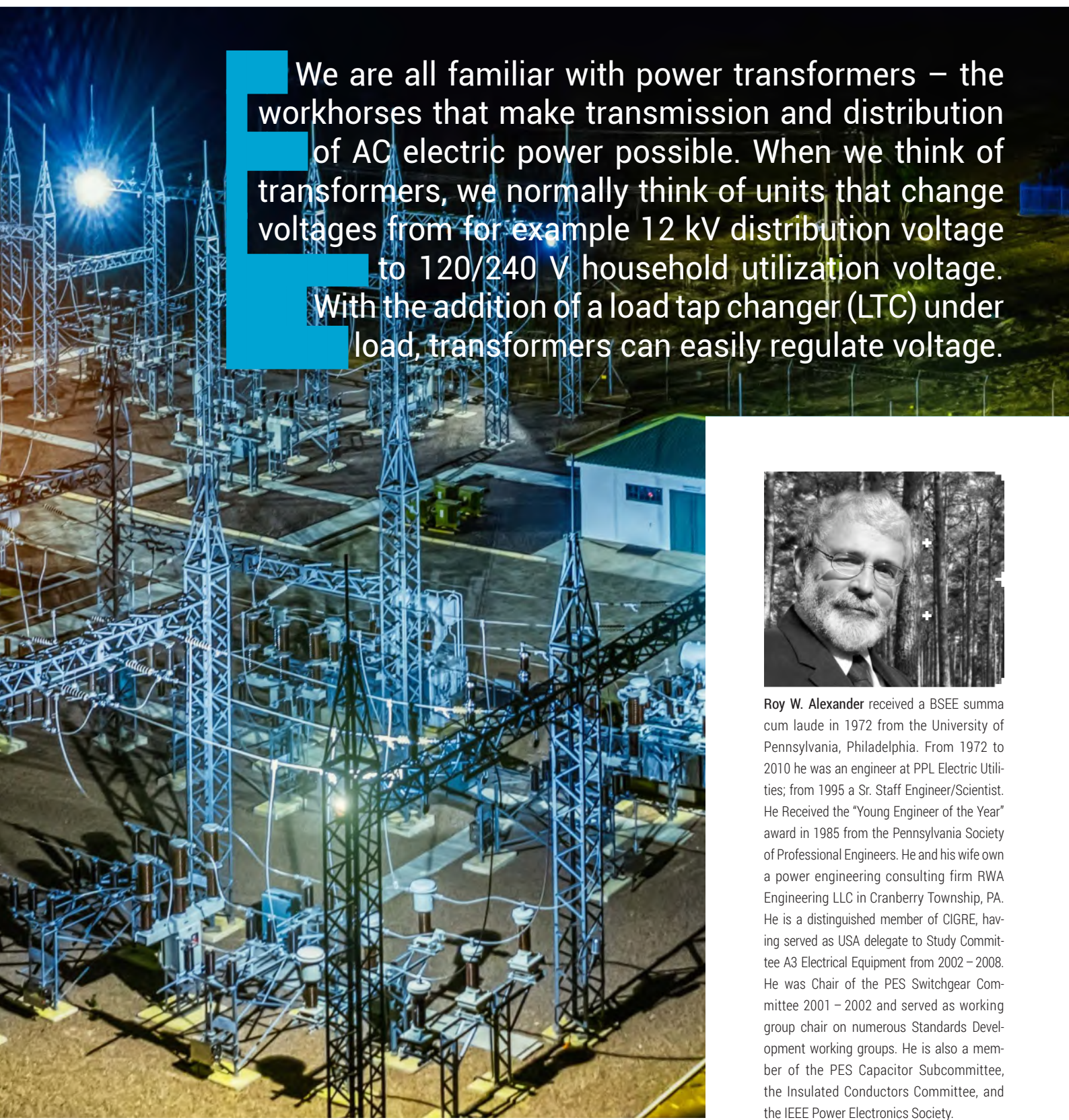


The Sen Transformer

by Roy W. Alexander
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We are all familiar with power transformers – the workhorses that make transmission and distribution of AC electric power possible. When we think of transformers, we normally think of units that change voltages from for example 12 kV distribution voltage to 120/240 V household utilization voltage. With the addition of a load tap changer (LTC) under load, transformers can easily regulate voltage.



