National Electrical Manufacturers Association

NEMA US 80026-2023

Source VA—Infrastructure Sizing for Polyphase Systems

Contents

Introduction 1

Executive Summary 1

Progression of Incentives 2

Total Consumption—kWh 2

Demand Metering—Peak kW 2

Apparent Power (Single-Phase VA)—kVA 4

Apparent Power (Polyphase VA)—Source VA 5

Polyphase Terminology 6

Polyphase VA Background 7

Source VA Objective 9

Source VA Method 10

Source VA: 4-Wire Wye System 10

Source VA: 3-Wire Delta System 10

Source VA and System Efficiency 12

Variant Service Types and "VA Basis" 17

Closing Summary 19

Figures

Figure 1 Progression of Incentives—Level 1 2

Figure 2 Demand Metering 3

Figure 3 Progression of Incentives—Level 2 3

Figure 4 Apparent Power (Single-Phase) 4

Figure 5 Progression of Incentives—Level 3 5

Figure 6 4-Wire Y, Single Cross Phase Load 7

Figure 7 4-Wire Y, One Lead and One Lag PF Load 8

Figure 8 3-Wire Delta, Single Phase to Phase Load 9

Figure 9 Typical 3-Wire Delta System 11

Figure 10 Unbalanced per Phase PF 12

Figure 11 4-Wire Wye, Single Cross Phase Load 13

Figure 12 4-Wire Wye, Balanced Cross Phase Load 14

Figure 13 3-Wire Delta, Single Cross Phase Load 15

Figure 14 3-Wire Delta, Balanced Cross Phase Load 16

Figure 15 Progression of Incentives—Level 4 17

Figure 16 3-Wire Open Delta 18

Figure 17 Progression of Incentives Level 4 with VA Basis 19

Introduction

Apparent power, in units of volt-amperes, VA, is one of several factors for sizing the infrastructure needed to deliver electrical energy. Source VA is a method of measuring VA specifically tailored for polyphase systems, and this paper gives an overview of this Source VA method. The rationale for Source VA is that unlike other methods of polyphase VA metering, Source VA gives a consistent physical interpretation of the VA requirements of the source regardless of the connection system (wye versus delta, etc.), whether loads are balanced or unbalanced, and in the presence of harmonics.

More complete information regarding Source VA and the differences between Source VA and other polyphase VA metering methods is provided in ANSI C12.24 TR-2022 *Definitions for Calculations of VA, VAh, VAR, and VARh for Electricity Meters*. This technical report includes associated service requirements for 4-wire Y, 3- and 4-wire delta, 3-wire wye, 3-wire network, and 4-wire Scott-T service configurations. The technical report can be downloaded at www.nema.org.

Executive Summary

This paper presents an improved method of polyphase VA metering called “Source Apparent Power” or “Source VA.” Unlike previous methods of polyphase VA metering, Source VA consistently gives VA sizing requirements of the source. Several methods of VA metering are in use for polyphase systems and except for Source VA, these methods do not consistently give the VA of the source. Some methods give the VA of the source for a wye system but then not for a delta system. Some methods give the VA of the source only when loads are balanced but not when loads are unbalanced. The presence of harmonics also introduces inconsistencies. Consequently, except for Source VA, the usefulness of VA metering is often limited.

The objective of VA (apparent power) metering presented in this paper is that VA is used to express the sizing needs (in units of VA) of the energy delivery infrastructure, i.e., “the source.” Then when active power (W) equals apparent power (VA), the infrastructure is being utilized optimally. Consequently, a method of VA metering is needed that provides accurate information of the electrical sizing requirements of the polyphase delivery system. The proposed “Source VA” method accomplishes this.

Total energy consumption is a basic factor in managing the efficient delivery and use of electrical energy. However, other factors such as maximum demand and VA also play significant roles in managing delivery and use of electrical energy.

The following Progression of Incentives provides a brief overview of factors important in managing the efficient use of electrical energy. The purpose is to illustrate that Source VA information for polyphase systems is a logical next step for managing the use of electricity following 1) total energy, 2) demand, and 3) single-phase VA. As total energy, demand, and single-phase VA are useful in designing rate structures to incentivize the efficient use of electrical energy, so is Source VA in polyphase systems.

Because of the complexities associated with determining polyphase VA that are not present in single-phase systems, polyphase VA is treated separately from single-phase VA.

Progression of Incentives

Total Consumption—kWh

The Progression of Incentives begins with total energy consumption, kWh. When kWh information is used as a basis for billing, there is incentive to reduce kWh; reference Figure 1: Progression of Incentives—Level 1.

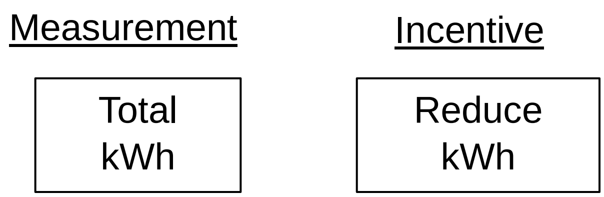
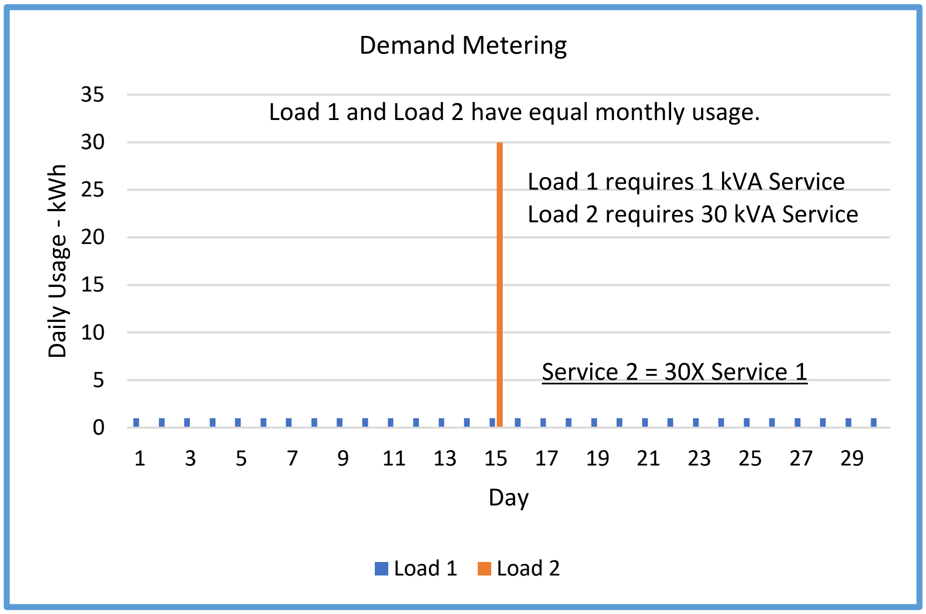


