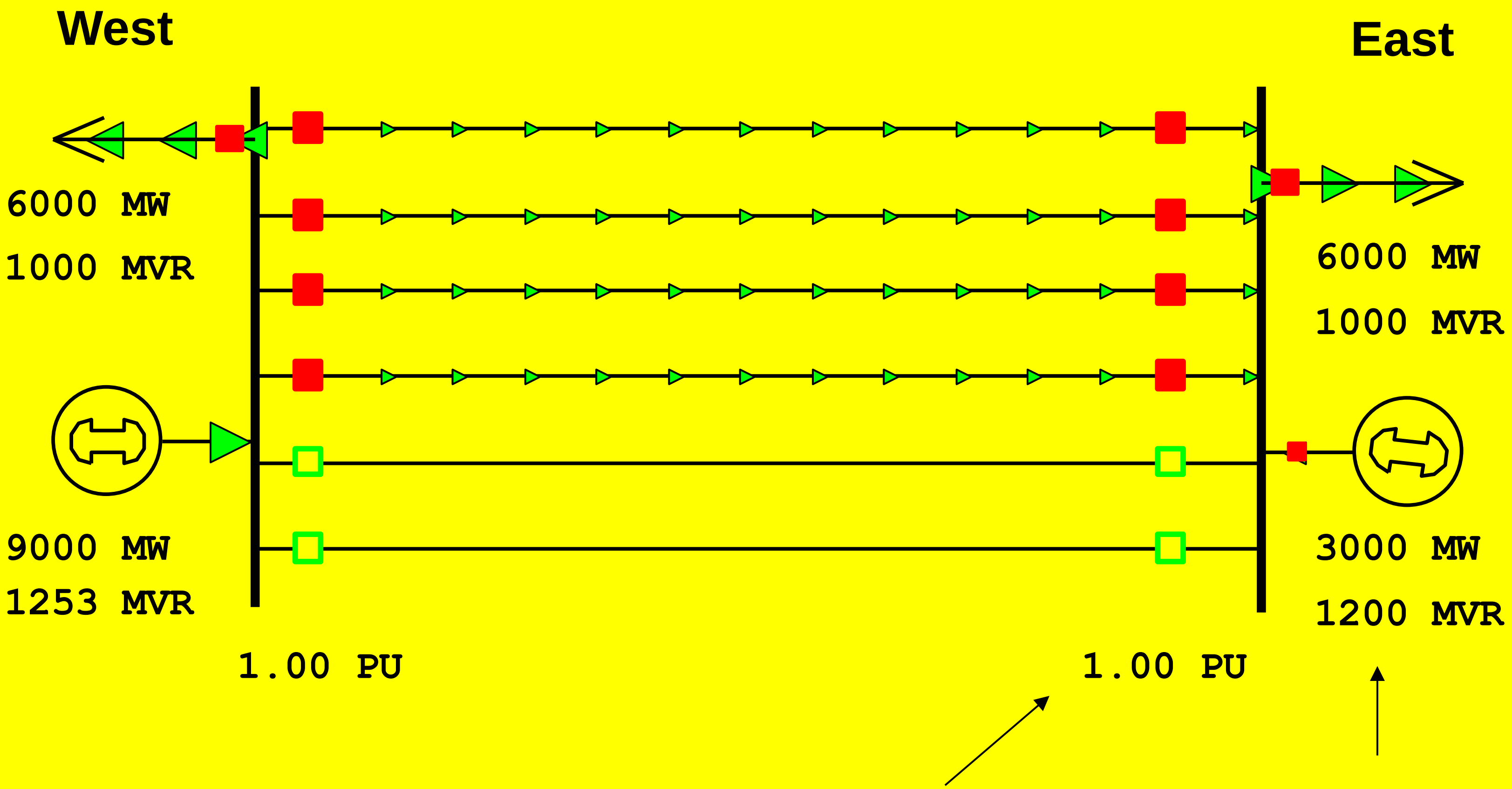
3,000 MW transfer – 600 MW per line

Voltage is 100% of rated voltage
(362 MVARs required by lines).

