UNBALANCED CURRENT BASED TARRIF

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ABSTRACT

The voltage &current unbalance are serious power quality problems with interaction on each other and mainly affecting low-voltage electricity distribution three-phase systems.

In a three- phase system the current unbalance is due to load unbalance while it is considered as the main cause of voltage unbalance,

The electricity utilities and distribution network operators are responsible for providing of symmetrical voltages system at the point of common coupling between distribution gird and customers' internal network.

The duty of current balancing is solidarity of both of electricity suppliers &customers. The utilities must do it for voltage balancing by equally distribution of single-phase customers between three phases while three- phase customers have no responsibility for doing it for theirs single phase loads.

According to this article the power quality penalty and unbalanced current based tariff are innovated for encouraging them to do it like as utilities.

UNBALANCE DEFINITION

A three-phase power system is called balanced or symmetrical if the three phase voltages and currents have the same amplitudes and phase shifting (angular difference) by 120° with respect to each other. If either or both of these conditions are not met, the system is called unbalanced or asymmetrical.

It is assumed that the waveforms are sinusoidal and thus do not contain harmonics.

UNBALANCE CAUSES

The network operators try to provide a balanced voltage system at the point of common coupling (PCC) between the distribution gird and the customers' internal network. Under normal condition, line voltages are determined by:

- Terminal voltages of generators
- The impedance of power transmission network
- The loads connected to the distribution gird.

The system voltages at generation power plants are generally symmetrical due to the construction and operation of synchronous generators used in power networks. Therefore the centralized generation generally has no unbalance.

The impedance of electricity system components is not exactly the same for each phase. The position of each phase in overhead lines with respect to the earth causes an unbalance in line impedances for each phase. But these differences are very small and can be neglected and compensated by changing the position of phase conductors toward the line sections.

In most cases, the asymmetry of the loads is the main cause of unbalance. The low voltage loads like as residential facilities are usually single-phase.

At high and medium voltage level the loads are usually three-phase and balanced.

The low voltage loads are usually single-phase, and load balance between phases is therefore difficult to guarantee. In the layout of an electrical wiring system feeding these loads, the load circuits are distributed among the three-phase systems, for instance one phase per floor of an apartment or building or alternating connection in rows of houses. Still, the balance of the equivalent load at the central transformers fluctuates because of the statistical spread of the duty cycles of the different individual loads. Therefore the unequal distribution of single-phase loads between three-phase lines is the main cause of current &voltage unbalance.

UNBALANCE MEASUREMENT

There are two different methods for measurement and calculation of unbalance quantity for voltage &current in a three-phase system:

<u>Symmetrical Sequences</u>

According to this method a three-phase unbalanced system is decomposed into three balanced components as: direct (positive) sequence, inverse (negative) sequence and homopolar (zero) sequence¸ indicated by subscripts: d (+), i (-), h (0).

The unbalance quantity of voltages and currents are calculated by the ratio of negative to positive sequences. According to this relation the negative sequence is expressed as percentage of the positive sequence:

$$V_{un}\% = \frac{Vi}{Vd} * 100 = \frac{V-}{V+} * 100$$

$$I_{un}\% = \frac{Ii}{Id} * 100 = \frac{I-}{I+} * 100$$

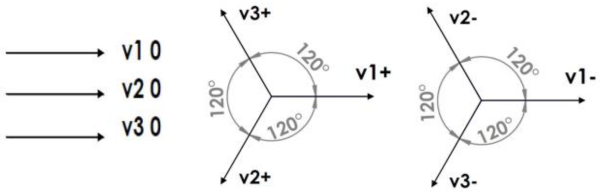


Figure1: The symmetrical sequences components of an asymmetrical three-phase system

Average of Three Phases' Values

In this method the quantities of voltage &current unbalance is measured and calculated by the ratio of maximum deviation from the average of three phases' values to the average. According to this relation the maximum deviation from the average is expressed as percentage of the average:

$$V_{un}\% = 100 \times \frac{\text{maximum deviation from average volage}}{\text{average voltage}}$$

$$I_{un}\% = 100 \times \frac{\text{maximum deviation from avarage current}}{\text{average current}}$$

In a three-phase symmetrical system the quantities of unbalance, inverse & homopolar sequences and maximum deviation from the average are equal to zero.

