Investigations on Influence of Ground Impedance on the Interconnected Three phase Four wire Balanced and Unbalanced Distribution System

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Abstract.

Numerous generating stations are connected in synchronism with different loads through LV and HV transmission lines at multiple stages in the power system (PS) network. These power generating stations and loads are balanced and unbalanced types: Single-phase and Three-phase, AC and DC, overhead and underground cables. The neutral point of generators, transformers, etc., is grounded at multiple points to serve the protection and safety of the PS components. Resistance of earth is affected by various parameters like type of soil, temperature, and moisture content in the ground clearly says that earth resistance is not constant or zero. Various research studies considered a balanced power generating system and loads, assumed zero neutral currents in load flow studies. This article considers the effect of ground Impedance on a three-phase transmission line and refined mathematical relations to transform voltage, current and power equations in sequence domine. To examine the influence of ground Impedance on the Three-phase transmission line an experimental setup was prepared in the laboratory and observed the effect of ground Impedance on the neutral current.

Keywords: Ground Impedance, Unbalanced loads, Transformation matrix (D).

1. INTRODUCTION

The use of electrical energy to run various electrical and electronic appliances for multiple purposes is a part of day-to-day activities to lead human life comfortable. In the early day's power was generated centrally with the help of various available sources to meet the required load demand. Consumption of energy in domestic and industrial needs created a massive demand for power production. Multiple reasons (lack of fossil fuels, global warming, cost of power production, latest technologies in power production) influence power production centrally (in MW) and locally (in KW) to meet the excess load demand. These days' various power plants (conventional, non-conventional, few KW to MW) and loads (AC, DC, Single Phase and Three Phase) operate in synchronism. The dynamic nature of power plants (PV, wind) and loads (switching ON/OFF large industrial loads, faults) introduces power quality (PQ) issues. Researchers proposed various mitigation techniques to address these PQ issues (centrally and locally), but the PQ in the PS network is a big challenge to researchers. Various research studies assumed the effect of earth resistance is negligible, but Earth resistance is one reason that influences the PQ issues, which cannot be considered zero [1].

In paper [4,12] proposed Primary control to maintain constant output voltage, reduction in THD, uniform power distribution, secondary control to compensate reactive power and maintain frequency within limits. A primary layer consisting of a multi-loop control scheme makes use of the orthogonal signal generation technique to transform output phase voltages (Van, Vbn, Vcn) to αβ frame and αβ frame to d-q frame with the help of park transformation. The LV system self, mutual admittance expressed in 4x4 matrix.

In paper [5] a PV distribution network with 4-wire medium and low voltage configuration with merged neutral return grounded at multiple points impedance matrix considered. The admittance matrix obtained from Carson's line equation, the mismatch between specified and calculated current at each node/bus overcome using NR load flow studies applied to radial and ring distribution networks.

PS components are higher in rating, bulk in size and costlier. These components are provided with primary and secondary protection schemes to protect them. These protective schemes sense the fault quickly, select the fault's location, and disconnect faulted phase/feeder. A protective scheme selectivity, sensitivity, and speed depend on the current at faulted phase. Ground resistance at fault location impacts the operating fault current of protective systems. The impact of ground resistance is higher during lighting because Lighting currents are at a high current magnitude, and frequency ranges from few Hz to kHz [8].

Paper [11] presents backwards current sweep, forward voltage sweep methods to minimise neutral current in 3 phase 4 wire multi grounded system with a ground return. The Kron reduction technique is applied to reduce the load flow problem, which eliminates a grounding resistance effect that is not realistic.

Line to Ground (LG) fault frequently occurs in the EHV line, which causes a massive amount of primary current flow through the fault path to the ground. The faulted phase is open-circuited with the help of a single-pole tripping mechanism. Even though faulted phase opened within the time interval, electrostatic and electromagnetic coupling between healthy phases causes a small secondary arc between contacts. Ground resistance at the fault location of phases is one more reason which influences the secondary arc during tripping between contact terminals of a faulted phase. The external line to ground faults causes zero-sequence current (ZSC) passing through the power transformer leading to differential protection false tripping because of the weak grounding of the neutral source [6,10].