East generator is below 1,200 MVAR limit.

Case 3: Two Lines Out

3,000 MW transfer – 750 MW per line



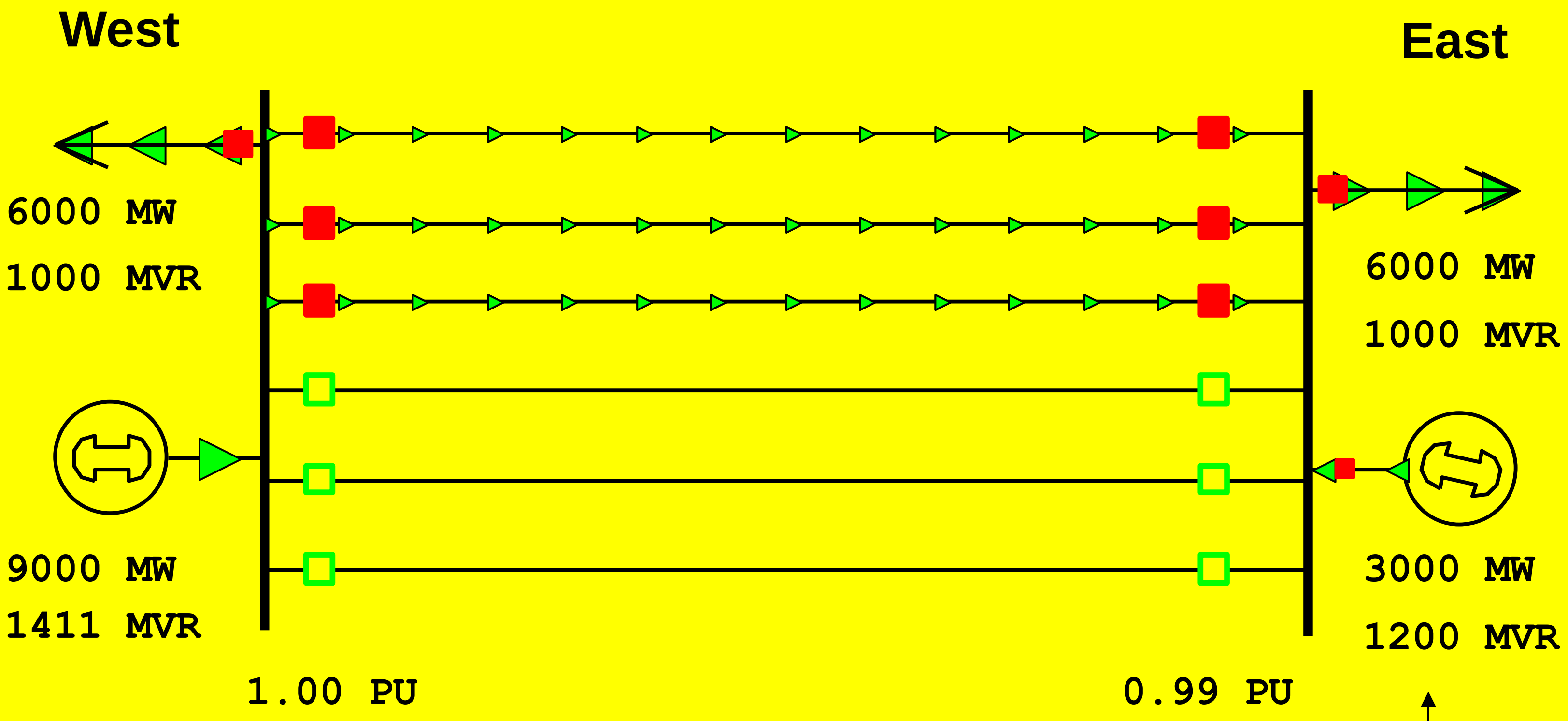
Voltage is 100% of rated

(453 MVARs required by lines).

East generator is at 1,200 MVAR limit.

