

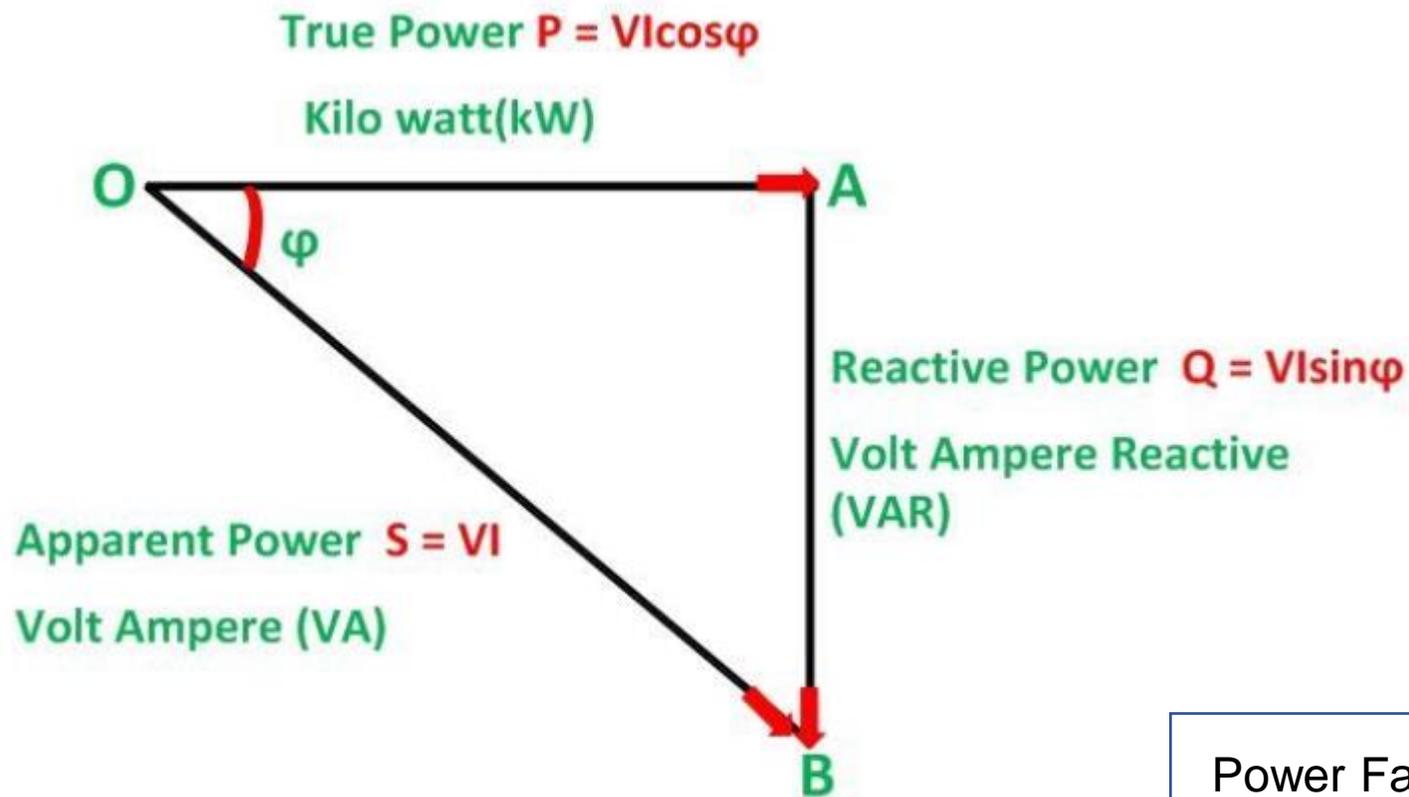


EMPOWERING THE ENERGY TRANSITION



POWER WAGON
Real & Reactive Power,
Power Factor, and
Phase Imbalance Explained

Power Triangle is the representation of a right-angle triangle showing the relation between true power, reactive power, and apparent power. True power is also known as active power or real power. When each component of the current that is the active component ($I\cos\phi$) or the reactive component ($I\sin\phi$) is multiplied by the voltage (V), a power triangle is obtained shown in the figure below:



Simple power means the product of voltage and current ($P=VI$), but in an AC circuit - except for pure resistive circuit - there is usually a phase angle difference between voltage and current and thus VI does not give real or true power in the circuit.

$$\text{Power Factor } \cos\phi = \frac{\text{True Power}}{\text{Apparent Power}} = \frac{\text{kW}}{\text{kVA}}$$

Power Factor (Leading and Lagging)