Figure 1
Progression of Incentives—Level 1

Demand Metering—Peak kW

In addition to total kWh, how evenly energy is used has a significant impact on infrastructure sizing needs. Figure 2 illustrates that even though Load 1 and Load 2 have equal monthly usage (kWh), Load 2 requires a service that is 30 times larger than Load 1. If billing is based only on total kWh, both customers are billed the same and Customer 2 has no incentive to reduce the demand placed on the delivery infrastructure. However, if demand metering (peak kW) is used, information becomes available to incentivize Customer 2 to level the load, thus reducing the infrastructure sizing requirements; reference Figure 3: Progression of Incentives—Level 2.



Metering only on total usage—kWh

- Usage 1 = Usage 2
- No data to bill 30X larger service to #2
- Billing not equitable
- No incentive for #2 to improve

Demand Metering—peak kW

- $kW_1 \neq kW_2$: Data available to bill 30X larger service to #2
- Billing equitable
- Incentive for #2 to improve

Figure 2
Demand Metering

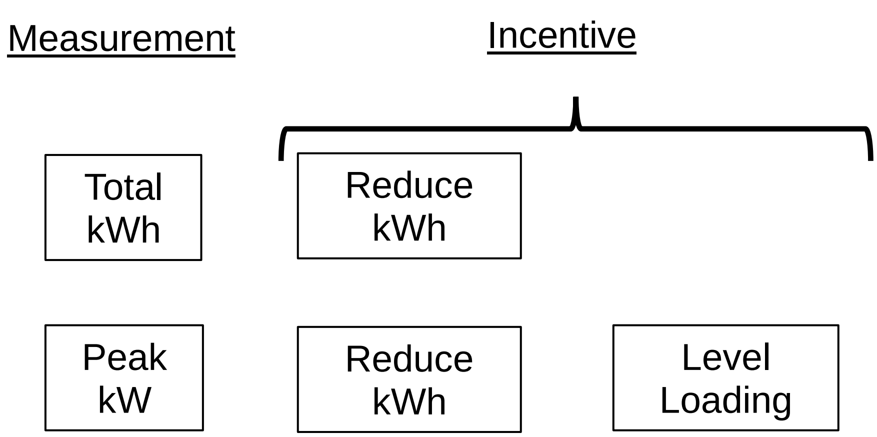


Figure 3
Progression of Incentives—Level 2

Apparent Power (Single-Phase VA)—kVA

A third factor influencing infrastructure sizing requirements is apparent power, kVA. In single-phase systems, apparent power is greater than active power if the power factor of the load is less than 1.0. For example, Figure 4 illustrates two customers, both with a 1 kW load; however, because Customer 2 has a power factor (PF) of only 0.5, the service Customer 2 needs is twice as large as that of Customer 1. If kVA metering is used, information becomes available to incentivize Customer 2 to maximize PF (kW/kVA). Reference Figure 5: Progression of Incentives—Level 3.

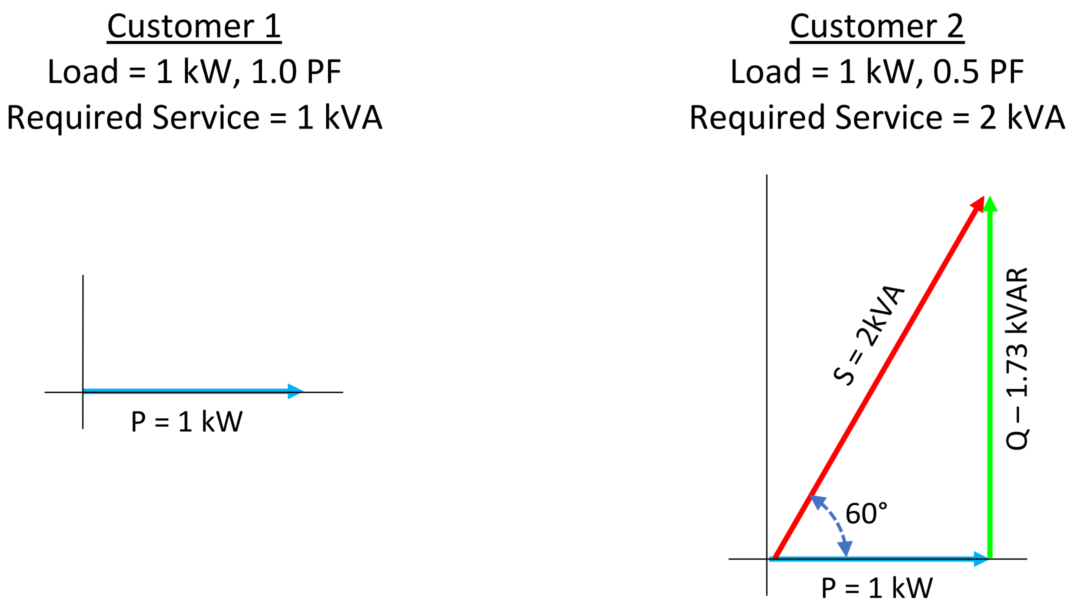


Figure 4
Apparent Power (Single-Phase)