Case 4: Three Lines Out

3,000 MW transfer – 1,000 MW per line



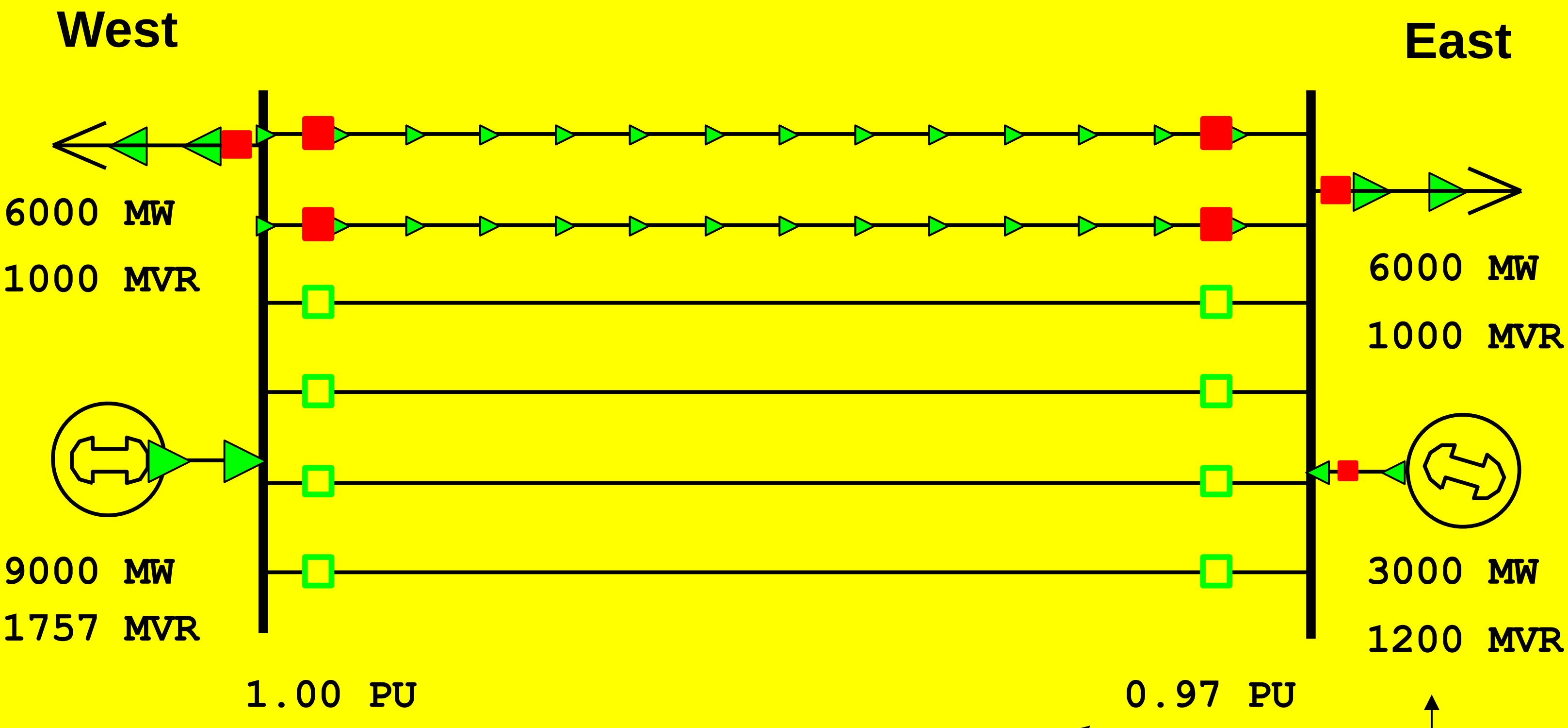
Voltage is only 99% of rated

(611 MVARs required by lines).

East generator is at 1,200 MVAR limit.