UNBALANCE EFFECTS

The current unbalance has effects as power and energy losses as follow:

Power Loss

The power losses are created because of reduction the capacity of three-phase electrical facilities as motors, transformers, cables and lines due to negative sequence. The operational limit is determined by RMS rating of total current being partially made up of useless inverse sequence currents as well. The maximum capacity can be expressed by a derating factor, to be supplied by the manufacturer, which can be used to select a larger system. The negative and positive voltage sequences are transformed by transformers. But the behavior of homopolar voltage sequences depends on the primary and secondary windings connection. If one side has a three-phase four wire connection, neutral currents can flow. If at the other side the winding is delta-connected, the homopolar current is transformed into a circulating (and heat causing) current in the delta.

Energy Loss

The copper (energy) loss is proportional to the square root of current and then increase due to current unbalance. For example:

If: $I_1 = I_2 = I_3 = 10$

So: $I_1 + I_2 + I_3 = 30, I_1^2 + I_2^2 + I_3^2 = 300$

If: $I_1 = 5, I_2 = 10, I_3 = 15$

So: $I_1 + I_2 + I_3 = 30, I_1^2 + I_2^2 + I_3^2 = 350$

It proves that 33% of current unbalance cause to 16% of energy losses.

UNBALANCE LIMITATION

For decreasing the effects of unbalance, this power quality problem must be managed and mitigated by both of utilities and customers (consumers) and it can be done by two methods as:

Technical and economical (tariff based) method.

Technical method

The first and most basic technical solution for unbalance mitigation is to rearrange or redistribute the loads in such a way that the system becomes more balanced.

The utilities and distribution network operators are responsible for keeping the voltage unbalance under the standard limit. If voltage unbalance at PCC exceeds the standard limit, then firstly the customer must contact an electrician for investigation of his private network by testing of three-phase installations and checking for equally distribution of single-phase loads between the phases.

If the result of testing and metering prove that utility has caused the voltage unbalance so the customer must contact utility for resolving the problem and has the right of claiming for compensation of the possible damages.

Since the load unbalance is the main cause of voltage and current unbalance then the duty of Load balancing must be shared between both sides. The equally distribution of single-phase customers between three phases is the duty of utilities & distribution operators while equally distribution of single–phase loads between phases is the duty of three-phase customers.

Tariff Based Method

The customer will be forced to do this duty by applying the unbalanced current based tariff & penalty.

For this purpose the first step is limits determination for current & voltage unbalance according to the international standards or national rules and the next step is tariff definition according to the determined limits.

UNBALANCE STANDARDS AND LIMITS

Voltage Unbalance

There are different standards about the limits of voltage unbalance:

The American National Standard for Electric Power Systems and Equipment ANSI C84.1 recommends that "**electric supply systems should be designed and operated to limit the maximum voltage unbalance up to 3% when measured at the electric-utility revenue meter no-load conditions.**" [1], [4]

The National Equipment Manufacturers Association (NEMA) only requires motors to give rated output for 1% of voltage unbalance per NEMA MG-1-1998.

The standard states that 1% of voltage current unbalance can create 6-10% current unbalance. [2], [4]

International standards as EN-50160 and IEC 1000-3-series give limits for the unbalance voltage calculated by the ratio of sequences method up to 2% for LV and MV systems measured as 10-minute values with an instantaneous maximum of 4%.

More detailed standardization can be found in IEC

61000-2-x, as a part of EMC standardization, and EN 50160 describing the voltage characteristic at the point of common coupling (PCC). [3]

Current Unbalance

Unfortunately there is no standard for current unbalance. But by attention to the NEMA MG-1 standard the maximum standard limit of current unbalance due to 3% of voltage unbalance can be advised as 30%.

Power Unbalance

The voltage &current unbalance cause to power unbalance. The quantity of power unbalance can be measured or calculated same as voltage and current unbalance by means of sequences or average methods:

$$S_{un}\% = 100 \times \frac{\text{maximum deviation from average power}}{\text{average power}}$$

$$S_{un}\% = \frac{Si}{Sd} * 100 = \frac{S-}{S+} * 100$$

There is no standard limit for power unbalance amplitude but the ideal quantity of it can be derived from the standard limits advised for voltage and current unbalance:

$$S = VI = \bar{V}(1 + V_{ub}) \times \bar{I}(1 + I_{ub})$$
$$S = \bar{V} \times \bar{I}\ (V_{ub} + I_{ub} + V_{ub} \times I_{ub} + 1)$$
$$S = \bar{S}\ (0.03 + 0.3 + 0.009 + 1)$$
$$\frac{S-\bar{S}}{\bar{S}} \approx 0.333 \approx \frac{1}{3} = S_{ub}$$
$$S_{ub}\% \approx 33\%$$

ENERGY UNBALANCE

The electricity energy measured by (kWh) unit is equal to the area under the power-time curve and is calculated by multiplying of average power (kW) to the time (Hour). For measuring of power unbalance during a period of time we need to the average power that is derived by dividing of energy to the time of energy consumption. Then the average power unbalance in a three-phase system during a time can be determined by metering and recording of energy consumption of each phase separately. As the power unbalance quantity depends on the amplitude and angle then the active and reactive energy consumed by each phase must be measured and recorded by the utility's metering device.