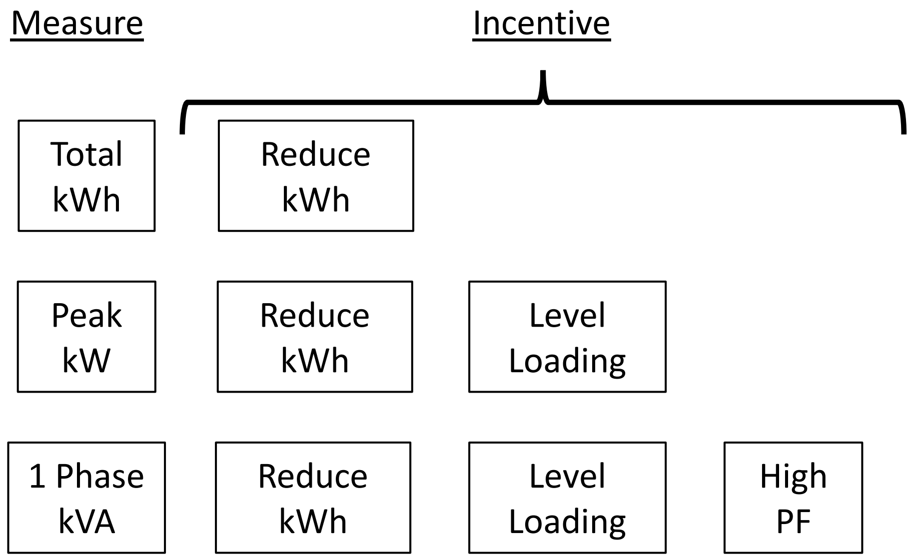


Figure 5
Progression of Incentives—Level 3

Apparent Power (Polyphase VA)—Source VA

Polyphase VA is more than a simple extrapolation of single-phase VA. In polyphase systems, a load can consist of a balanced 3-phase load such as with a 3-phase induction motor or can consist of individual and independent load elements connected between the various polyphase lines. For example, in a 4-wire wye polyphase system, these individual load elements can be connected either between a phase line and neutral or between two phase lines. Additionally, these individual load elements are not necessarily equal (balanced) in either magnitude or power factor. The effect these load elements have on the VA sizing needs of the source is influenced not only by the magnitude and power factor of the individual load elements themselves but also by how the load elements are connected to the system, specifically line to neutral or line to line. A load connected line to neutral has a different impact on the VA sizing needs of the source compared to the same magnitude load connected line to line.

Polyphase VA metering, if based on the Source VA method described herein, can account for factors present in polyphase systems that do not apply in single-phase systems. Factors unique to polyphase systems include:

- Connection systems (wye, delta, etc.);
- Aggregation of per phase power factor into a single “system” PF;
- Imbalance of per phase (phase to neutral) loads;
- Imbalance of cross phase (phase to phase) loads.

Polyphase Terminology

Following is a list of polyphase VA terms and associated definitions used in this document.

1) Arithmetic VA:

- $VA = \sum(V \times I)_{Per\ Phase}$
- Where *V* and *I* represent the rms value of phase voltage and current, respectively.

2) Vector VA:

- $VA = \sqrt{{Watt_{Total}}^2 + {VAR^*_{Total}}^2}$
- Where $Watt_{Total}$ is the arithmetic sum of power for each phase.
- Where VAR_{Total} is the arithmetic sum of VAR for each phase.

*Note that the calculation of total VAR in this definition is the arithmetic sum of the measured VAR for each phase. Various methods are in use for determining VAR, but a discussion of VAR measurement methods is outside the scope of this paper. For more information, refer to the technical report ANSI C12.24 TR.

3) Source VA (proposed new VA method):

- Equations specific to service type

4) Load VA:

- No method proposed

Polyphase VA Background

Both Arithmetic VA and Vector VA methods have been used for polyphase VA metering. However, these two methods do not always give comparable results and do not always reflect the VA sizing needs of the source. Because of these inconsistencies, Source VA is proposed as an alternate method. Following are three examples illustrating the inconsistencies associated with the Arithmetic VA and Vector VA methods.

<u>Example 1:</u>

An example where Arithmetic VA does not equal Vector VA is illustrated in Figure 6 for a 4-wire Y system. Here the source is on the left, an electric meter is shown pictorially in the center, and a single cross phase load is shown on the right. Let the source line to neutral voltage be 120 volts rms and the load be 208 watts resistive. The line current would then be 1 ampere rms.

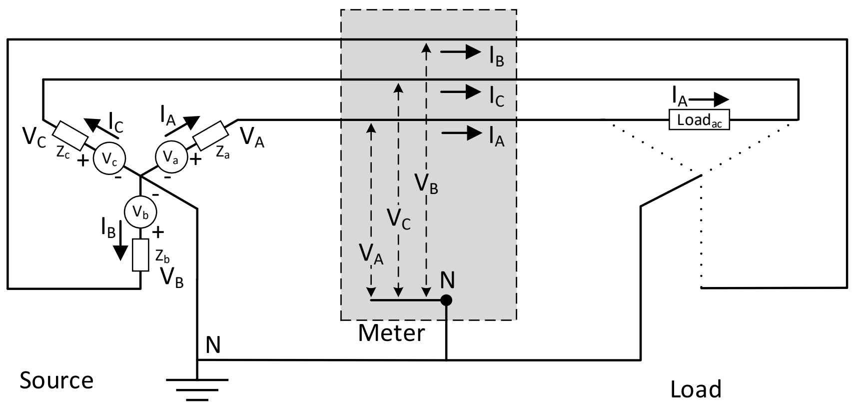


Figure 6
4-Wire Y, Single Cross Phase Load

Arithmetic VA yields:

$$VA = (V_A \cdot I_A) + (V_B \cdot I_B) + (V_C \cdot I_C) = (120 \cdot 1) + (120 \cdot 0) + (120 \cdot 1) = 240\,VA$$

In contrast, Vector VA yields:

$$VA = \sqrt{{Watt_{Total}}^2 + {VAR_{Total}}^2} = \sqrt{208^2 + 0^2} = 208\ VA$$

In this example, Arithmetic VA gives the VA sizing needs of the source, whereas Vector VA does not give the VA sizing needs of the source. Vector VA in this example does give the VA of the single load element. Unlike active power (watt), where the active power delivered by the source must equal the active power consumed by the load, VA of the source and VA of the load are not equal here. The reason for this, as stated earlier, is that both VA of the load and how the load is connected affect the VA sizing needs of the source.