The Monopolar HV-DC system inserts many amps of DC into the ground through the ground electrode. The current inseminates within the ground media and returns to the power line due to the current flow into the environment, a rise in ground potential through the ground electrode. Because of differences in earth's surface potentials in different substations, the flow of DC through the neural grounding transformer and the transmission lines. The DC that flows through the windings of transformers has driven transformers into half-cycle saturation (i.e., dc bias), which can increase the hotspot, harmonic generation, reactive power absorption, audible noise, and vibration of transformers [2,7].

2. THREE PHASE FOUR WIRE DISTRIBUTION SYSTEM MODEL

Many PS algorithms assumed a three-phase four wired network in distribution systems to evaluate PS parameters considering the balance distribution system and loads. The neutral voltage and current equations are eliminated by assuming zero neutral voltages. Given IEEE standards [1], stating that voltage drop across neutral and ground not be zero under an unbalanced system.

The proposed article, to understand the influence of ground Impedance on a three-phase four-wire unbalance Distribution line with its self and mutual impedance reference to ground considered [3]. Figure 2.1 shows a three-phase four-wire star connected distribution system.

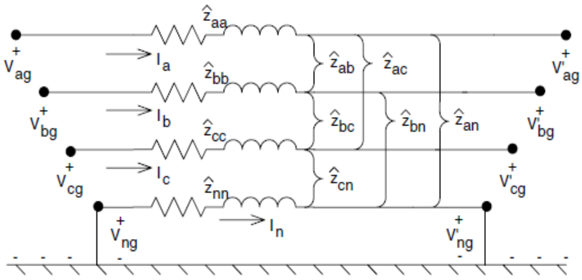

Figure 2.1 Three phase four wire star connected Distribution system

The voltage equation for the network shown in figure 2.1 is written as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \end{bmatrix} + \begin{bmatrix} V_a{}' \\ V_b{}' \\ V_c{}' \\ V_n{}' \end{bmatrix} \tag{2.1}$$

Equation (2.1) also written as

$$\begin{bmatrix} [V_{abc}] \\ [V_{ng}] \end{bmatrix} = \begin{bmatrix} [Z_{ij}] & [Z_{in}] \\ [Z_{nj}] & [Z_{nn}] \end{bmatrix} * \begin{bmatrix} [I_{abc}] \\ [I_n] \end{bmatrix} + \begin{bmatrix} [V'_{abc}] \\ [V'_{ng}] \end{bmatrix} \tag{2.2}$$

Because the neutral is grounded, the voltages Vng and V'_{ng} are equal to zero. Applying Kron's reduction technique, the final phase impedance matrix becomes

$$[V_{abc}] = [Z_{abc}][I_{abc}] + [V_{abc}{}'] \tag{2.3}$$

Considering impedance between neutral and ground the effect of ground impedance in Figure 2.1 is modified as shown in Figure 2.2.

The effect of ground impedance is equally distributed half considered at sending end and another half considered at receiving end. We know that in an unbalanced system-neutral current is not equal to zero(I_n≠0). The voltage equation for the three-phase four-wire system represented as the equation (2.4).

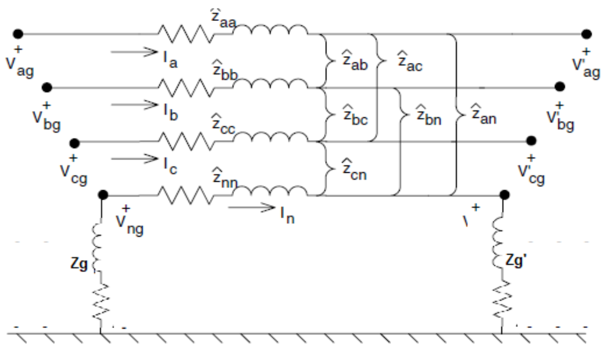

Figure 2.2 Modified Three phase four wire Distribution system

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} Z_{nc} & Z_{nn} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \end{bmatrix} + \begin{bmatrix} V_a' \\ V_b' \\ V_c' \\ V_n' \end{bmatrix} \tag{2.4}$$

$$[V_{abcn}] = [Z_{abcn}][I_{abcn}] + [V_{abcn}'] \tag{2.5}$$

$$V_n = Z_g I_n = Z_{nn} I_n + V_n' \tag{2.6}$$

$$\therefore V_n' = Z_g' I_n \tag{2.7}$$

The ground impedance

$$Z_g = Z_g' = \frac{1}{2}\ ground\ impedance\ from\ sending\ end\ to\ receiving\ end$$