Case 5: Four Lines Out

3,000 MW transfer – 1, 500 MW per line

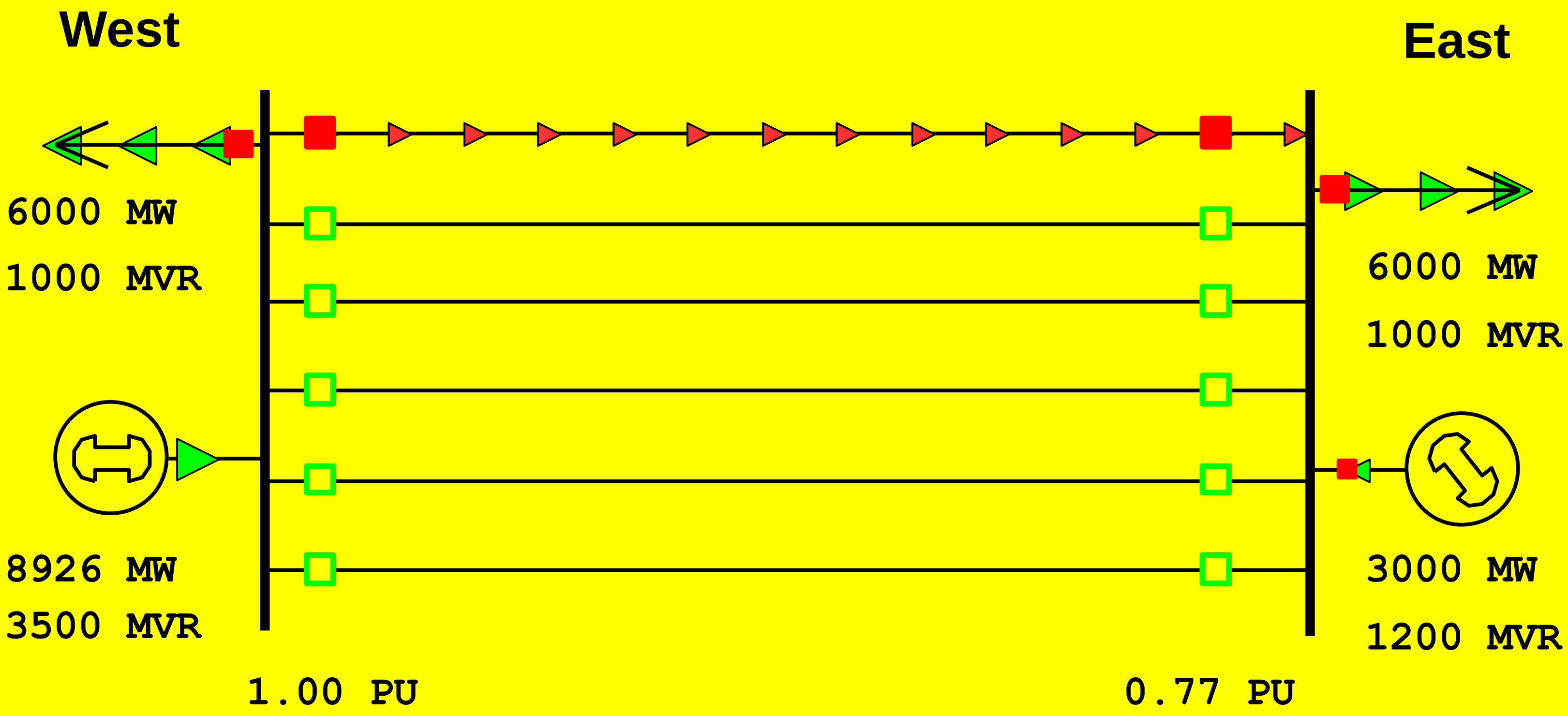


Voltage has dropped to 97% of rated voltage (957 MVARs required by lines).

East generator is at 1,200 MVAR limit.