Example 2:

A second example where Arithmetic VA does equal Vector VA is illustrated in Figure 7, again for a 4-wire Y system. Let the source line to neutral voltage be 120 volts rms. The load now consists of one separate and independent load of 104 watts on Phase A with a leading 0.866 PF and a second separate and independent load of 104 watts on Phase C with a lagging 0.866 PF. The line current is again 1 ampere rms.

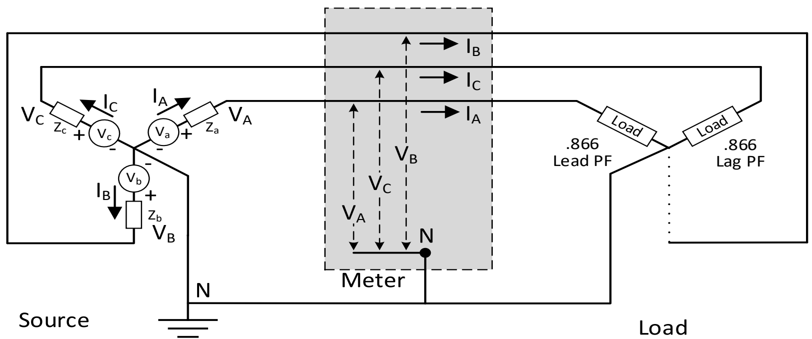


Figure 7
4-Wire Y, One Lead and One Lag PF Load

Arithmetic VA yields:

$$VA = (V_A \cdot I_A) + (V_B \cdot I_B) + (V_C \cdot I_C) = (120 \cdot 1) + (120 \cdot 0) + (120 \cdot 1) = 240\,VA$$

Vector VA yields:

$$VA = \sqrt{Watt_{Total}{}^2 + VAR_{Total}{}^2} = \sqrt{208^2 + 0^2} = 208\ VA$$

As in the first example, VA sizing needs of the source are given by Arithmetic VA but not by Vector VA. However, unlike the first example, Vector VA does not give the total VA of the load, i.e., the sum of the VA of the individual load elements.

Interestingly, from the meter's perspective, the load of the first example, Figure 6, cannot be differentiated from the load of the second example, Figure 7. Hence, even though Vector VA gives VA of the load in the first example, it does not give VA of the load in the second example.

Example 3:

In this example, a single phase to phase load is placed on a 3-wire delta connected system. Here, Arithmetic VA does not equal Vector VA, nor does Arithmetic VA or Vector VA give the VA sizing needs of the source.

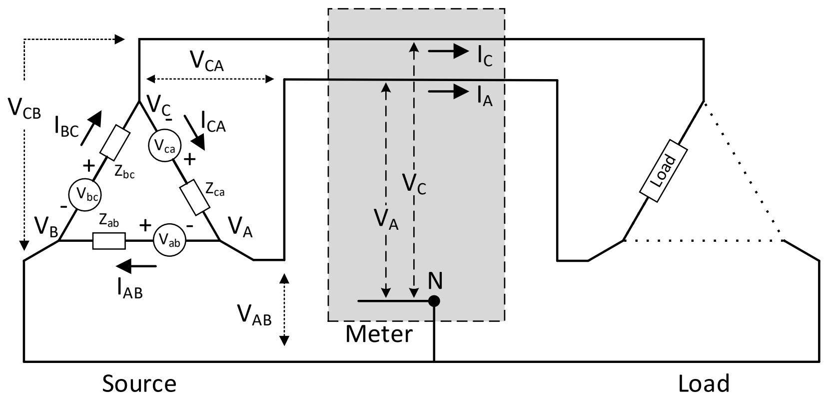


Figure 8
3-Wire Delta, Single Phase to Phase Load

Let the source line to line voltage be 240 volts rms with a single resistive load of 720 watts connected between Phase A and Phase C lines. The resultant line current is 3 amperes rms.

Arithmetic VA yields:

$$VA = (V_A \cdot I_A) + (V_C \cdot I_C) = (240 \cdot 3) + (240 \cdot 3) = 1440\,VA$$

Vector VA yields:

$$VA = \sqrt{Watt_{Total}{}^2 + VAR_{Total}{}^2} = \sqrt{720^2 + 0^2} = 720\ \ VA$$

VA of the source is:

$$VA_{Source} = (V_{AB} \cdot I_{AB}) + (V_{CB} \cdot I_{BC}) + (V_{CA} \cdot I_{CA}) = (240 \cdot 1) + (240 \cdot 1) + (240 \cdot 2) = 960\,VA$$

Source VA Objective

The objective of the Source VA method is providing a measurement of apparent power (VA) for polyphase systems that is an accurate indication of the sizing needs placed on the source (delivery infrastructure).

It should be noted that in polyphase systems, unlike active power (watt), where conservation of energy dictates that power delivered by the source equals power consumed by the load, apparent power (VA) of the source does not necessarily equate to the apparent power (VA) of the load. Active power is the rate of energy transfer from the source to the load. In contrast, VA is not something transferred from the source to the load, but rather a measure of the electrical sizing needs of the system. One interesting characteristic of VA with polyphase systems is that the sizing needs (VA) of the source can be impacted not only by the VA of the load but also by how the load is connected to the source. This is why the VA of the source and the VA of the load are not necessarily equal. Since optimizing efficiency of the delivery infrastructure requires accurate information of the delivery infrastructure, the focus of the Source VA method is on the VA sizing needs of the delivery infrastructure (source) rather than the VA of the load.

Source VA Method

As stated earlier, the objective of the Source VA method is to provide a measurement of apparent power (VA) for a polyphase system that is an accurate indication of the sizing requirements being placed on the delivery infrastructure or source. To accomplish this, voltage and current characteristics of the various source elements are derived based on parameters measurable at the metering location. For example, in a polyphase system being supplied using a 3-wire delta connected transformer, an electric meter typically measures voltages of two lines with respect to the third line and current in the same two lines used for voltage. Then using this information, current flowing through each of the three secondary windings of the transformer is derived. The voltages across two of the transformer secondary windings are directly measured by the meter, whereas the voltage across the third winding is derived. Knowing the current and voltage associated with each of the three secondary windings, the VA of the individual windings is determined and then summed for total VA. This total VA is the VA of the source or “Source VA.”