Figure 1 - Leading Power Factor

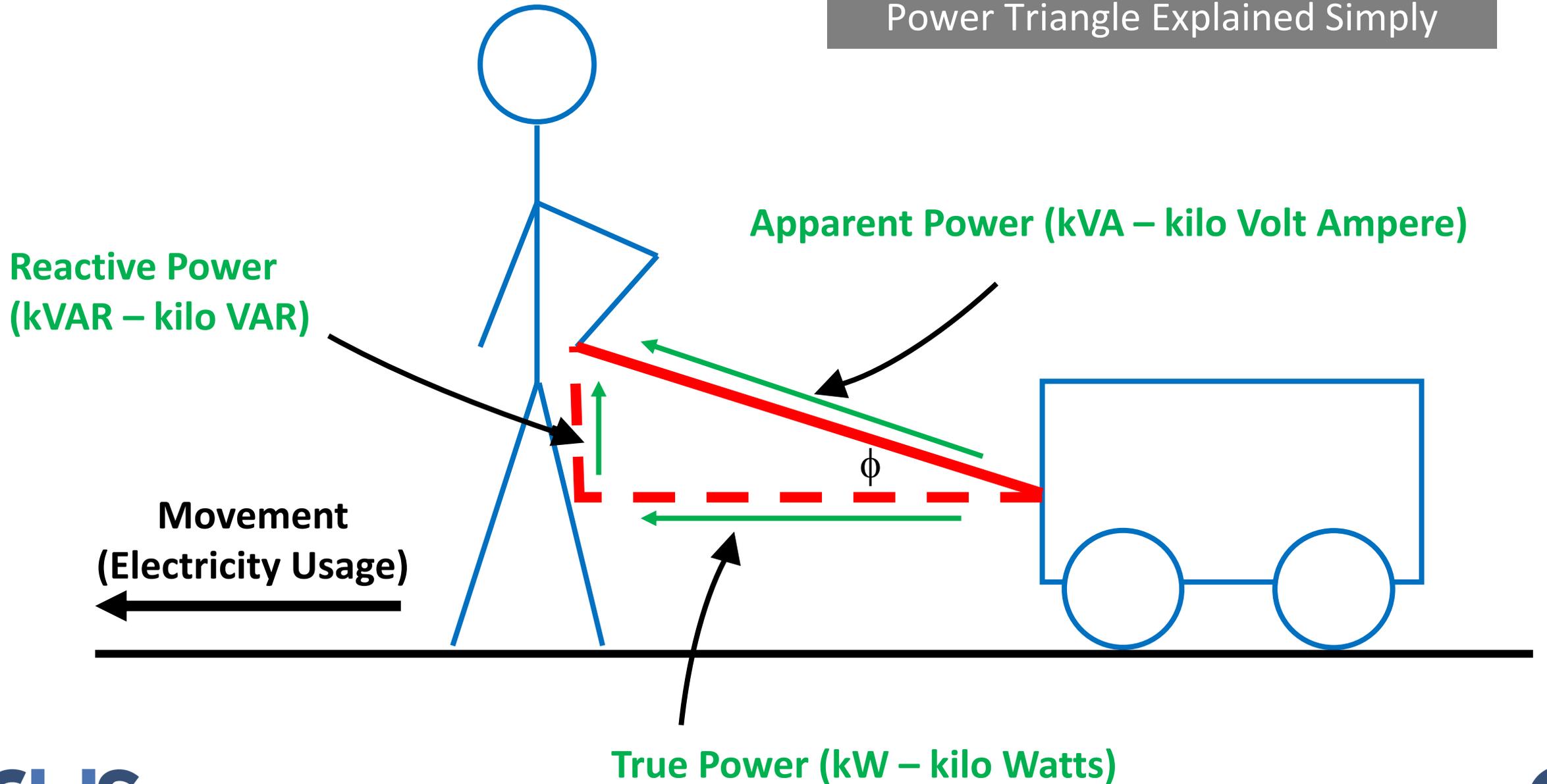
The leading power factor of the load signifies that the load is capacitive, and it will deliver reactive power. When the load current leads the supply voltage, then the load is said to have **leading power factor**.