Case 6: Five Lines Out

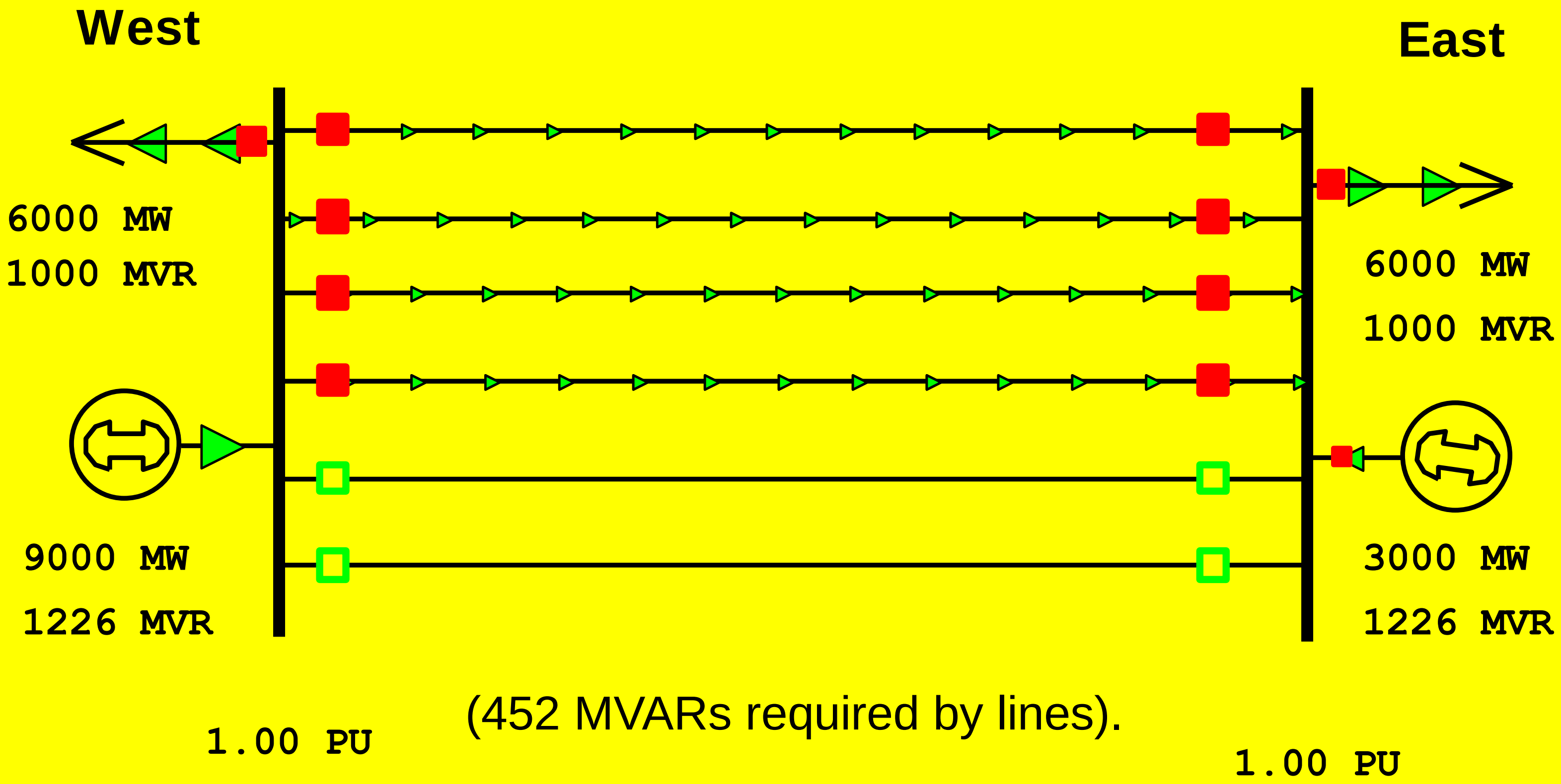
System Collapse



This simulation could not solve the case of 3,000 MW transfer with five lines out. Numbers shown are from the model’s last attempt to solve. The West generator’s unlimited supply of VARs is still not sufficient to maintain the voltage at the East bus.