Using digital technologies, calculations are performed on a per sample basis yielding the voltage and current information of the source elements also on a per sample basis. From this derived per sample data, rms values of voltage and current of the source elements can be calculated. If desired, additional information regarding the source elements can also be derived such as the rms value of the fundamental frequency component or total harmonic distortion, etc.

Because the VA needs of the source can vary based on the source connection system (wye, delta, open delta, etc.), knowledge of the connection system is needed to select the appropriate equations for deriving source parameters.

Source VA: 4-Wire Wye System

Source VA for a 4-wire wye system is determined using the traditional Arithmetic VA method.

Source VA: 3-Wire Delta System

Source VA for a 3-wire delta system is determined by first deriving the per sample voltage and current information for each of the three legs (elements) of the delta source. Referring to Figure 9, the current of element AB is designated I_{AB} and the voltage of element AB is designated V_{AB}. The current and voltage for each of the other two elements are similarly designated. If the rms value of Source VA is desired, the rms values of voltage and current are used in the following equation for Source VA. If the fundamental frequency value of Source VA is desired, the rms value of only the fundamental frequency component of voltage and current is used.

$$VA_{Source} = (V_{AB} \cdot I_{AB}) + (V_{CB} \cdot I_{BC}) + (V_{CA} \cdot I_{CA})$$

The rms values of the voltage and current of the three elements of the source are calculated using the per sample information derived for the specific element. The electric meter—reference Figure 9—does not have direct access to the currents flowing in the three elements of the source. Consequently, the currents of the three source elements are derived using the two line currents the meter does have access to, on a per sample basis. In other words, every time digital samples of the two line currents are obtained, the associated digital sample of the currents of the three source elements are derived. The equations for deriving the currents of the three source elements from the two line currents on a per samples basis are as follows.

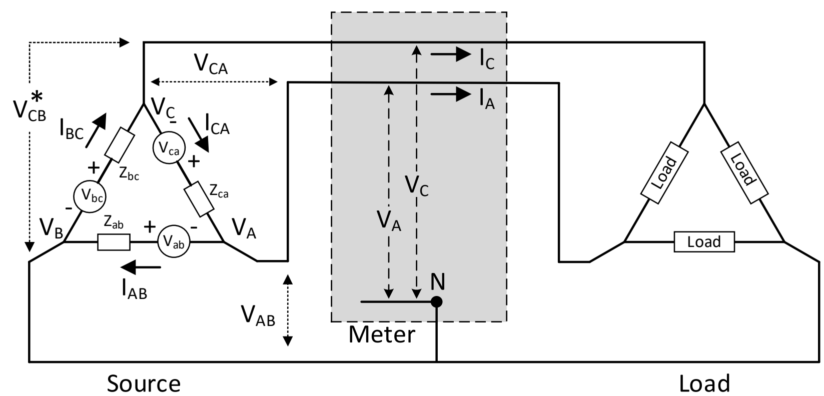
$$I_{CA}(t) = \frac{I_A(t) - I_C(t)}{3}$$

$$I_{AB}(t) = -\frac{2I_A(t) + I_C(t)}{3}$$

$$I_{BC}(t) = \frac{I_A(t) + 2I_C(t)}{3}$$

The equations for deriving source element currents from line currents are based on the following assumptions:

- Source is known to be a 3-wire closed delta typology.
- The three transformers are electrically balanced.
- Because delta connected systems are based on balanced primary voltages, i.e., $v_{ca}(t)+v_{ab}(t)+v_{bc}(t)=0$, there are no significant circulating currents in the source due to unbalanced primary voltages.



*This voltage is labeled as V_{CB} (rather than V_{BC}) because this is as viewed by the electric meter.

Figure 9
Typical 3-Wire Delta System

A 2-phase electric meter as depicted in Figure 9 does not necessarily measure V_{CA} directly. If this is the case, the element CA voltage is derived from the voltages the meter does measure using the following equation, on a per sample basis:

$$V_{AC}(t) = V_{AB}(t) - V_{CB}(t)$$

Because the voltage and current of each of the source elements is determined on a per sample basis, the source element waveform information (magnitude, phase, harmonic content, etc.) is retained. Hence, Source VA accurately reflects the VA sizing being required of the source regardless of load imbalance or harmonic distortion, etc.

In a 4-wire wye connected system, Arithmetic VA gives the VA sizing requirements of the source and is therefore the Source VA method when a 4-wire wye system is used. The Source VA method for a 3-wire delta connected system described above does not use Arithmetic VA (as a 4-wire wye system does) but is directly analogous in that it gives the VA sizing requirement of the source.

Source VA and System Efficiency

In a polyphase system, the maximum amount of energy can be delivered to the load, based on the size of the infrastructure, when the active power (watt) of the source equals the apparent power (VA) of the source. If the Source VA method is used, the VA needs of the source are accurately reflected and can be used in determining how efficiently energy is being delivered.

Following are three examples of how Source VA information is used to improve the efficiency of energy delivery in polyphase systems.

<u>Example 1:</u> 4-wire wye, increasing per phase PF

Service type: 4-wire wye, 120 Vrms line to neutral

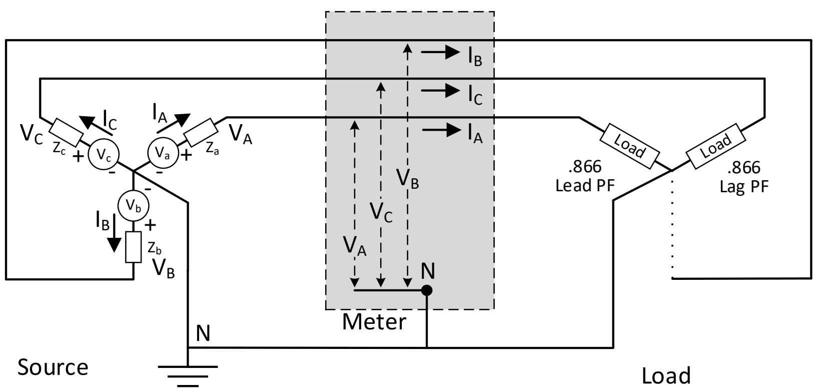


Figure 10
Unbalanced per Phase PF

Let:

- Phase A load = 104 watt, .866 PF Lead
- Phase C Load = 104 watt, .866 PF Lag

Source Active Power (W): 104 + 104 = 208 watts

Source VA (VA): 104/0.866 + 104/0.866 = 120 + 120 = 240 VA

Source PF: PF = Watt/VA = 208/240 = 0.866

In this example, if Source VA information is used in creating a rate structure incentivizing the customer to increase PF, the VA capacity of the infrastructure can be fully utilized, hence, energy is being delivered efficiently. In contrast, if something other than Source VA is used, such as Vector VA, which would indicate a PF of 1.0 in this example, energy would appear as if it were being delivered efficiently when it is not.

