Per-unit system

In electrical engineering in the field of power transmission a **per-unit system** is the expression of system quantities as fractions of a defined base unit quantity. Calculations are simplified because quantities expressed as per-unit are the same regardless of the voltage level. Similar types of apparatus will have impedances, voltage drops and losses that are the same when expressed as a per-unit fraction of the equipment rating, even if the unit size varies widely. Conversion of per-unit quantities to volts, ohms, or amperes requires a knowledge of the base that the per-unit quantities were referenced to.

A per-unit system provides units for power, voltage, current, impedance, and admittance. Only two of these are independent, usually power and voltage. All quantities are specified as multiples of selected base values. For example, the base power might be the rated power of a transformer, or perhaps an arbitrarily selected power which makes power quantities in the system more convenient. The base voltage might be the nominal voltage of a bus. Different types of quantities are labeled with the same symbol (**pu**); it should be clear from context whether the quantity is a voltage, current, etc.

Per-unit is used primarily in power flow studies; however, because parameters of transformers and machines (electric motors and electrical generators) are often specified in terms of per-unit, it is important for all power engineers to be familiar with the concept.

Purpose

There are several reasons for using a per-unit system:

- Similar apparatus (generators, transformers, lines) will have similar per-unit impedances and losses expressed on their own rating, regardless of their absolute size.
- Use of the constant $\sqrt{3}$ is reduced in three-phase calculations.
- Per-unit quantities are the same on either side of a transformer, independent of voltage level
- By normalizing quantities to a common base, both hand and automatic calculations are simplified.

The per unit system was developed to make manual analysis of power systems easier. Although power system analysis is now done by computer, results are often expressed as per-unit values on a convenient system-wide base.

Base quantities

Generally base values of power and voltage are chosen. The base power may be the rating of a single piece of apparatus such as a motor or generator. If a system is being studied, the base power is usually chosen as a convenient round number such as 10 MVA or 100 MVA. The base voltage is chosen as the nominal rated voltage of the system. All other base quantities are derived from these two base quantities. Once the base power and the base voltage are chosen, the base current and the base impedance are determined by the natural laws of electrical circuits.

Relationship between units

The relationship between units in a per-unit system depends on whether the system is single phase or three phase.

Single phase

Assuming that the independent base values are power and voltage, we have:

$$P_{base} = 1pu$$
$$V_{base} = 1pu$$

Alternatively, the base value for power may be given in terms of reactive or apparent power, in which case we have, respectively,

$$Q_{base} = 1pu$$

or

$$S_{base} = 1pu$$

The rest of the units can be derived from power and voltage using the equations $S = IV$, $P = Scos(\phi)$, $Q = Ssin(\phi)$ and $\underline{V} = \underline{I}\underline{Z}$ (Ohm's law), Z being represented by $\underline{Z} = R + jX = Zcos(\phi) + jZsin(\phi)$. We have:

$$I_{base} = \frac{S_{base}}{V_{base}} = 1pu$$
$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_{base}^2}{I_{base}V_{base}} = \frac{V_{base}^2}{S_{base}} = 1pu$$
$$Y_{base} = \frac{1}{Z_{base}} = 1pu$$

Three phase

Power and voltage are specified in the same way as single phase systems. However, due to differences in what these terms usually represent in three phase systems, the relationships for the derived units are different. Specifically, power is given as total (not per-phase) power, and voltage is line to line voltage. In three phase systems the equations $P = Scos(\phi)$ and $Q = Ssin(\phi)$ also hold. The apparent power S now equals $S_{base} = \sqrt{3}V_{base}I_{base}$

$$I_{base} = \frac{S_{base}}{V_{base} \times \sqrt{3}} = 1pu$$
$$Z_{base} = \frac{V_{base}}{I_{base} \times \sqrt{3}} = \frac{V_{base}^2}{S_{base}} = 1pu$$
$$Y_{base} = \frac{1}{Z_{base}} = 1pu$$

Example of per-unit

As an example of how per-unit is used, consider a three phase power transmission system that deals with powers on the order of 500 MW and uses a nominal voltage of 138 kV for transmission. We arbitrarily select $S_{base} = 500MVA$, and use the nominal voltage 138 kV as the base voltage V_{base}. We then have:

$$Z_{base} = \frac{V_{base}^2}{S_{base}} = 38.1\Omega$$
$$I_{base} = \frac{S_{base}}{V_{base} \times \sqrt{3}} = 2.09kA$$

$$Z_{base} = \frac{V_{base}}{I_{base} \times \sqrt{3}} = 38.1\Omega$$

$$Y_{base} = \frac{1}{Z_{base}} = 26.3mS$$

If, for example, the actual voltage at one of the buses is measured to be 136 kV, we have:

$$V_{pu} = \frac{V}{V_{base}} = \frac{136kV}{138kV} = 0.9855pu$$

References

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- B. M. Weedy, *Electric Power Systems Second Edition*, John Wiley and Sons, London, 1972, ISBN 0-471-92445-8

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