Case 7: Two lines out - full voltage control

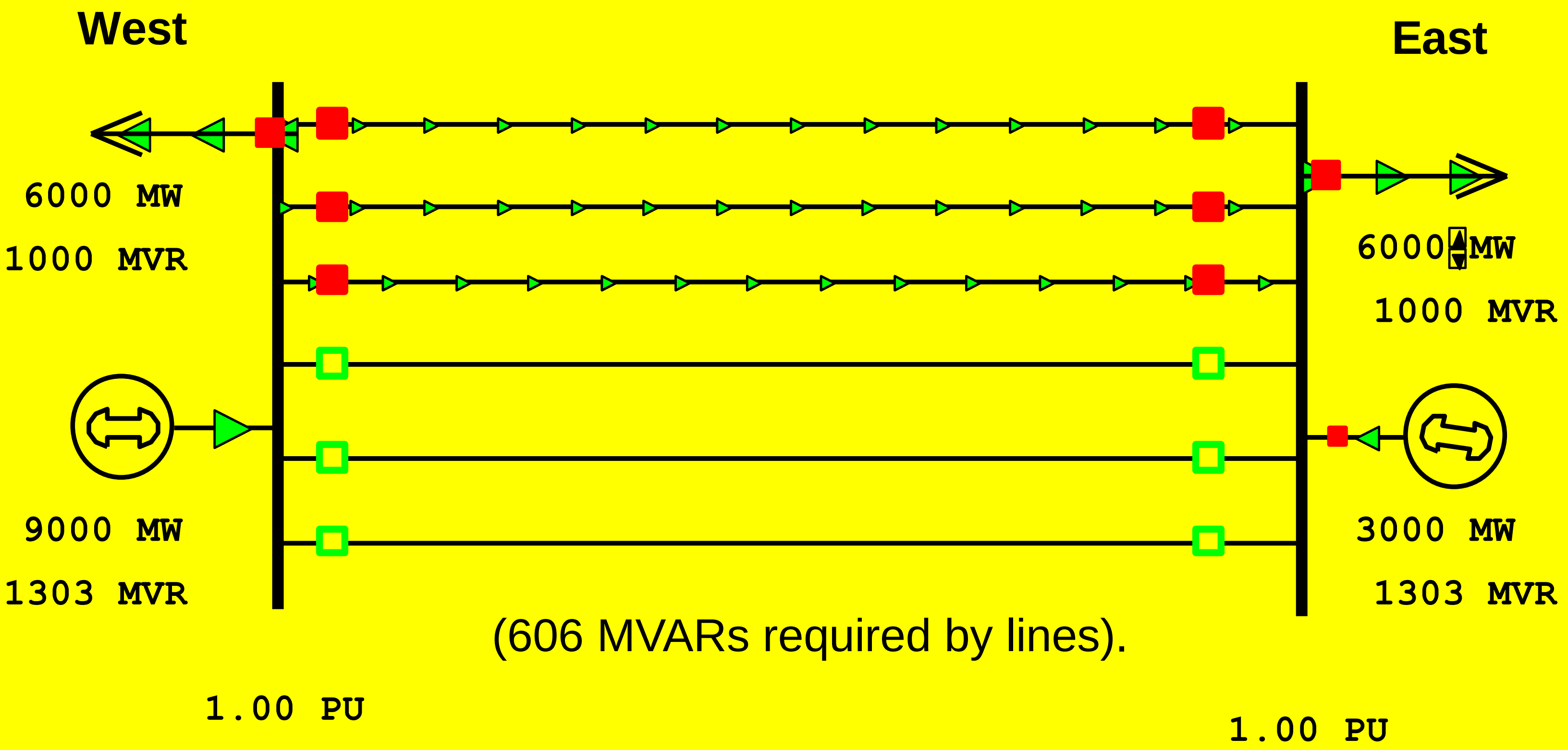
(infinite VARS available at both ends)



(452 MVARs required by lines).

