Power System Neutral Grounding Fundamentals

An Online Continuing Education Course for Engineers

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Power System Neutral Grounding Fundamentals

by

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One of the decisions that must be made in designing a power system is how the neutral of the system should be connected to ground. The designer has several options from which to choose:

- No intentional connection between the neutral and ground
- Solid (no intentional impedance) connection between neutral and ground
- Insertion of resistance between neutral and ground
- Insertion of inductive reactance between neutral and ground

And within the resistance and inductive choices, the designer has a further decision regarding the relative magnitude of the impedance to be inserted into the circuit. Ultimately, each of these choices affects the way that the power system performs in response to various contingencies, so the choice between these options is not a trivial matter.

It is possible to devote an entire career to studying the implications of these choices. Recently, three noted authors published a nearly 600 page book[1] that addresses the concerns involved in grounding decisions in great detail. This seminal book should be included in every serious library treating power system engineering fundamentals. IEEE has published a number of standard references on the subject that should be available to every power system engineer.[2] [3]

But it is also possible to visualize the impact of the basic choices in an intuitive fashion that does not rely on heavy use of mathematics. This course will present the basic choices as well as the resulting system performance characteristics.

Introduction

Figure 1 illustrates a simplified power system consisting of a three-phase voltage source connected to a set of conductors. The three-phase source consists of three Thevenin equivalent fundamental frequency sinusoidal voltage sources that are each equal in magnitude to the phase-to-ground system voltage, and that are displaced 120 electrical degrees. The electrical system is represented by a set of three inductive reactances, designated as jX_L, that are equal in magnitude. There may be some unbalance on practical power systems, but the impact of unbalance between phases is beyond the scope of the present treatment.

Practical power systems also include resistance, but in most instances the inductive reactance is about an order of magnitude larger than the resistance. So for the sake of this development, system resistance can be ignored.

Attention is drawn to two important aspects of Figure 1. First, two terminal points have been identified in the figure. **N** is a terminal point at the neutral of the power system – the neutral of the three-phase voltage source. **G** is a terminal point that is connected to ground. In this context, “ground” is a reference plane that is connected to earth (in Europe, the term “earthing” is used to convey the same meaning as the term “grounding” in North America) and that is the reference point for all voltages throughout the system. Those two terminal points will be retained as the figure is later transformed into an equivalent circuit for analysis so that it is possible to explore the impact of the various choices of how **N** and **G** may be interconnected.

Figure 1 also shows that there is a capacitance, shown here as capacitive reactance, $-jX_{C0}$, between each phase conductor and ground. This is a distributed capacitance that exists by virtue of the fact that the power system conductor is physically in parallel with earth. The negative sign indicates that this distributed parameter is capacitive. The suffix 0 has a meaning drawn from the study of symmetrical components. However, it is not necessary for the reader to understand symmetrical components, and it is sufficient to simply accept that the suffix is a convenient handle to assign to the distributed parameter that may reappear later in some other aspect of power system engineering analysis.

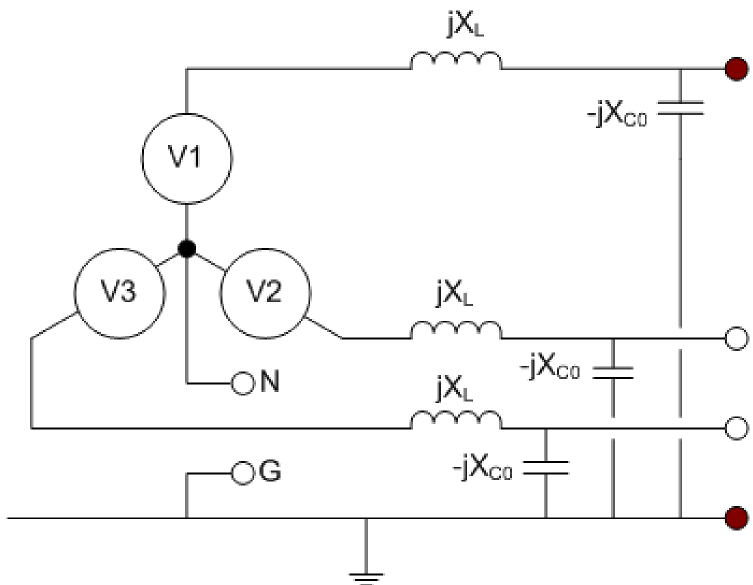

Fig 1 Typical three-phase power system with system inductive reactance (JX_L) and distributed capacitance ($-JX_{C0}$), and with terminal points that can subsequently be used to explore options for connecting the system neutral (**N**) to ground (**G**).