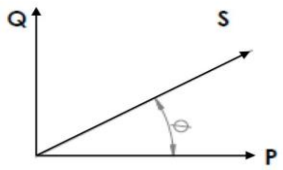


Figure 2: The diagram of apparent power's vector and its active and reactive components in a single-phase and symmetrical three-phase system

$$|S| = \sqrt{P^2 + Q^2}$$

$$kva = \sqrt{(kW)^2 + (kvar)^2}$$

$$kvah = \sqrt{(kWh)^2 + (kvarh)^2}$$

$$\cos\phi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}$$

$$\cos\phi = \frac{P}{S} = \frac{kW}{kva}$$

$$\overline{\cos\phi} = \frac{P}{S} = \frac{kWh}{kvah}$$

$$P_{total} = P_1 + P_2 + P_3 \qquad Q_{total} = Q_1 + Q_2 + Q_3$$

POWER QUALITY PENALTY

According to the power factor(reactive) based tariff and load factor based tariff that are defined previously [5] and the unbalanced current based tariff that is defined here, an extra charge as power quality penalty is applied to those customers consuming electricity energy with poor power quality parameters like power factor, load factor and three-phase unbalanced current etc.

This overhead cost encourages the customers toward improving their bad load profile and poor power quality parameters for money saving.

The electricity tariffs &penalties based on power quality parameters can be used by electricity utilities as a method of demand side management (DSM).

This kind of tariffs and penalties are proportional to the ratio of power quality parameters in two different conditions: ideal and real.

The ideal amount determines the maximum or minimum limit of power quality parameters according to the international standards or national rules while the real power quality parameter can be measured by metering and calculated by definition a formula.

If the real amount of parameter be equal to the ideal amount so the ratio will be equal to 1 and the customer will not pay any penalty and extra charge.

When the real (measured) power quality parameter be not equal to the standard limit so the customer must pay a penalty or extra charge according to the electricity bill .

When the real power quality parameter is not equal with the standard limit then there are two states:

Maximum Limit of Power Quality Parameter

If the utility has defined a maximum limit as the ideal amount of a power quality parameter, so the power quality based tariff is proportional to the amount of:

$$\frac{\text{ideal quantity of the power quality parameter}}{\text{real quantity of the power quality parameter}} \geq 1$$

Like as the standard limit of power factor ($\cos\phi$) that is determined as o.85- 0.9 in the most utilities as the maximum (ideal) amount. So the power quality based tariff is proportional to the amount of $(\frac{0.9}{\cos\phi})$.

In this case the **electricity energy bill** (**E-bill**) according to the power quality tariff is calculated as:

$$\mathrm{E-bill} = \frac{0.9}{\cos\phi} \times (₵/\mathrm{kWh}) \qquad (1)$$

$$\text{If: } \cos\phi = 0.9 \quad \text{then: } \frac{0.9}{\cos\phi} = 1 \rightarrow$$

$$\mathrm{E-bill} = (\mathrm{kWh} \times ₵/\mathrm{kWh}) \qquad (2)$$

Reactive (Power Factor) Penalty = (1)-(2)

$$= (\frac{0.9}{\cos\phi} - 1) \times (\mathrm{kWh} \times ₵/\mathrm{kWh})$$

$$\frac{0.9}{\cos\phi} - 1 = \frac{\text{ideal quantity of power quality parameter}}{\text{real quantity of quality parameter}} - 1 \geq 0$$

$$(\frac{0.9}{\cos\phi} - 1) = \text{Loss factor (LF)}$$

For example if the standard limit of power factor in a utility be 0.9 and the average power factor of customer during a period be 0.8 then:

$$\mathrm{L.F} = \frac{0.9}{\cos\phi} - 1 = \frac{0.9}{0.8} - 1 = 0.125$$

It means that the customer must pay a penalty of 12.5% furthermore than the standard condition with $\cos\phi$= 0.9.

Minimum Limit of Power Quality Parameter

Where the utility according to the national or its internal rules defines a minimum limit for a power quality parameter as the ideal amount so the power quality based tariff will be proportional to the amount of:

$$\frac{\text{real quantity of the power quality parameter}}{\text{ideal quantity of the power quality parameter}} \geq 1$$

The ideal amount of amplitude unbalance of power or energy consumption in the three-phase systems previously is advised as $(S_{ub} = \frac{1}{3})$ so the power quality based tariff is proportional to the ratio of$(\frac{S_{ub}}{\frac{1}{3}} = 3S_{ub})$.