Case 8: Three lines out - full voltage control

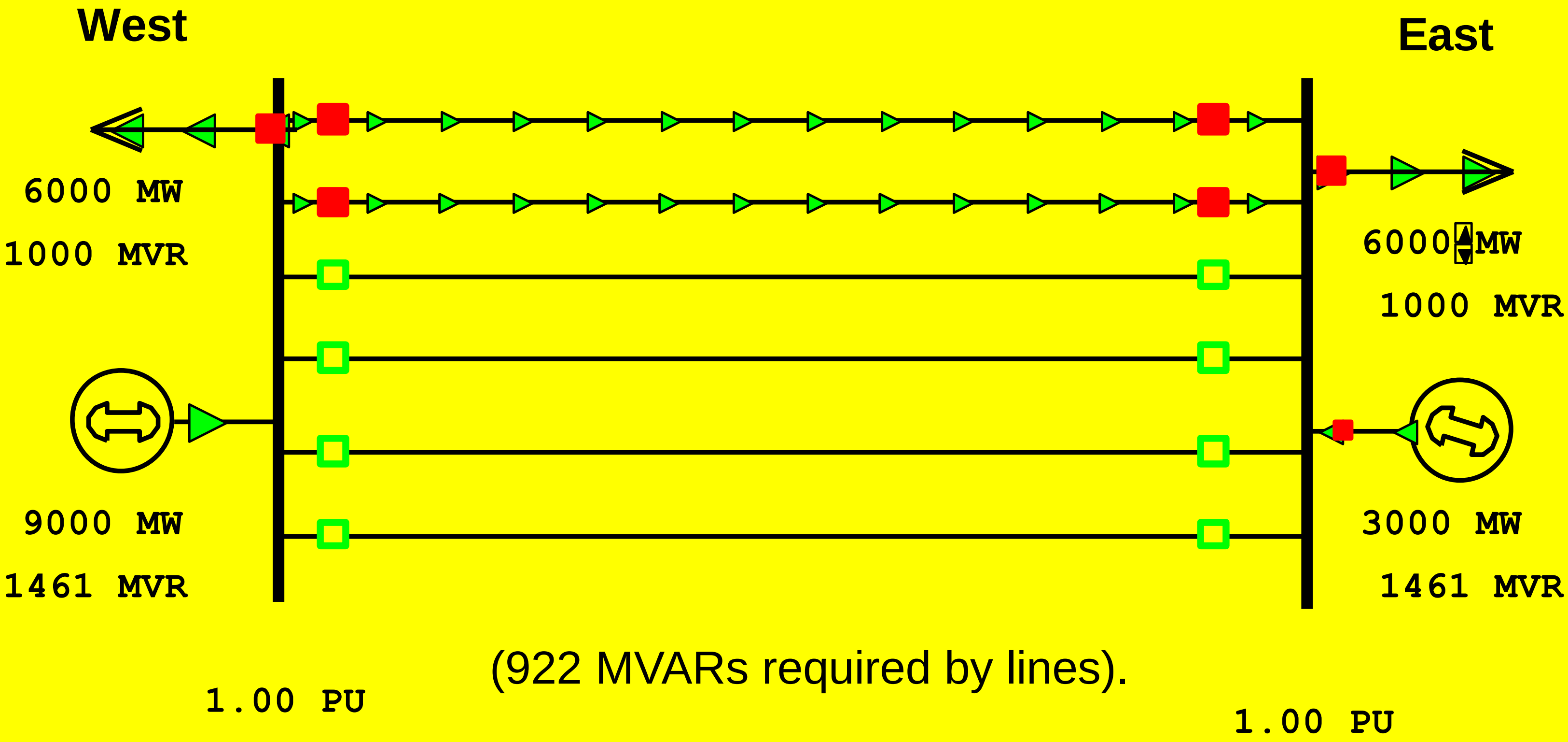
(infinite VARS available at both ends)



(606 MVARs required by lines).