Example 2: 4-wire wye, balancing cross phase loads

Customer 1 (Figure 11) and Customer 2 (Figure 12) both have a 3 kW resistive load. Customer 1 places the entire 3 kW load across lines A and C, whereas Customer 2 balances the load across all three phases.

In this example, if Source VA is used in creating a rate structure to increase PF, Customer 1 is incentivized to balance the 3 kW load since the way to increase PF in this case is by balancing the load. Customer 2 shows that balancing the same 3 kW load results in a PF of 1.0 instead of 0.866 for the unbalanced load of Customer 1. Hence, energy is being delivered more efficiently to Customer 2 compared to Customer 1.

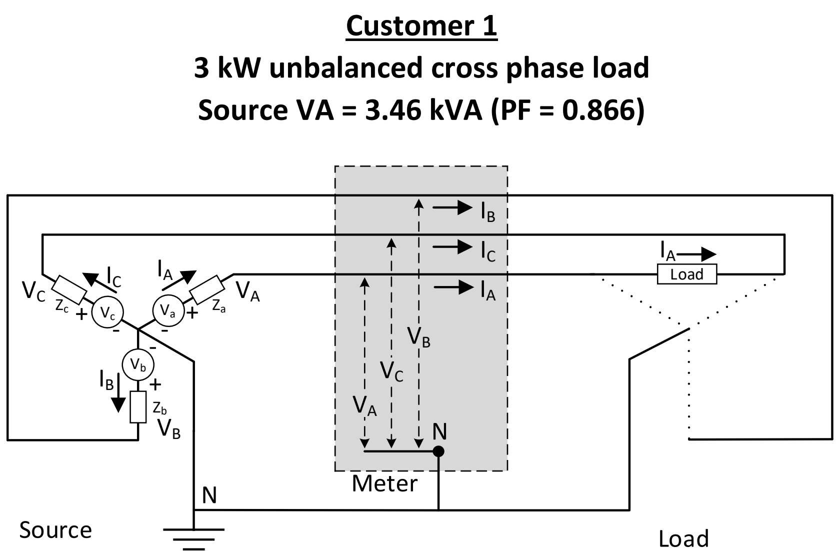


Figure 11
4-Wire Wye, Single Cross Phase Load

Customer 2

3 kW balanced cross phase load

Source VA = 3 kVA (PF = 1.00)

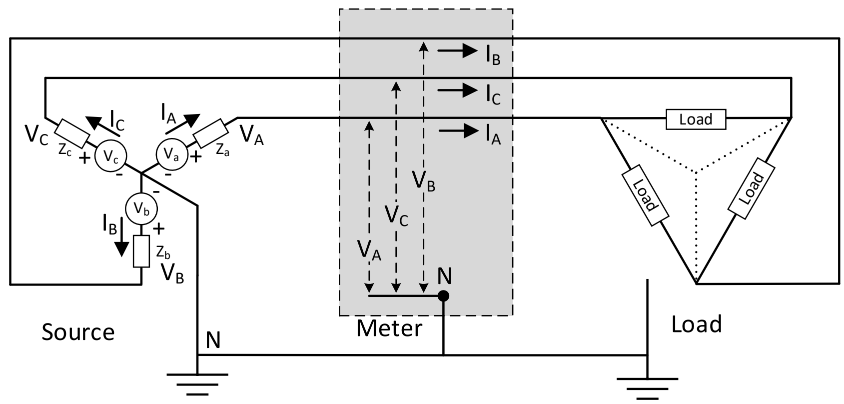


Figure 12
4-Wire Wye, Balanced Cross Phase Load

In contrast, if something other than Source VA is used, such as Vector VA, which would indicate a PF of 1.0 for both Customer 1 and Customer 2, there would be no incentive for Customer 1 to balance the load and improve the energy delivery efficiency.

Example 3: 3-wire delta, balancing cross phase loads

Customer 1 (Figure 13) and Customer 2 (Figure 14) both have a 3 kW resistive load on a 3-wire delta connected system. Customer 1 places the entire 3 kW load across lines A and C, whereas Customer 2 balances the load across all three phases.

In this example, if Source VA is used in creating a rate structure to incentivize the customer to increase the load PF, Customer 1 is incentivized to balance the 3 kW load since the way to increase PF in this case is by balancing the load. Customer 2 shows that balancing the same 3 kW load results in a PF of 1.0 instead of 0.75 for the unbalanced load of Customer 1. Hence, energy is being delivered more efficiently to Customer 2 compared to Customer 1.

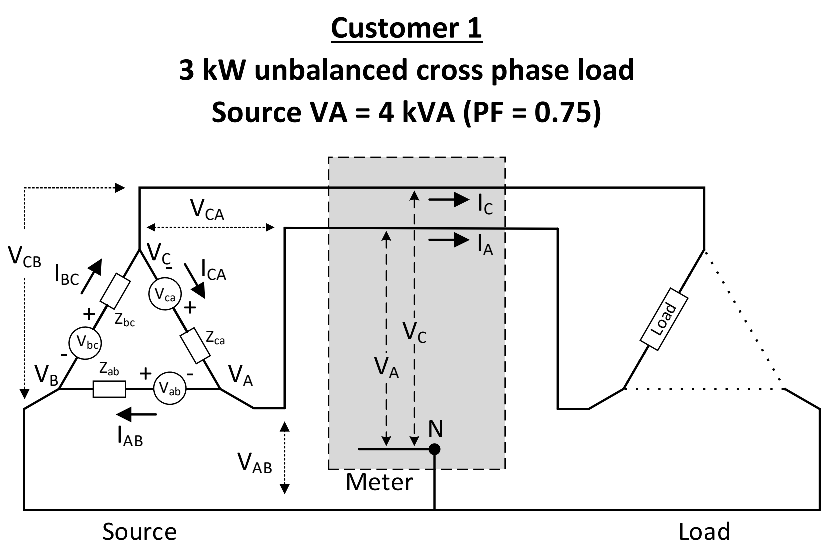


Figure 13
3-Wire Delta, Single Cross Phase Load

Customer 2

3 kW balanced cross phase load

Source VA = 3 kVA (PF = 1.00)