3. HARDWARE IMPLEMENTATION

The experimental setup is established in the laboratory to evaluate the voltage drop, current flow in neutral during unbalanced system due to the effect of ground Impedance. In the first experimental setup, a 3 KVA star connected alternator is driven by a 5 HP DC shunt motor. The output of a 3 KVA alternator is connected to the primary side of a 3 phase (Y-Y) connected transformer. An ammeter connected in series with the line for the measurement of current (I_1) flow in the R-phase. Further, an ammeter connected to measure current I_2 through the neutral point of an alternator out put through the rheostat, also an ammeter is connected in series through a rheostat to measure the effect of earth resistance (R_1), current flow on the secondary side of a transformer.

4. RESULTS AND DISCUSSION

Figure 3.1 (a) shows a circuit diagram of an Unbalanced Load on R-Phase of the Transformer secondary, and Figure 3.1 (b) shows Laboratory setup for an Unbalanced Load on R-Phase of the Transformer secondary. The results observed from the experimental setup are given in Table-1. From Table-1, it is observed that due to the effect of earth resistance (R_1), there is a change in transformer primary neutral current (I_2) and also secondary voltage (V_R).

Rating & Specifications:

Alternator : 3KVA, 3-Ø 415V, 50Hz
Transformer : 3-Ø 0-415V, 50Hz Y-Y connected
Transmission line Rheostat: 360Ω/1.2A
Resistive Load : 400Ω/2A (R,Y,B phases), 18Ω/5A (for neutral)
Inductive Load : 3 Phase, 415V, 10A

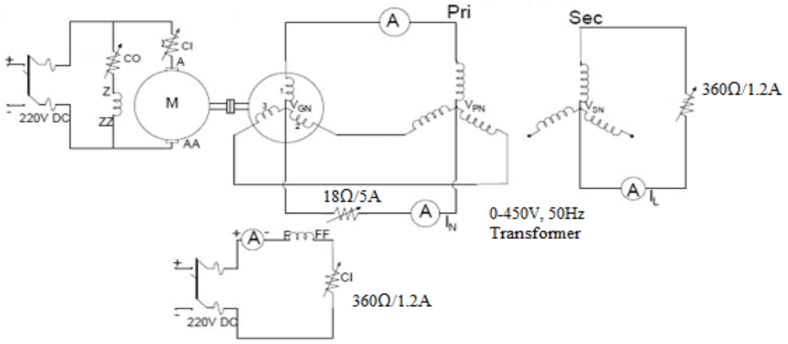

Figure 3.1 (a) Experimental setup for Unbalanced Load on Phase-A of Transformer secondary

Figure 3.1 (b) Laboratory setup for Unbalanced Load on Phase-A of Transformer secondary

Where, the different electrical parameters for Figure 3.1 (a) are defined as follows

R_1= Resistance at generator & Transformer primary Neutral
I_1= Neutral Current flow through Generator & transformer primary
I_2= R-phase current at generator side
R_2= change in ground Impedance at R phase of transformer secondary
I_3= Current flow in R-Phase of a Transformer secondary
V_R = Voltage across R-Phase at Secondary side of a Transformer

Table-1: System Voltage & Current During both transmission, Loads, are balanced with the effect of change in earth resistance

Generator side			Transformer side		
R_1 (Ohms)	I_1 (A)	I_2 (A)	R_2 (Ohms)	I_3 (A)	V_R (Volts)
0	1.4	2.22	17.8	0.66	240
6.7	1.4	2.2	17.8	0.65	238
9.5	1.4	2.18	17.8	0.64	236