Case 9: Four lines out - full voltage control

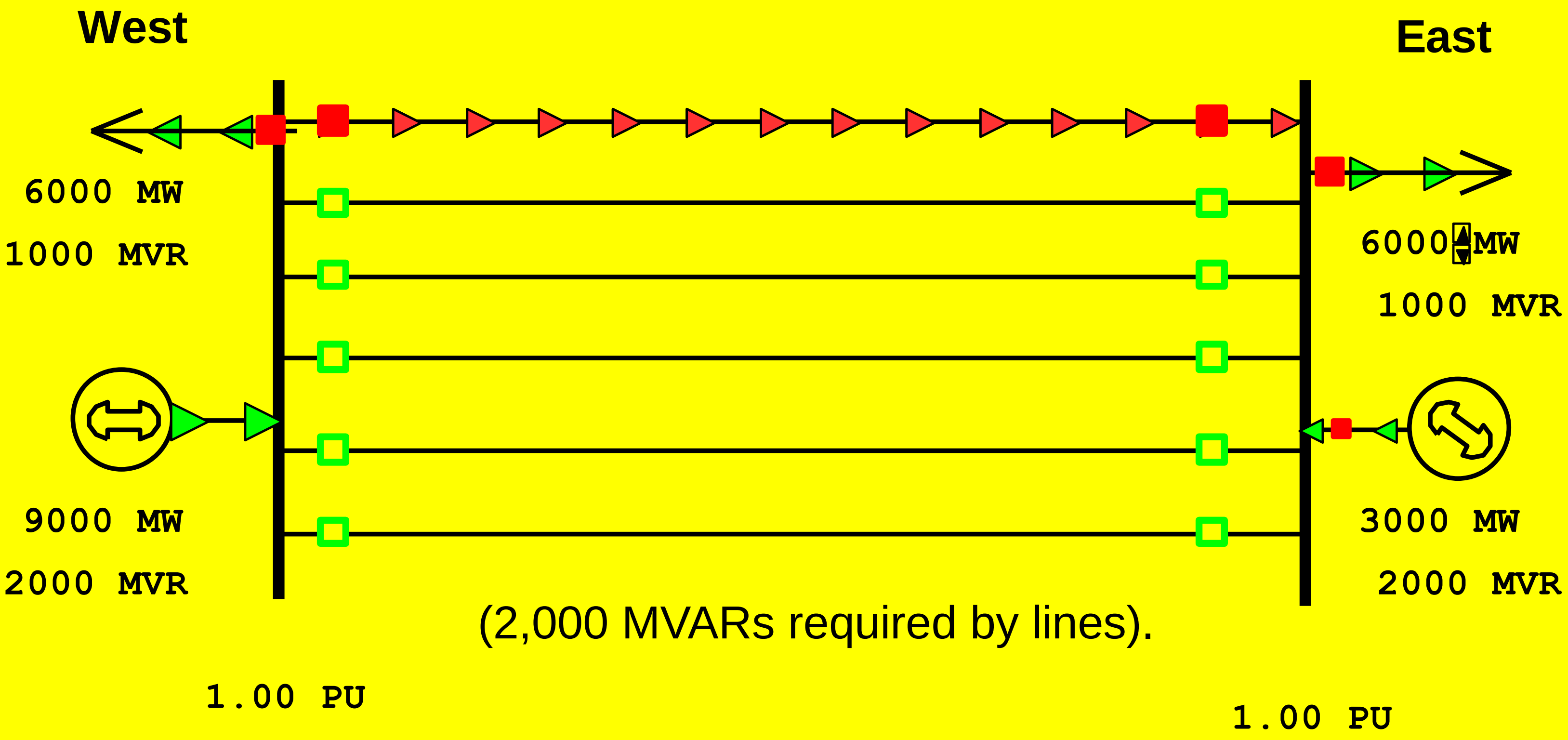
(infinite VARS available at both ends)



(922 MVARs required by lines).

Case 10: Five lines out - full voltage control

(infinite VARS available at both ends)



(2,000 MVARs required by lines).

Case 11: How much could this have handled (even an infinite supply of VARS at both ends would not help)?

4,900 MW