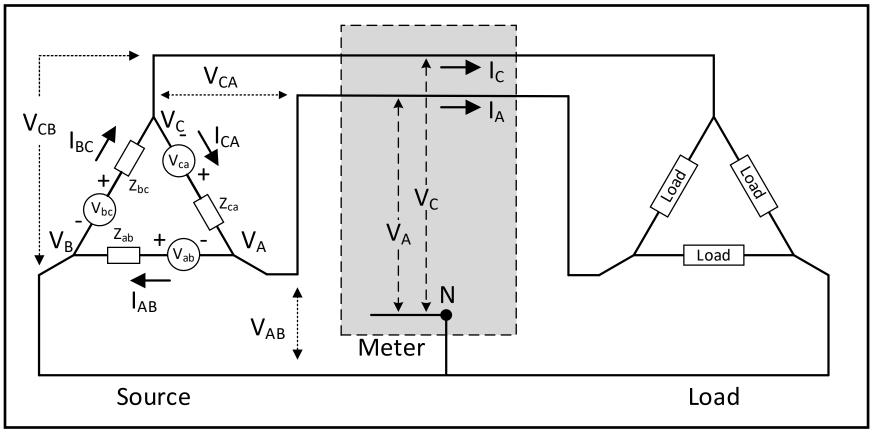


Figure 14
3-Wire Delta, Balanced Cross Phase Load

In contrast, if something other than Source VA is used, such as Vector VA, which would indicate a PF of 1.0 for both Customer 1 and Customer 2, there would be no incentive for Customer 1 to balance the load and improve energy delivery efficiency. Also, the use of Arithmetic VA with delta systems is in general problematic because even with the balanced load of Figure 14, Arithmetic VA yields 3.464 kVA and a PF of 0.866. Hence, Arithmetic VA does not properly reflect when the efficiency of a delta system is optimized.

Based on the above three examples, Source VA, in contrast to Arithmetic VA or Vector VA, provides consistent information useful for optimizing the efficiency of the energy delivery infrastructure in polyphase systems. For information on a more complete list (see below) of Source VA algorithms, reference ANSI C12.24 TR-2022.

Source VA Algorithms Available in ANSI C12.24 TR-2022

1) 4-Wire Wye*
2) 3-Wire Network*
3) 3-Wire Delta
4) 3-Wire Open Delta*
5) 4-Wire Delta
6) 4-Wire Open Delta
7) 3-Wire Wye Open (Floating) Neutral
8) Scott-T*

*Note: Source VA method for these polyphase systems uses the Arithmetic VA algorithm.

Figure 15 adds Source VA for polyphase systems as level 4 to the Progression of Incentives hierarchy.

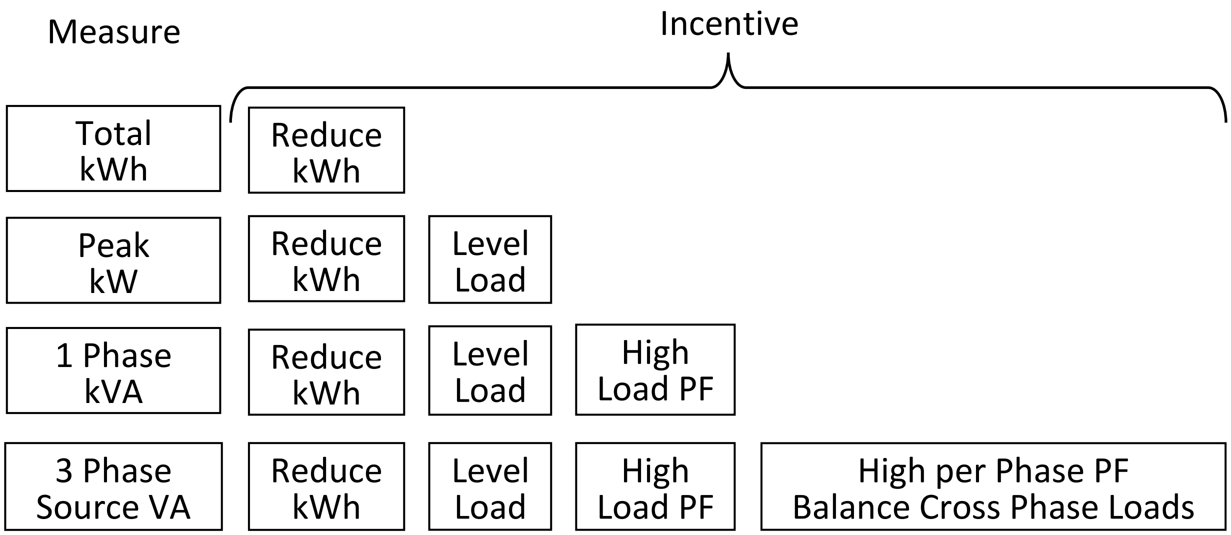


Figure 15
Progression of Incentives—Level 4

Variant Service Types and "VA Basis"

Some polyphase systems can be serviced by a variant of the common connection system such as using a 3-wire open delta system in place of the common 3-wire closed delta system—reference Figure 16 versus Figure 14. In this document, the common service type will be referred to as the "ideal service type" and the service type variant will be referred to as the "variant service type." The VA sizing requirements of a variant service type are not the same as those of the corresponding ideal service type. For example, the VA of a 3-wire closed delta source (ideal service type) is only 0.866 that of a 3-wire open delta source (variant service type) when powering identical balanced loads. In other words, the sum of the VA of the three transformers in a closed delta system needs to be only 0.866 that of the sum of the VA of the two transformers in an open delta system to provide the same power to a balanced load.