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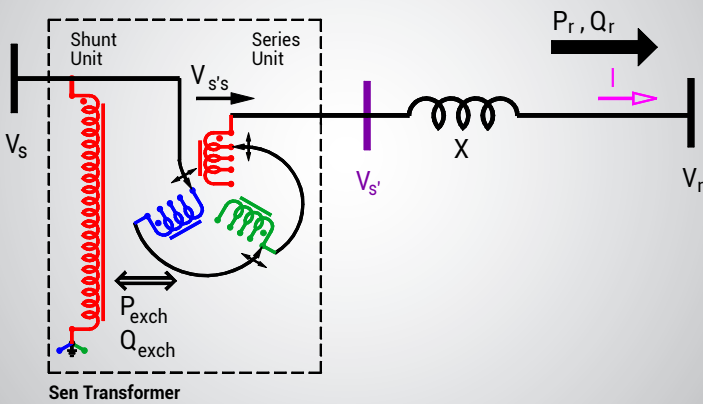
Special transformers can also regulate phase angle. But imagine a transformer which can independently regulate voltage and phase angle. Imagine a transformer that injects a compensating voltage ($V_{s's}$) in series

with the line, as shown in the single-line diagram in Figure 1, to act as a series-connected emulated impedance of all kinds – inductive, capacitive, resistive, or negative resistive while these real and reactive

components are independently variable. The ratio of the compensating voltage ($V_{s's}$) and the prevailing line current (I) through the line reactance (X) results in a virtual four-quadrant emulated impedance.

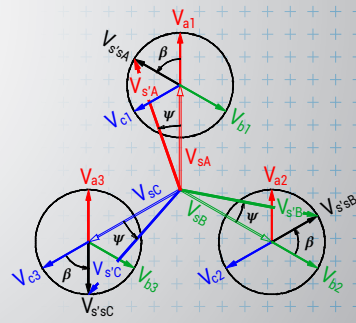
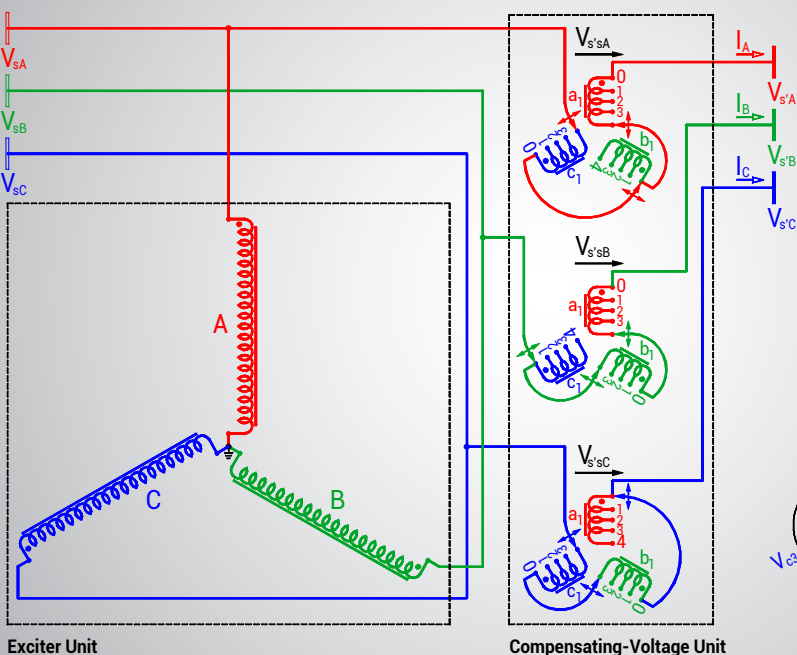
Imagine a transformer that injects a compensating voltage ($V_{s's}$) in series with the line, to act as a series-connected emulated impedance of all kinds – inductive, capacitive, resistive, or negative resistive while these real and reactive components are independently variable.