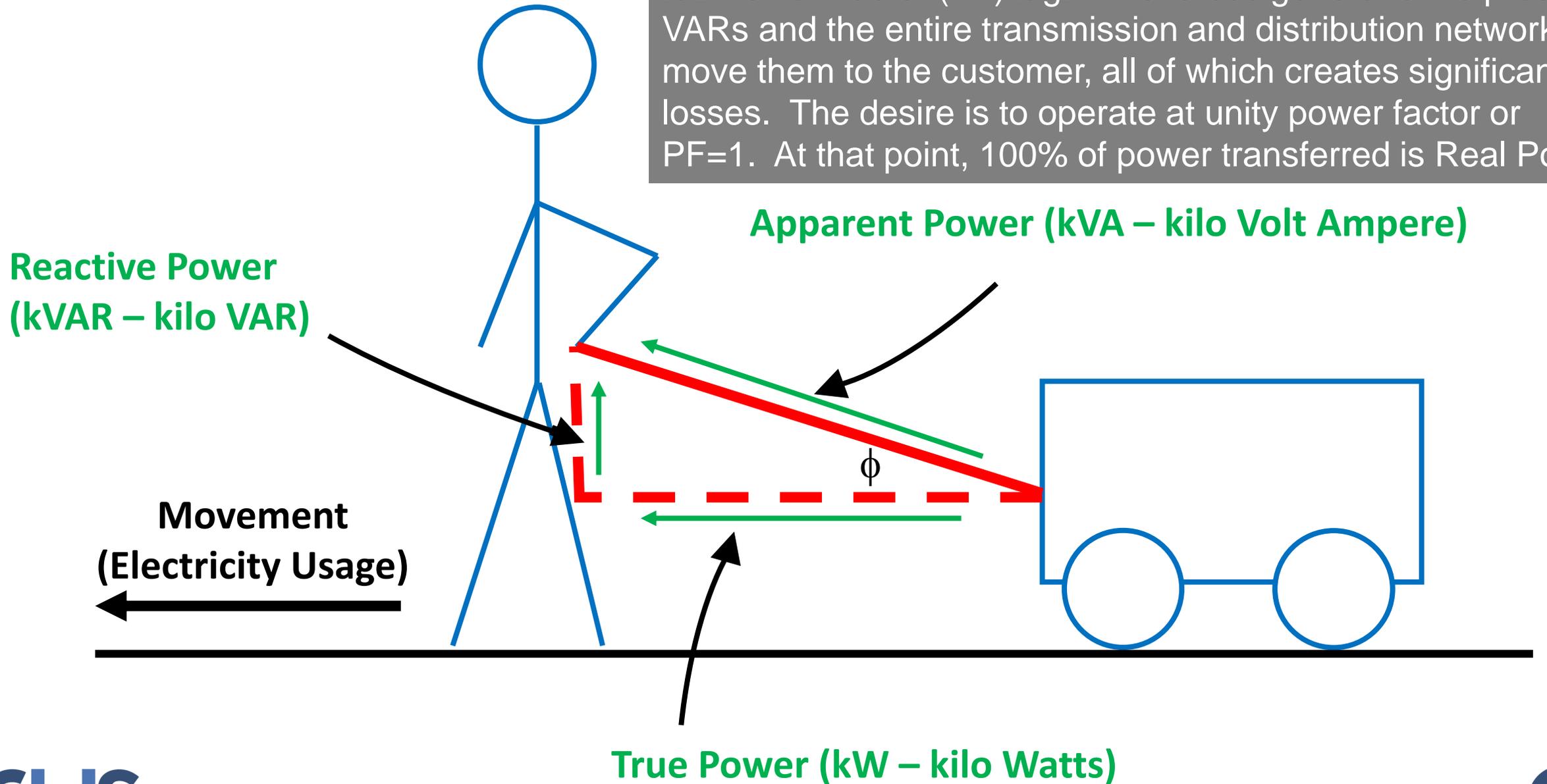
Figure 2 - Lagging Power Factor

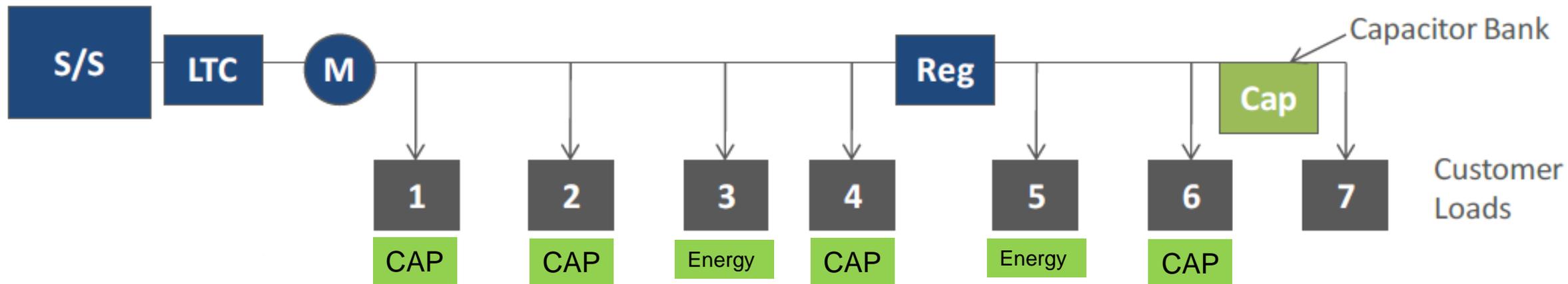
The lagging power factor of the load signifies that the load is inductive, and it will consume the reactive power. When the load current lags behind the supply voltage, then the load is said to have **lagging power factor**. Most load on the grid drive power to lag and our distribution feeders typically operate between 0.80 and 0.95 PF lagging. (Average typically below 0.90)

The 'Power Wagon' Power Triangle Explained Simply



Today, distribution feeders typically operate between .84 and .92 Power Factor (PF) lag. This forces generation to produce VARs and the entire transmission and distribution network to move them to the customer, all of which creates significant losses. The desire is to operate at unity power factor or PF=1. At that point, 100% of power transferred is Real Power.