System inductive reactance in ohms can be calculated from the inductance of the system using equation 1:

$$jX_L = j\,2\pi\;f\;L \qquad (1)$$

where

f	is system frequency
L	is the inductance in the system in henries

Likewise, the distributed capacitive reactance (also in ohms) can be calculated using equation 2.

$$-\,jX_{C0} = \frac{1}{j\,2\pi\,f\,C} \qquad (2)$$

where

f	is system frequency
C	is the distributed capacitance to ground in Farads

Readers will recognize that the capacitive reactance looks a bit like a load. If fact, this capacitive reactance is a parasitic charging capacitance through which current is always flowing. The only reason it is normally not considered is that $-jX_{C0}$ is very much larger than jX_L – several orders of magnitude larger – so it is normally negligible.

Because $-jX_{C0}$ is much larger than $jX_{L,}$ it really doesn't matter where the distributed capacitors are actually connected in the equivalent circuit. In fact, we can easily move the connection point from where it is shown in figure 1 across the series inductive reactance to a set of points between the three voltage sources and their associated reactances. Having made that change, and recognizing that the voltage source is a Thevenin equivalent voltage and therefore impedanceless, we can further move those shunt capacitance elements down to the neutral of the voltage source. However, when that is done, the distributed capacitive reactances of the three phases are in parallel, and can be replaced with an equivalent distributed capacitance value of $-jX_{C0}/3$ as shown in figure 2.

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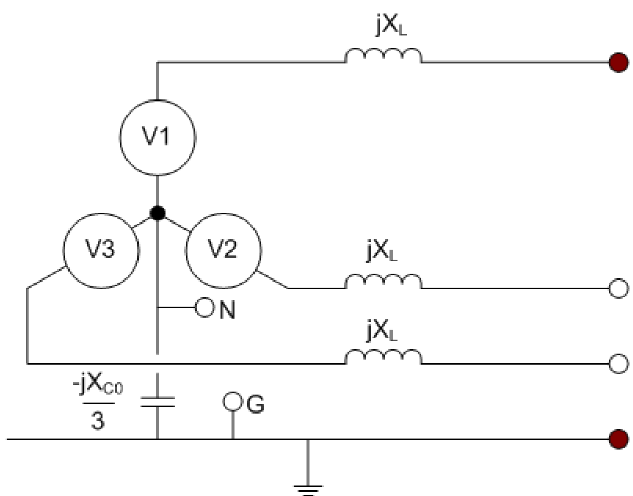

Fig 2 – Equivalent circuit with the distributed capacitance lumped at the neutral

Note that in figure 2, terminals **N** and **G** have been retained.

Finally, we can take one further step in the evolution of this equivalent circuit by observing that figure 2 is totally symmetrical – it represents three phases that are equal in magnitude and displaced from each other by 120 electrical degrees. Therefore, for the sake of analysis, we can ignore two of those three phases, perform our analysis on the third phase only, and then observe that whatever we find happening on that phase will also happen on the other two phases 120^o (approximately 5.555 msec) and 240^o (about 11.11 msec) later, respectively. That then leads us to the simple, single phase equivalent circuit shown in figure 3. And once again, we observe that the neutral, **N**, and ground, **G**, terminals have been retained.

So now the question is: considering the simplified equivalent circuit of figure 3, what is the consequence of the following options:

1. Open circuit between **N** and **G**
2. Zero-impedance connection between **N** and **G**
3. Insertion of a low magnitude of resistance between **N** and **G**
4. Insertion of a high magnitude of resistance between **N** and **G**
5. Insertion of a low magnitude of inductive reactance between **N** and **G**
6. Insertion of a high magnitude of inductive reactance between **N** and **G**