Figure 1. Single-line diagram of the Sen Transformer



The Sen Transformer uses a Shunt Unit, referred to as Exciter Unit, and a Series Unit, referred to as Compensating-Voltage Unit (Figure 1 and Figure 2). The Compensating-Voltage Unit creates a series-connected compensating voltage ($V_{s's}$) that is variable in magnitude and phase angle to modify the sending-end voltage (V_s) to the modified sending-end voltage (V_s') with desired magnitude and phase angle, needed for desired active and reactive power flows (P_r and Q_r) at the receiving end of the line with voltage (V_r). The compensating voltage ($V_{s's}$) is also at any phase angle with the prevailing line current. Therefore, it exchanges active and reactive powers (P_{exch} and Q_{exch}) with the line, which is equivalent to emulating an inductor (L) or a capacitor (C) and a positive resistor ($+R$) or a negative resistor ($-R$) in series with the line and, thereby, acting as an Impedance Regulator.

Figure 2. (a) Schematic winding development of the Sen Transformer; (b) Phasor diagram in power flow control mode

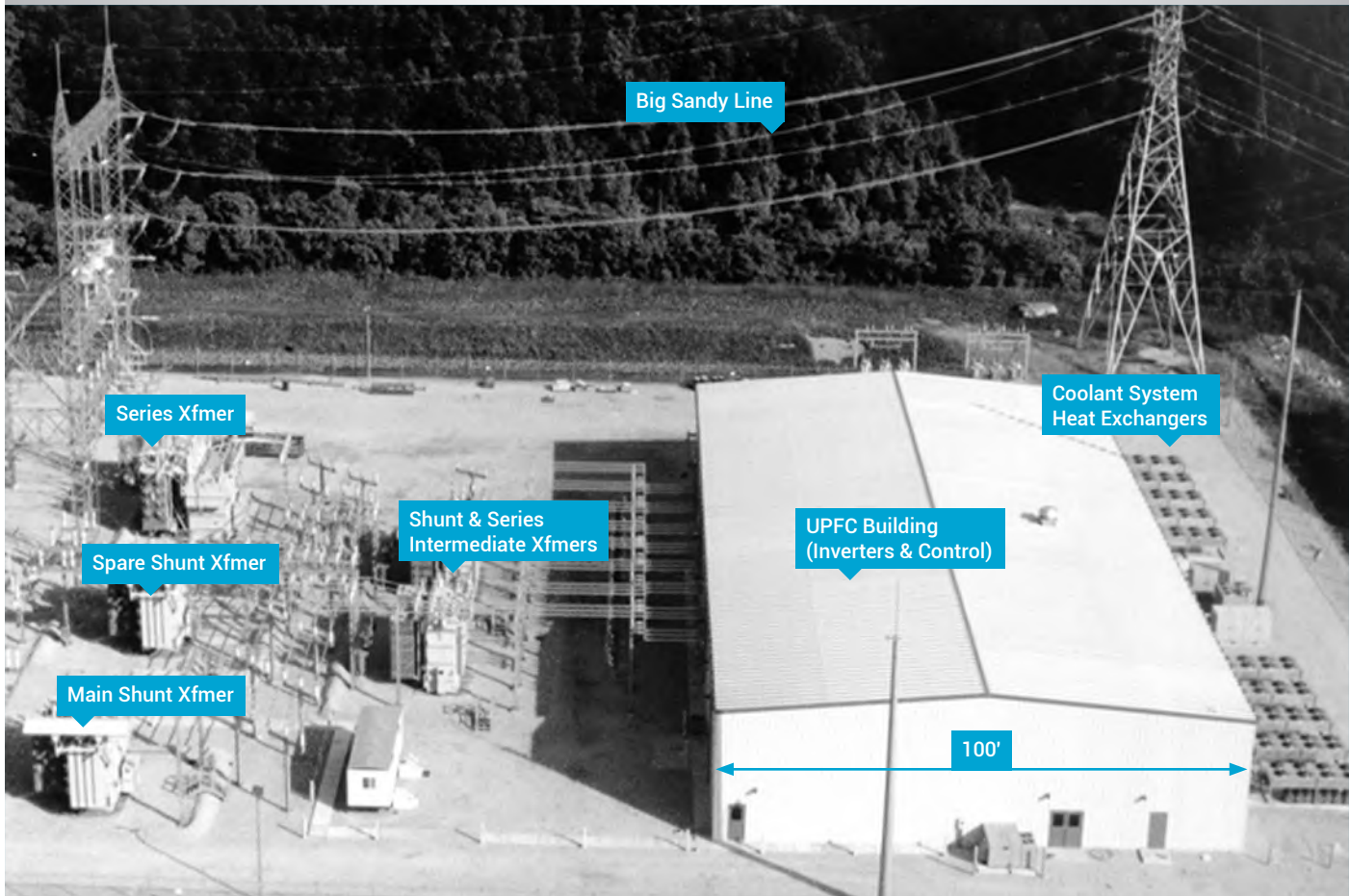


(a)

(b)

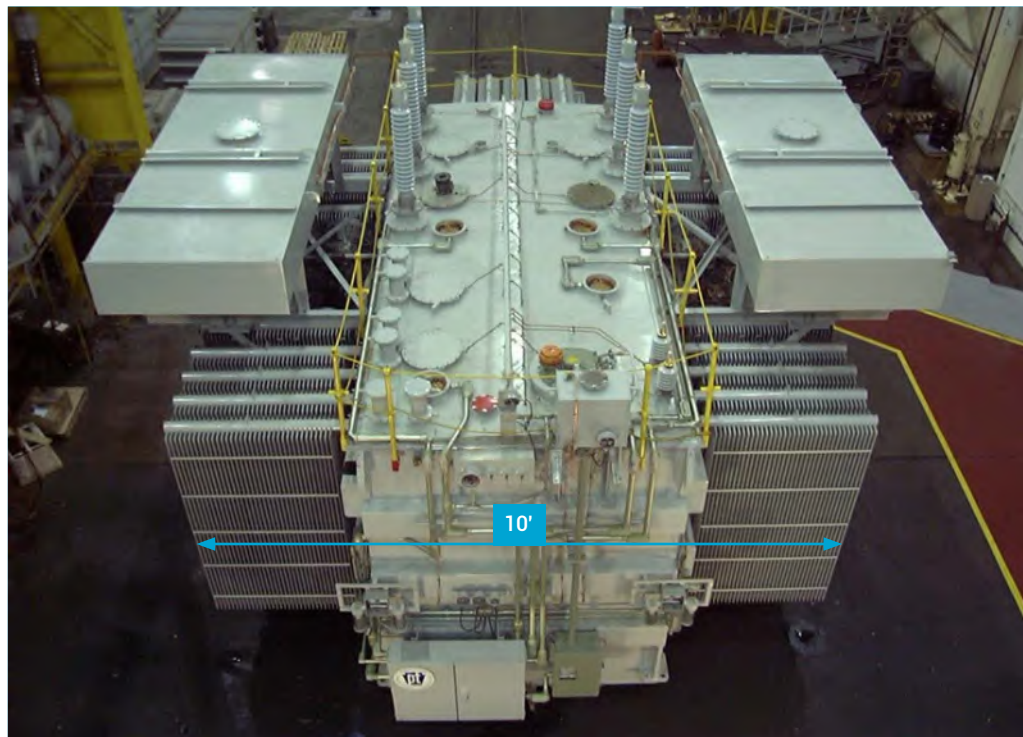


Figure 3. (a) Westinghouse-made power electronics inverter-based FACTS Controller at AEP's Inez substation; (b) Sen Transformer of comparable rating