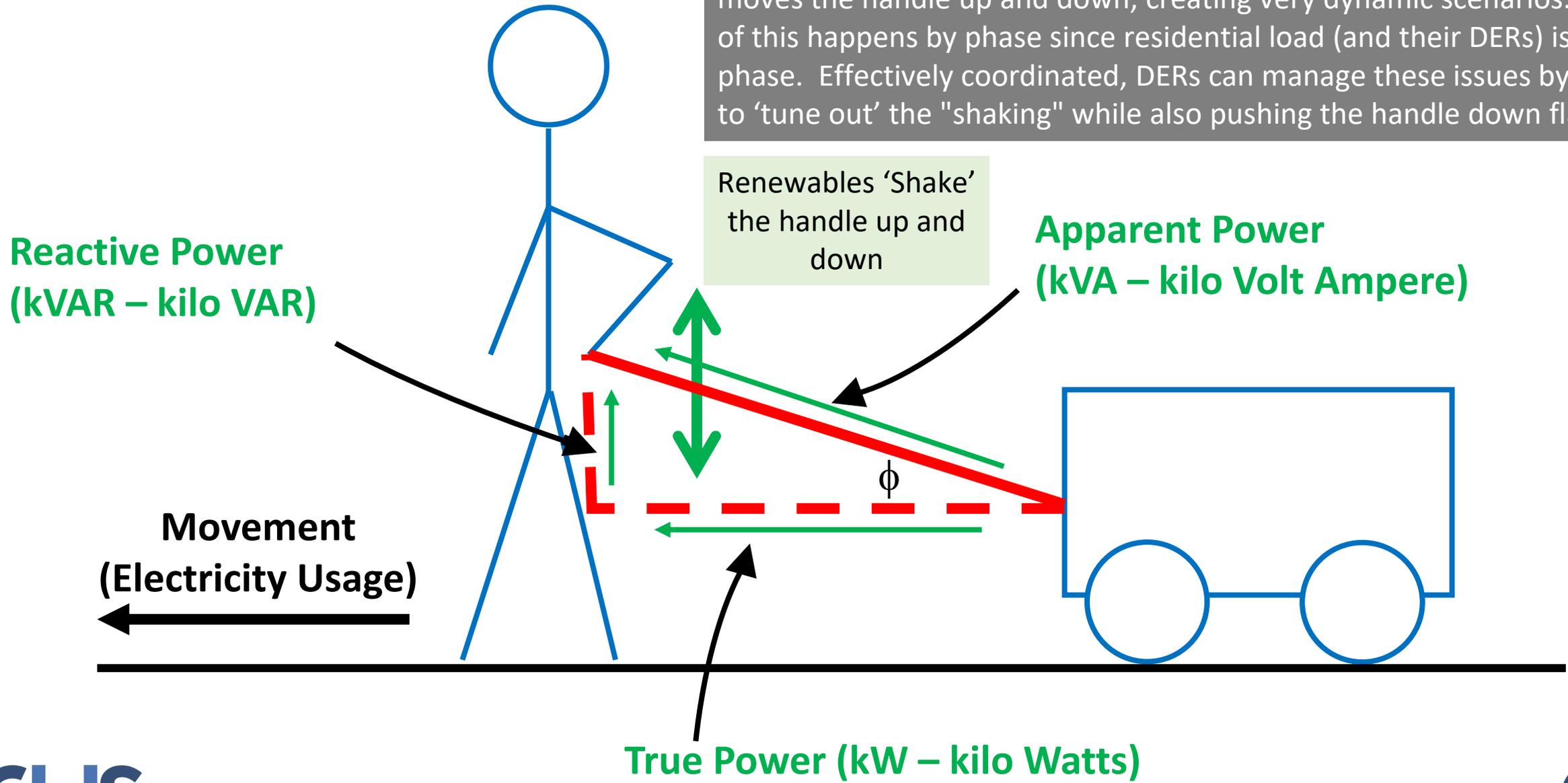




DERs have the ability to create new sources of VARs on the distribution system to optimize Power Factor (close to unity). Each premise with a DER and a four-quadrant inverter can dynamically make decisions to operate the DER (for example, a roof-top solar installation) as a real power generator or a capacitor bank. This means these resources can optimize the grid from the edge and eliminate significant technical losses on the entire grid. These savings will swamp traditional EE program savings.

In addition, DERs have the ability to do this **BY PHASE** of the distribution system. Each phase of a distribution system feeder operates independently, and Phase Imbalance can get so bad that it actually causes the entire feeder to trip offline. With significant introduction of renewables and batteries, phase balance is getting more difficult to maintain. Phase Imbalance and low Power Factor have been issues on the grid since Westinghouse and Tesla won the "current war" and we built AC power systems. DERs can fix these issues.