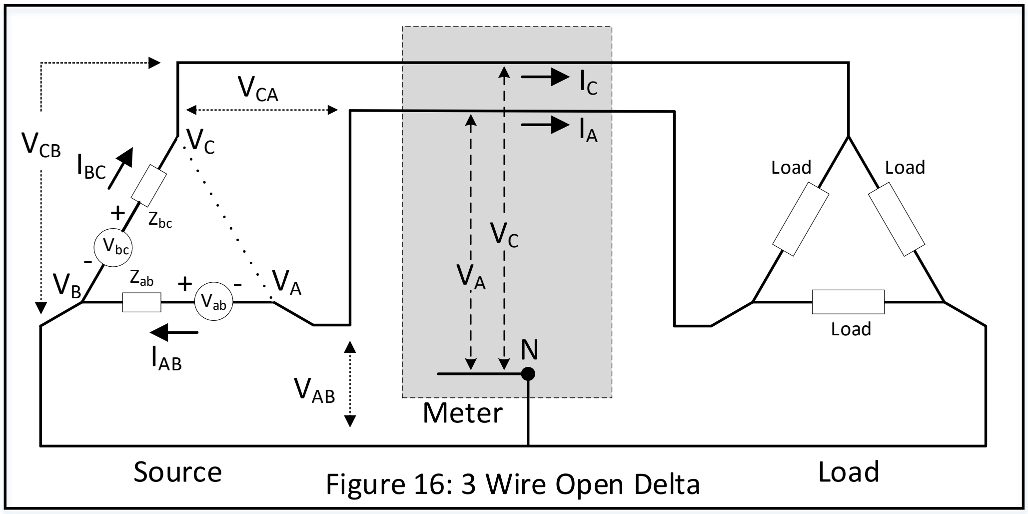


Figure 16
3-Wire Open Delta

The maximum power provided to a load for a given VA capacity source is achieved when the load and source typologies match (are electrically analogous). Even though a utility may choose to use a variant service type, it may be undesirable to incentivize the customer based on the variant service type. A solution to this is to incentivize the customer based on the corresponding ideal service type. In such a scenario, the VA sizing needs of the “variant service type” are used for managing the infrastructure whereas the VA sizing needs of the associated “ideal service type” are used in billing for purposes of incentivizing the customer.

To accommodate the scenario where VA sizing information is provided for both a variant service type and the associated ideal service type, the term “VA Basis” is introduced.

VA Basis: When a variant service type is involved, VA Basis is defined as Source VA of the associated ideal service type. For example, the VA Basis of a 3-wire open delta service is Source VA calculated as if a 3-wire closed delta service is being used.

Figure 17 adds the use of VA Basis to level 4 of the Progression of Incentives hierarchy.

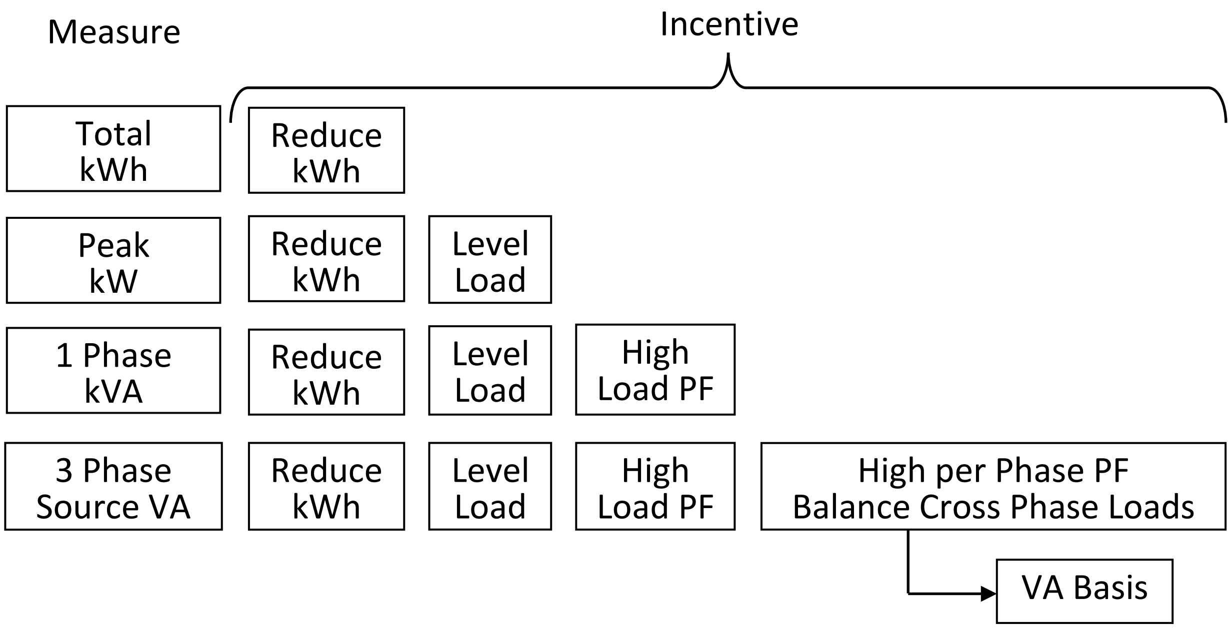


Figure 17
Progression of Incentives Level 4 with VA Basis

Closing Summary

In polyphase systems, the various calculation methods in use for metering apparent power (VA) can give significantly different results based on such factors as polyphase configuration (wye or delta, etc.), load imbalance, and harmonic content. However, recognizing that an important use for VA metering is providing information on the sizing needs of the energy delivery infrastructure, a calculation method referred to as Source VA is proposed that gives consistent sizing information. Source VA is not a simple extrapolation of single-phase VA but is tailored specifically for polyphase systems and gives an accurate indication of the size of the source needed in delivering energy to a load. Because Source VA brings consistency to sizing information, both the management of the delivery infrastructure and the basis for providing incentives in the rate structure to use energy more efficiently can be improved.

In the Progression of Incentives hierarchy, incentives to use energy more efficiently first utilized measurements of total energy, demand, and a single-phase view of apparent power. These measurements gave consistent information useful in managing the sizing needs of the source infrastructure. Similarly, Source VA for polyphase systems is viewed as a logical next step in the Progression of Incentives hierarchy, giving consistent information useful in managing the sizing needs of the source infrastructure.

§