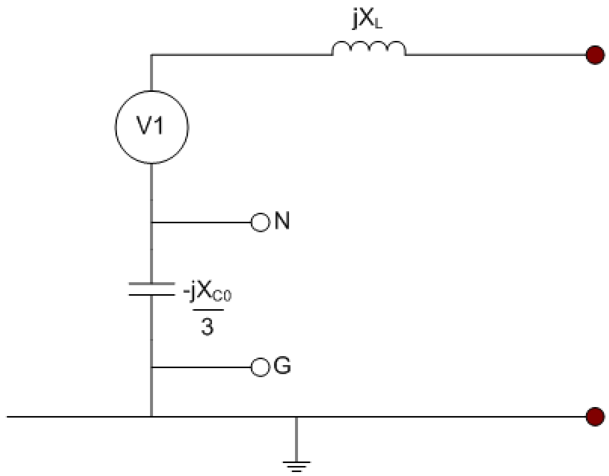

Fig 3 Single phase equivalent circuit for a three-phase power system

In order to investigate those six options, however, we do need to make one final modification to the equivalent circuit. The basic problem that the options present relates to what happens when there is a single-phase-to-ground fault on the power system, and to represent such a fault, we need a switch. Hence, the final equivalent circuit is shown in figure 3. Closing this switch has the effect of applying a single-line-to-ground fault on the system. Leaving the switch open is equivalent to having the system unfaulted.

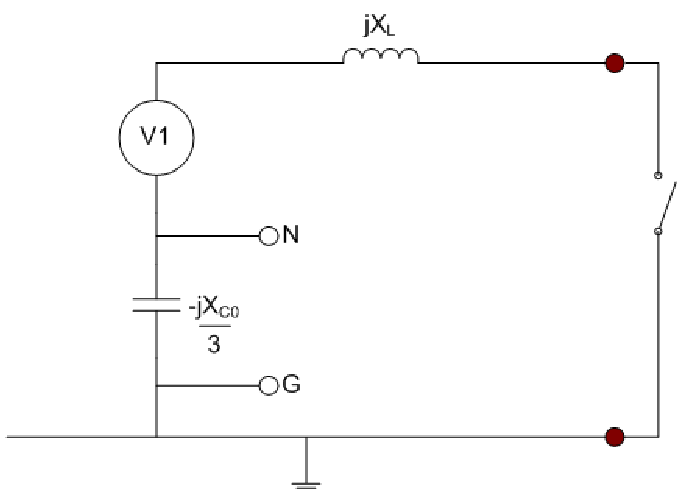

Fig 4 Single-phase equivalent circuit for investigating system neutral grounding options

Case 1: Open circuit between N and G

This case represents the system application in which there is no intentional connection between **N** and **G**; that is, the system is nominally "ungrounded". In reality, of course, the term "ungrounded" is inexact because the neutral is really connected to ground through the reactance of the distributed charging capacitance in the system. That is, an "ungrounded" system is actually capacitively grounded through $-jX_{C0}/3$.

Because the impedance that actually limits ground fault current is rather high, the magnitude of current that will flow to a ground fault is often so low that automatic tripping is not required. That is the most-cited advantage of the ungrounded system – the fact that ground fault tripping is not required means that system availability can be attractively high. This is especially appealing in mission critical applications such refinery and power house auxiliary systems

Earlier it was noted that $-jX_{C0}$ is several orders of magnitude larger than $jX_{L.}$ Therefore, it also must be true that $-jX_{C0}/3$ is much larger than $jX_{L.}$ For this reason, jX_L can be ignored, and this case then becomes a matter of capacitor switching.

When the switch is open, the voltage acro… o-ground voltage on the system… Therefore, when… $-jX_{C0}$, must be z… voltage V1 r…

C… be zero. Th… w). But pr… *to change the* … ss the equ…

So t… witching of an e… on, and the solut…

- …
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Recall… taneous value … the open s… ss the switch … e will gradua… increase…

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But if V1 … at the instant the switch is closed, then a transient component must be generated by the switching event. That is –

- Prior to closing the switch, the voltage across the switch is V1 and is at its crest value
  - The voltage source is also V1 and is also at its crest
  - Therefore the voltage across the equivalent capacitance must be zero
- But in the instant after closing the switch, the voltage across the switch is zero
  - The voltage source continues to be V1 and continues to be at crest.
  - The voltage across the equivalent capacitor must continue to be zero since it cannot change instantaneously.