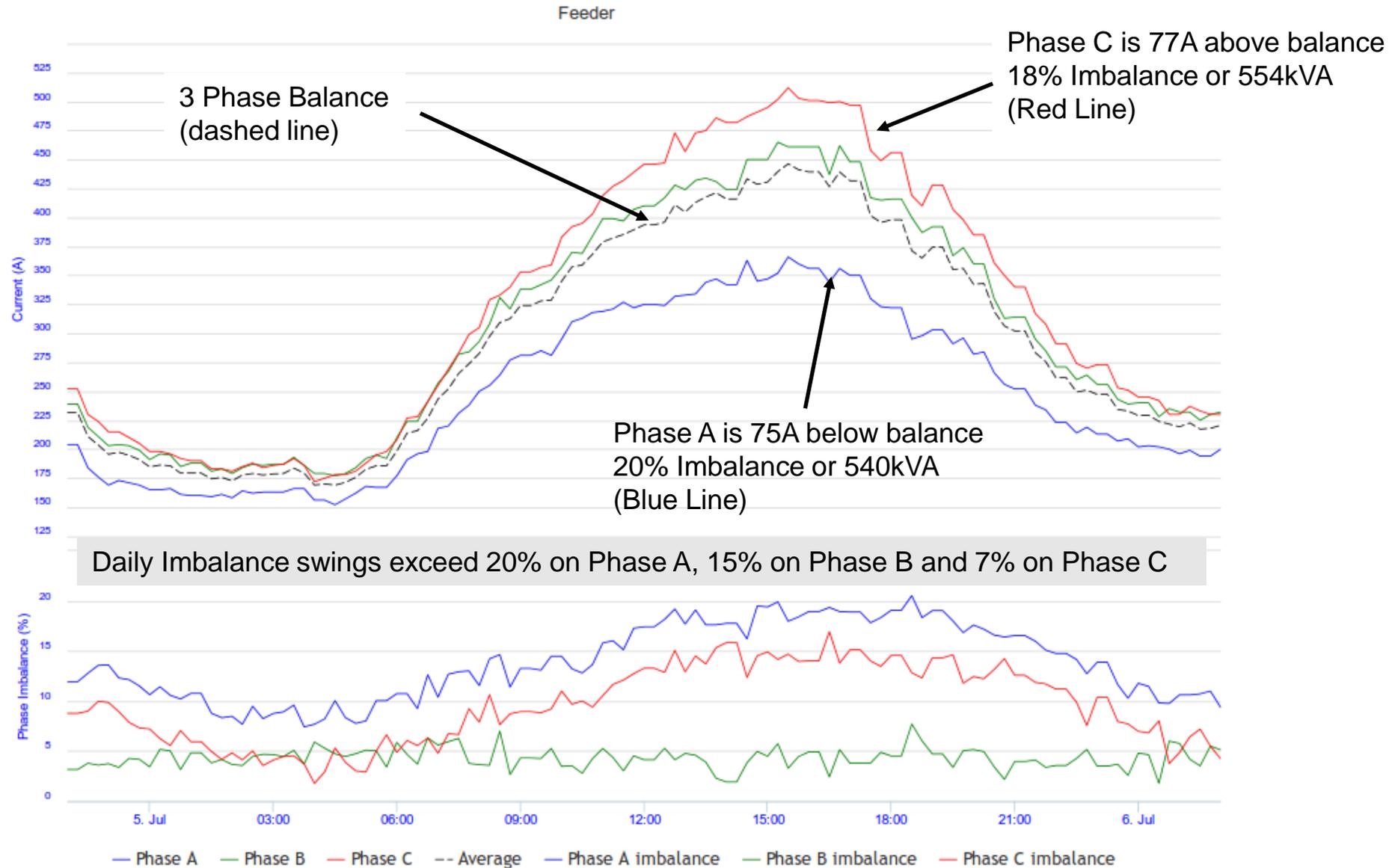
Today's grid operates inefficiently with the handle constantly being pulled at an angle. Moreover, distributed renewable generation rapidly moves the handle up and down, creating very dynamic scenarios. All of this happens by phase since residential load (and their DERs) is single phase. Effectively coordinated, DERs can manage these issues by phase to 'tune out' the "shaking" while also pushing the handle down flat.