(a)

As you can see from Figure 2(a), the Sen Transformer is a three-phase transformer with a shunt wye primary winding that provides the input energy to the transformer. The series-connected secondary windings induce the compensating voltage, using LTCs. Physically, consider a three-legged core. All four red windings are on one leg, all four blue windings on an adjacent leg, and all four green windings are on the third leg. Therefore, three windings, one from each core leg, are placed in series on each phase of the Series Unit of the Sen Transformer (see Figure 2(a) Compensating-Voltage Unit). Each core leg will have one shunt winding, connected phase to ground on the input side (Exciter Unit) and three series windings to be connected in series – one from each leg on each phase of the output side (Compensating-Voltage Unit).



(b)

To reiterate, in total there are three shunt windings, one per phase on each core leg of a three-leg core transformer (Exciter Unit); and nine secondary windings, three in series, one from each core leg connected on each phase of the Series Unit (Compensating-Voltage Unit) of the Sen Transformer. There are nine LTCs, so the nine series windings can each be controlled separately. The Series Unit of the Sen Transformer can be made to look like an inductor or a capacitor, and a resistor or a negative resistor with respect to the phase under consideration. With the series winding of a Sen transformer placed into a network, the line which it is connected with can have its real and reactive impedance controlled independently. Thus, active and reactive power flows can be varied independently as desired. The switches for the tap changer are preferably mechanical vacuum or oil switches. These can respond in seconds, which is usually fast enough for utility power flow control needs.

If faster response is needed, the switches can be based on power electronics thyristors which, once turned on, commute naturally. This will move response time from seconds to 50 ms, a 100-fold increase in response speed. This would increase cost and decrease reliability significantly. Almost never is such a faster response time needed.

The response time can even be reduced further to a few milliseconds if a power electronics inverter-based FACTS controller is used, as shown in Figure 3(a). These inverters use force-commuted switches such as gate-turn-off (GTO) thyristors.

The Sen Transformer can provide the same power flow control functionality as the more expensive, high maintenance, and non-mobile power electronics inverter-based FACTS controllers does. Compare the sizes and footprints of the two similarly capable power flow controllers in Figure 3.

The power electronics inverter-based solution offers a response time

that is several orders of magnitude (several seconds versus several milliseconds) faster than the Sen Transformer, but this superfast response capability goes unused in most utility applications. The Sen Transformer uses time-tested, readily available, highly reliable power transformer components. It is inherently more efficient because the mechanical switches in LTCs do not suffer from the high conduction loss from on-state voltage drop and



even higher switching loss from transitioning on-to-off and off-to-on several thousand times every second. These two losses the semiconductor switches cannot avoid.

Another drawback of power electronics inverter-based solutions is that the semiconductor devices, such as GTO thyristors, used in the first-generation FACTS controllers, are not available. The industry moved on to using Insulated Gate Bipolar Transistors (IGBTs).

The upcoming switches are based

on Gallium Nitride (GaN) and Silicon Carbide (SiC) due to their inherent advantages of high-speed operation, which results in lower losses, high-temperature operation, lower cooling requirement and smaller gate drive and smaller snubber circuits.

Therefore, FACTS controllers become obsolete in a relatively few years so that one-for-one component replacement becomes impossible in less than 10 years. In the utility world where 40-year equipment life is the norm, this means the entire power electronics inverter-based FACTS installation may need to be replaced several times in that 40 years. Simple maintenance of the power electronics requires highly skilled personnel that are not readily available. The global standard and interoperability do not exist due to a limited number of manufacturers. The inverter-based power electronics FACTS Solution is a highly expensive proposition, perhaps two orders of magnitude more expensive than a long-lived and easily-maintained Sen Transformer.

The Sen Transformer is an obvious winner for power flow control needs for the utilities worldwide.

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