In this case the electric bill (E-bill) according to the power quality based tariff is calculated by:

$$\mathrm{E-bill} = 3S_{ub} \times (\mathrm{kWh} \times ₵/\mathrm{kwh}) \quad (1)$$

$$\text{If: } S_{ub} = \frac{1}{3} \quad \text{then: } 3S_{ub} = 1 \rightarrow$$

$$\mathrm{E-bill} = (\mathrm{kWh} \times ₵/\mathrm{kWh}) \qquad (2)$$

Power Quality Penalty =

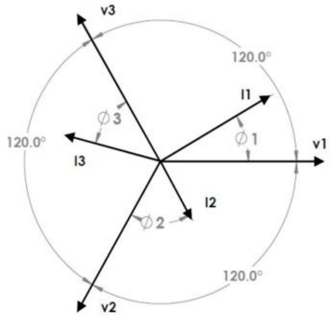
$$(1) - (2) = (3S_{ub} - 1) \times (\mathrm{kWh} \times ₵/\mathrm{kWh})$$

$$3S_{ub} - 1 = \frac{\text{real quantity of the quality parameter}}{\text{ideal quantity of the quality parameter}} - 1 = LF$$

UNBALANCED CURRENT BASED TARIFF

In balanced voltages three-phase system, the current unbalance is appeared due to the loads are differing by amplitudes and/or angles (phase shifting) in each phase to the other phases.fig.3:

Figure 3: The diagram of voltages and currents vectors' in a symmetrical voltages three-phase system with unbalanced loads (currents).



Amplitudes' Unbalance

In a three-phase system if the average active and reactive power or energy consumption of three phases are measured separately as:

$$P_1, P_2, P_3, Q_1, Q_2, Q_3 \qquad \text{then:}$$

$$P = P_1 + P_2 + P_3 \qquad Q = Q_1 + Q_2 + Q_3$$

$$\bar{P} = \frac{P_1 + P_2 + P_3}{3}$$

$$\bar{Q} = \frac{Q_1 + Q_2 + Q_3}{3}$$

$$P_{ub} = \frac{\text{maximum deviation from average active power}}{\text{average active Power}}$$

$$If: \ P = P_1 = P_2 = P_3 \quad \text{so: } \bar{P} = P, P_{ub} = \frac{P - \bar{P}}{\bar{P}} = 0$$

$$If: P = P_1 = P_2, P_3 = 0 \quad so: \bar{P} = \frac{P + P + 0}{3} = \frac{2P}{3}$$

$$P_{ub} = \frac{|P - \bar{P}|}{\bar{P}} = \frac{|0 - \frac{2P}{3}|}{\frac{2P}{3}} = 1$$

$$P_{ub}\% = 100\%$$

LF= $3S_{ub}$ -1=$3P_{ub}$-1= (3×1) -1=2=200%

It means that when one phase has no load and the other phases are equally loaded then the unbalanced current penalty is 200% of the ordinary tariff in the balanced amplitudes condition.

If: $P = P_1 = P_{max}$ & $P_2 = P_3 = 0$

So: $\bar{P} = (P + 0 + 0)/3 = \frac{P}{3}$

$$P_{ub} = \frac{|P - \bar{P}|}{\bar{P}} = \left(P - \frac{P}{3}\right)/\frac{P}{3} = 2$$

$P_{ub}\% = 200\%$

LF= $3S_{ub}$ -1=$3P_{ub}$-1= (3×2) -1=5=500%

This amount of penalty is too much, illogical and not possible. In such conditions the electricity bill based on unbalanced amplitudes' current based tariff can be calculated easily by tripling of the maximum amplitude:

$P_{ub}\% > 100\% \rightarrow E - bill = 3P_{max}(kWh) \times ₵/kwh$

Penalty $= (3 - 1)P_{max}(kWh) \times ₵/kwh$ →LF=2=200%

Then the maximum penalty due to the current unbalance in the worst condition can't exceed 200% of the ordinary tariff in the balanced condition.