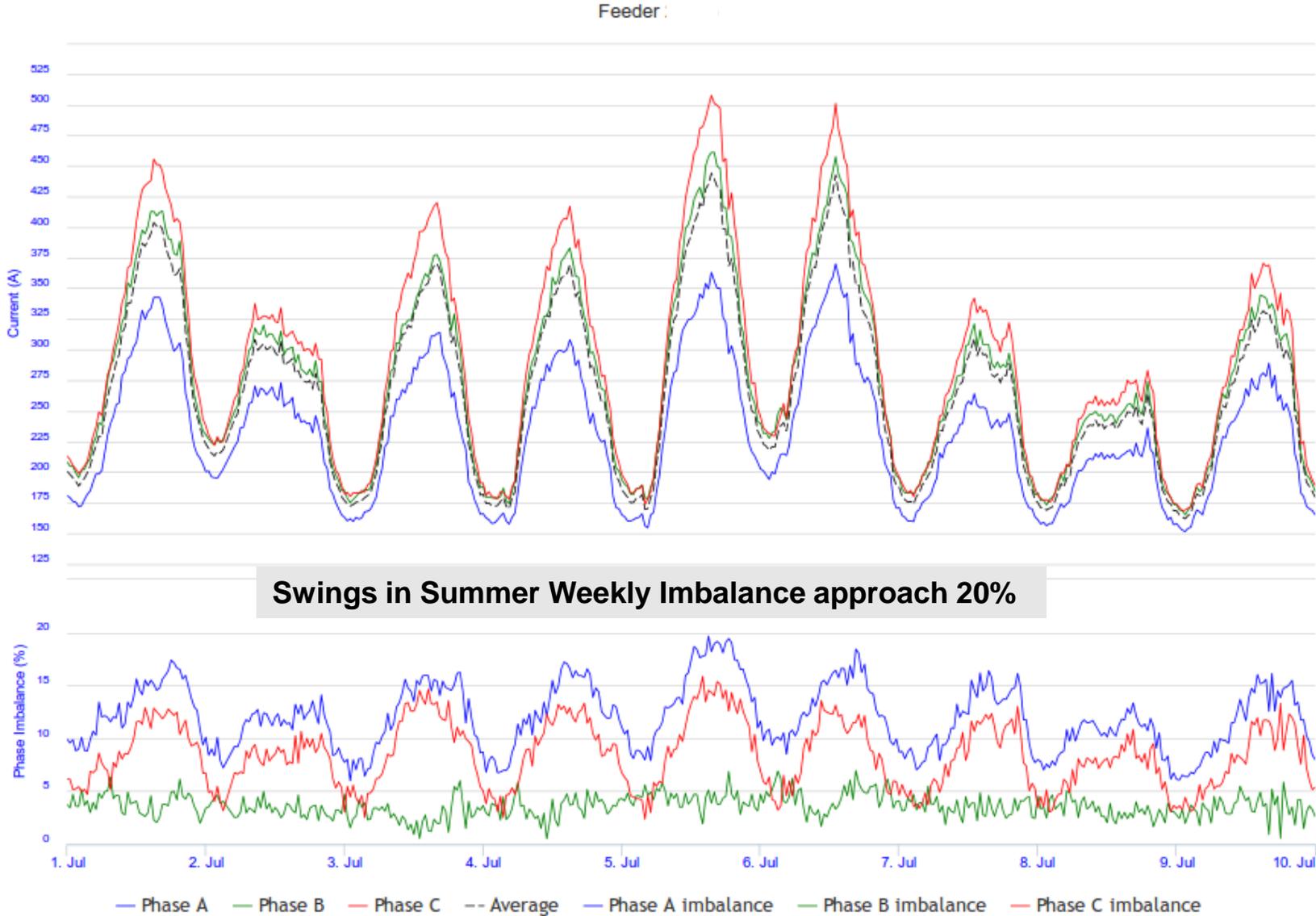
Phase Balancing

- Imbalance is very dynamic.
- Imbalance changes throughout the day and from season to season.
- Due to its dynamic nature, traditional solutions for correcting imbalance cannot bring systems into balance.
- For example, fixing summer imbalance could make winter imbalance worse as the same loads causing imbalance in each season are not the same.

Feeder Imbalance (Single Day – July 5th)

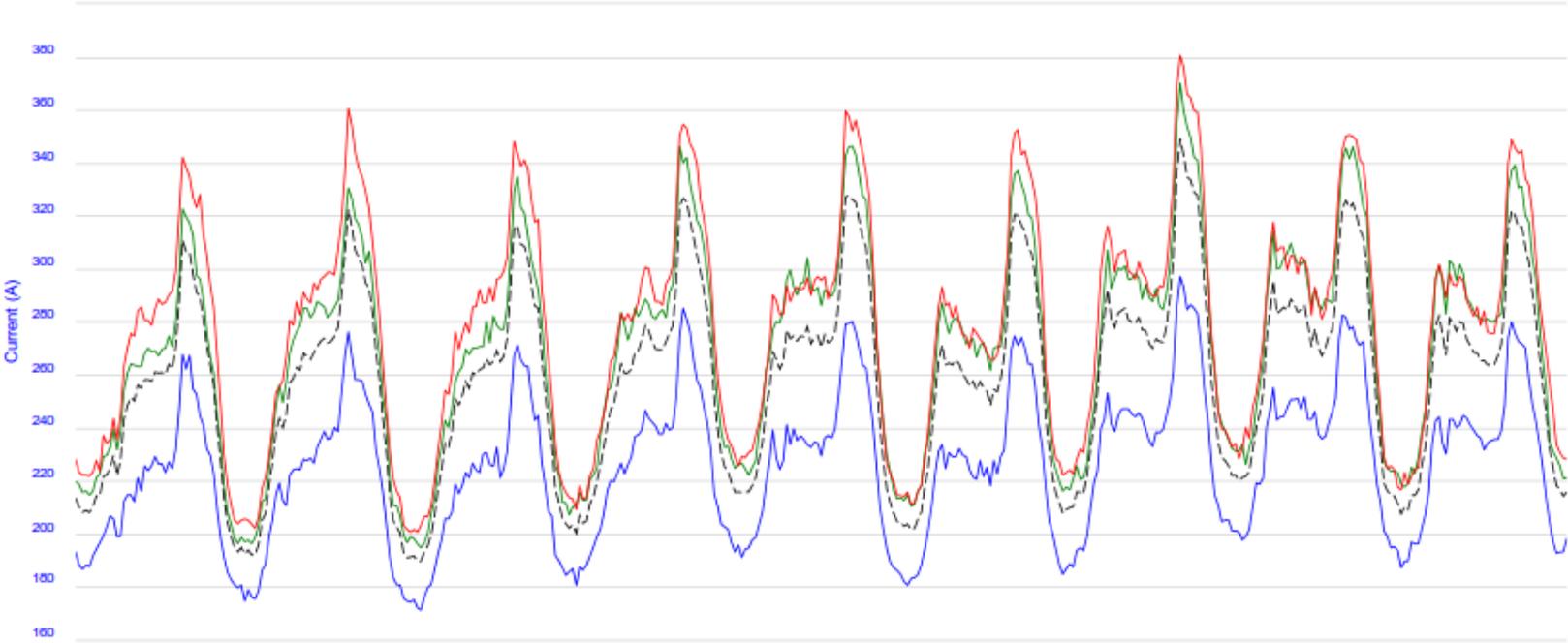


Feeder Multi Day Summer

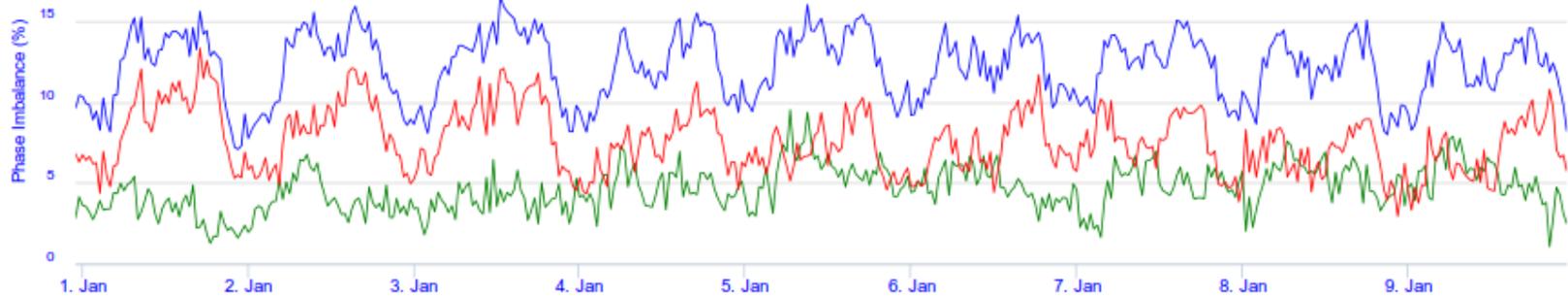


Feeder Multi Day Winter

Feeder



Swings in Winter Weekly Imbalance exceed 15%



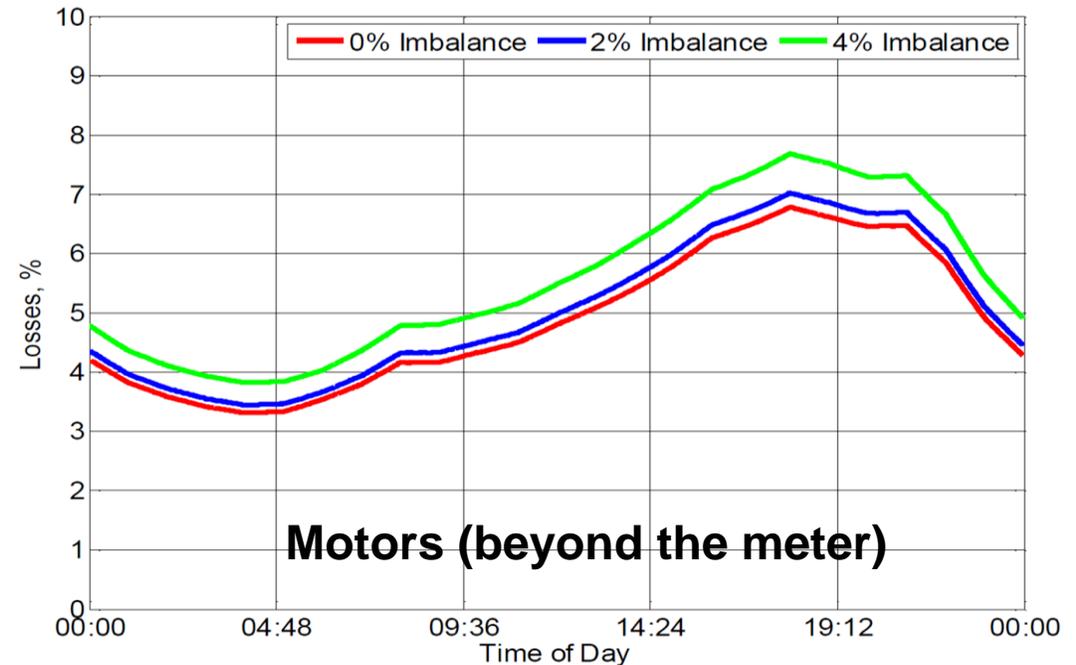
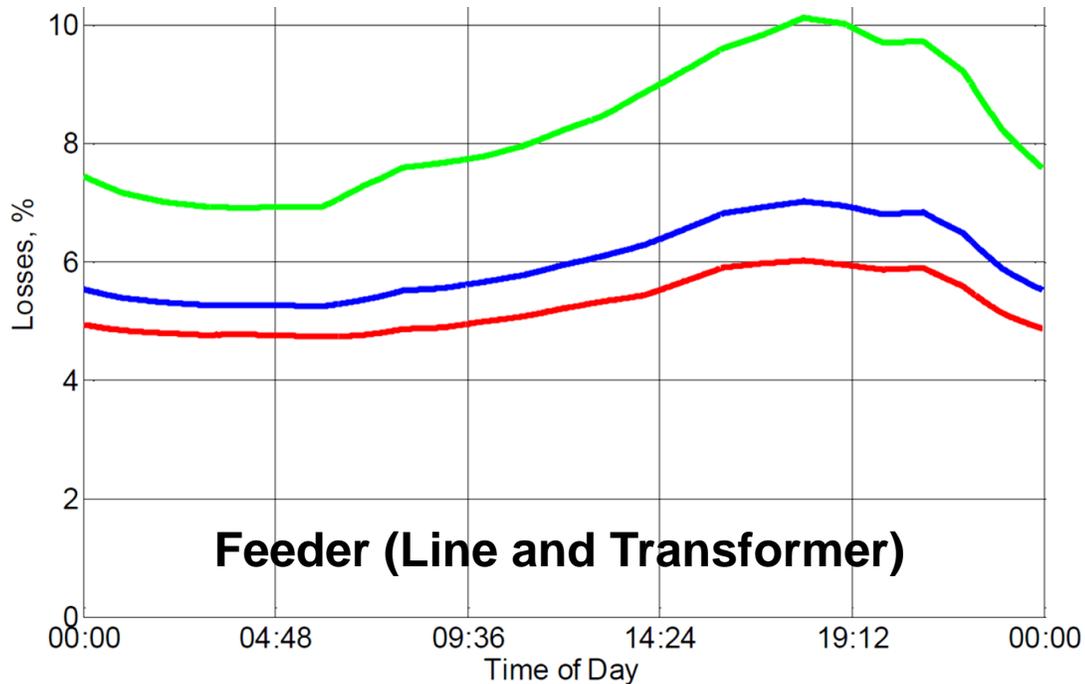
— Phase A — Phase B — Phase C -- Average — Phase A imbalance — Phase B imbalance — Phase C imbalance



Total Losses Due to Imbalance

- In a detailed study with Enernex, a typical feeder was modeled under the ideal of 0% imbalance (balanced condition) to determine expected grid losses and motors losses on the customer side of the meter (red lines).