Phase Shifting (Angular) Unbalance

If a three- phase balanced voltage system at PCC is loaded at the customer side with balanced active energy and unbalanced reactive energy consumption in a period of time in this system the customer has consumed power with balanced current amplitudes and unbalanced average power factors, so the current and power is unbalanced and the customer be penalized and pay an extra charge.

power is unloads are balanced in the amplitude(with same active powers) but unbalanced in power factors (not same 3-phase reactive powers) so the current is unbalanced due to phase shifting of current's vectors that is not 120° with respect to each other in the customer's side

If: $P = P_1 = P_2 = P_3$, $Q = Q_1 = Q_2 = Q_3$

So: $\cos\phi = \cos\phi_1 = \cos\phi_2 = \cos\phi_3$, $LF = (\frac{0.9}{\cos\phi} - 1)$

$$If: \frac{P_1}{Q_1} \neq \frac{P_2}{Q_2} \neq \frac{P_3}{Q_3} \rightarrow \cos\phi_1 \neq \cos\phi_2 \neq \cos\phi_3$$

$$\cos_1 = \frac{P_1}{\sqrt{{P_1}^2 + {Q_1}^2}} \quad \cos_2 = \frac{P_2}{\sqrt{{P_2}^2 + {Q_2}^2}}$$

$$\cos\phi_3 = \frac{P_3}{\sqrt{{P_3}^2 + {Q_3}^2}}$$

In a balanced voltage system the unbalanced power factors cause to current unbalance due to the different angular (phase shifting). In this case the three-phase power factors will be substituted in the LF formula separately instead of single-phase power factor:

$$L.F = \left(\frac{0.9}{\cos\phi_1} * \frac{0.9}{\cos\phi_2} * \frac{0.9}{\cos\phi_3}\right) - 1$$

Amplitudes & Angular Unbalance

The final formula of unbalanced current based tariff is derived with effecting of both of amplitude and angular unbalance:

$$L.F = \left(\frac{0.9}{\cos\phi_1} * \frac{0.9}{\cos\phi_2} * \frac{0.9}{\cos\phi_3} * \frac{P_{ub}}{0.333}\right) - 1$$

$$E.Bill = \left(\frac{0.9}{\cos_1} * \frac{0.9}{\cos_2} * \frac{0.9}{\cos_3} * \frac{P_{ub}}{0.333}\right)(kwh * ¢/kwh)$$

Unbalanced current penalty =

$$= \left(\left\{\frac{0.9}{\cos_1} * \frac{0.9}{\cos_2} * \frac{0.9}{\cos_3} * \frac{P_{ub}}{0.333}\right\} - 1\right) \ (kwh * ¢/kwh)$$

For example if the utility's power meter has recorded the unbalanced components of energy consumption for a three-phase customer during a period as follow, so the electricity bill due to the unbalanced current based tariff, penalty and loss factor are calculated in two conditions with and without current unbalance effect as:

$P_1 = 4, P_2 = 5, P_3 = 6 \quad (kWh)$

$Q_1 = 2, Q_2 = 3, Q_3 = 4 \quad (kvarh)$

1-Solution without the unbalance effect:

$P = P_{total} = 15$, $Q = Q_{total} = 9$

$S = \sqrt{P^2 + Q^2} = \sqrt{306} \approx 17.5$

$$\overline{\cos\phi} = \frac{\bar{P}}{\bar{S}} = \frac{15}{17.5} = 0.85$$

$$LF = \frac{0.9}{\cos\phi} - 1 = \frac{0.9}{0.85} - 1 = 0.05 = 5\%$$

It means that the customer must pay 5% penalty due to the power factor neglecting the unbalance effect.

2- Solution with the unbalance effect:

$\bar{P} = 5 \qquad P_{ub} = 0.2$

$$\cos\phi_1 = P_1/\sqrt{{P_1}^2 + {Q_1}^2} = \frac{4}{\sqrt{20}} = 0.894$$

$\cos\phi_2 = 0.857 \quad \cos\phi_3 = 0.832$

$$L.F = \left(\frac{0.9}{\cos_1} * \frac{0.9}{\cos_2} * \frac{0.9}{\cos_3} * \frac{P_{ub}}{0.333}\right) - 1 = 0.14 = 14\%$$

The difference of loss factors (LF) in two conditions is 7% and then the customer's bill with effect of current unbalance is 7% more than the balanced current.

REFERENCES

[1] American National Standard for Electrical Power Systems and Equipment, 1995, voltage ratings, ANSI C84. 1

[2] National Electrical Manufacturers Association (NEMA), 1998, motors and generators, MG1

[3] Dr. J. Driesen & Dr.T.V. Craenenbroeck, 2002, "Power Quality Application Guide, Introduction to Unbalance", European Copper Institute, Belgium

[4] Pacific Gas and Electric Company, 2009, "voltage unbalance and motors".

[5] H. Arghavani, 2011, "load factor based tariff", *CIRED conference*, paper 0368

[6] CHK Grid Sense PTY Ltd., "voltage and current unbalance", West Sacramento, Australia.

[7] J. Teylor, 2011, "load imbalance", *MILSOFT* con.