Modeling the phase imbalance of 2%(blue) and 4%(green) create the baselines for the problem to be solved: **These graphs demonstrate an opportunity of 40% in reduced losses with a 4% correction in imbalance.**



Grid Efficiency Savings for PF and PB correction

- Correcting Power Factor and Phase Balance on the grid could eliminate 40%-60% of the technical losses on the grid and consumer load technical losses.
- Consider that technical losses on the grid are typically between 6%-12% and consumer technical losses due to low PF and Phase Imbalance are another 20%-50%.
- One example: For a grid with approximately 400 million MWH consumed in each year, a 4% improvement in PB and moving PF to unity would yield a 5.5% savings in grid losses. That would yield 22 million MWH hours saved, or ~2,500MW of baseload generation running 24x7x365. This swamps the value of other EE measures, and these savings on the distribution grid would have a material impact on the transmission grid and its stability.
- There is enough capacity in the distribution grid to absorb high penetration rates of EVs with no infrastructure additions if we optimize DERs and their deployment.
- At the same time, resiliency, reliability, and markets can be stabilized, helping to drive high peak pricing and grid instability out of the energy ecosystem.

Utilities don't talk PF and PB problems

Name	Source Voltage (kV)	Nominal Voltage (kV)	Max Nm Plate Rt	Limit Cap (MVA)	Limit Factor	Power Factor (%)	Unbal. Factor (%)	2016	Forcst Adj. (MVA)	AGR (MVA)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Comments
SUBSTATION NAME	69.0	12.47	9.38	12.83	Winding	0.00	28.57	6.88	0.00	0.00	6.88	<u>6.73</u>	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73	Unbalanced
Feeder 21		12.47		11.45	OH Exit	0.00	10.19	2.82	0.00	0.00	2.82	<u>2.67</u>	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	Unbalanced
Feeder 22		12.47		11.45	OH Exit	0.00	18.91	3.76	0.00	0.00	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	Unbalanced
SUBSTATION NAME	138.0	12.47	22.40	25.92	Switching	0.00	4.13	21.95	0.00	0.20	<u>22.85</u>	23.05	23.25	23.45	23.65	23.85	24.05	24.25	24.45	24.65	24.85	Approaching rated capacity
Feeder 21		12.47		11.45	OH Exit	86.60	10.20	8.82	0.00	0.10	<u>9.62</u>	9.72	9.82	9.92	10.02	10.12	10.22	10.32	10.42	10.52	10.62	Approaching rated capacity and Unbalanced
Feeder 22		12.47		13.67	UG Exit	93.17	2.27	5.28	0.00	0.00	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	
Feeder 23		12.47		11.45	OH Exit	92.68	9.52	3.78	0.00	0.10	3.88	3.98	4.08	4.18	4.28	4.38	4.48	4.58	4.68	4.78	4.88	
Feeder 24		12.47		13.67	UG Exit	92.89	27.66	2.82	0.00	0.00	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	Unbalanced
SUBSTATION NAME	138.0	12.47	12.50	15.56	Winding	91.40	15.70	8.22	0.00	0.08	8.30	8.38	8.46	8.54	8.62	8.70	8.78	8.86	8.94	9.02	9.10	Unbalanced
Feeder 21		12.47		13.85	UG Exit	89.14	32.02	4.62	0.00	0.04	4.66	4.70	4.74	4.78	4.82	4.86	4.90	4.94	4.98	5.02	5.06	Unbalanced
Feeder 22		12.47		13.85	UG Exit	93.17	12.35	3.81	0.00	0.04	3.85	3.89	3.93	3.97	4.01	4.05	4.09	4.13	4.17	4.21	4.25	PF and Unbalanced

The reality is that we have had limited, or no, options to solve these problems for past 100 years so they are fundamentally ignored unless they become critical. DERs change this entire discussion.

The importance of fixing existing grid issues

- PF and PB Effects are dramatic – We know it but have not been able to fix it, so we ignore it. An example from a utility IRP is shown below. We make it the consumer's problem through riders like this one. While 'bad actor' consumers should pay their own way as this rider stipulates, the entire grid is operating below a PF of 0.90 every day and DERs can help us solve this.

D. Reactive Adjustment Rider

Customers with low power factors impose a burden on the electrical system causing a utility to increase its generation, transmission, distribution, transformer capacities and energy generation. Power factors are functions of real power (kW) and the apparent power (kVA) a utility must supply to the customer. For any given-metered load in kW, the lower the power factor, the greater the amount of power (kVA) a utility must generate and deliver to the customer. For example, in order to supply a load of 100 kW having a power factor of 85% the utility would have to generate and deliver approximately 117.6 kVA. An 85% power factor would require equipment with 17.6% more capacity to meet this demand. Further, since system losses vary as the square of the amperage required to serve the load, there is at the same time a 36% increase in system losses. BPU rates are designed to permit a customer to have a power factor equal to or greater than 90%. Customers with power factors less than 90% are penalized.