12.9	1.4	2.16	17.8	0.64	233
16.5	1.4	2.12	17.8	0.63	231
18	1.4	2.12	17.8	0.63	229

In the second experimental setup, Figure 3.2 (a) illustrates three identical rheostats that are used to implement an unbalanced distribution. Three variable rheostats with inductive load are connected in series to form RL load. A variable rheostat is considered between the common neutral of an alternator and RL load. These two experimental setups are shown in Figure 3.1 &Figure 3.2 are implemented to observe the neutral voltage across an alternator neutral and three-phase RL load, connected series with ground Impedance.

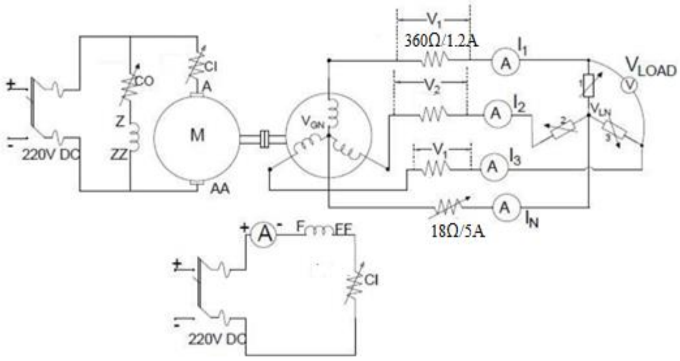

Figure 3.2 (a) Experimental setup for Three Phase Four wire with Unbalanced Transmission and RL Load.

Figure 3.2 (b) Laboratory setup for Three Phase Four wire with Unbalanced Transmission and RL Load.

Where the different electrical parameters for Figure 3.2 (a) are defined as follows:

I_R = Current flow in R-Phase in Amp's
I_Y = Current flow in Y-Phase in Amp's
I_B = Current flow in B-Phase in Amp's
I_{NG} = Current flow in Neutral conductor in Amp's
V_{NG} = Voltage drop across Ground rheostat
R_{GE} = Ground Impedance in Ohms

The experimental results obtained from the Figure-3.2 are tabulated in Table-2,3,4 and 5. It is observed from Table-2 that a rise in neutral voltage (V_{NG}) and an increase in neutral current (I_{NG}) due to the effect of ground Impedance (R_{GE}) during both transmission and loads are balanced.Further it is observed from Table 3,4 and 5 that the rise in neutral voltage and flow of neutral current during various unbalanced conditions (between Transmission line and Load) with the affect of ground impedance.

Table-2: System Voltage &Current during Balanced transmission & Balanced Load

I_R (A)	I_Y (A)	I_B (A)	I_{NG} (A)	V_{NG} (V)	R_{GE} (Ω)
0.25	0.25	0.23	0	0.021	4
0.25	0.25	0.23	0	0.024	4.6
0.25	0.25	0.23	0.01	0.057	5.2
0.25	0.25	0.23	0.01	0.088	6.1
0.25	0.25	0.23	0.01	0.124	7.4
0.25	0.25	0.23	0.02	0.172	8.9
0.25	0.25	0.23	0.02	0.236	9.7
0.25	0.25	0.23	0.02	0.284	10.8
0.25	0.25	0.23	0.02	0.338	11.9
0.25	0.25	0.23	0.03	0.391	13.1
0.25	0.25	0.23	0.03	0.446	14.4
0.25	0.25	0.23	0.03	0.511	16.2
0.25	0.25	0.23	0.03	0.576	17.5
0.25	0.25	0.23	0.03	0.63	18

Table-3: System Voltage & Current during Unbalance in transmission & Balanced Load

I_R (A)	I_Y (A)	I_B (A)	I_{NG} (A)	V_{NG} (V)	R_{GE} (Ω)
0.25	0.25	0.24	0.01	0.23	2.4
0.28	0.24	0.23	0.04	0.24	2.4
0.3	0.24	0.22	0.065	0.24	2.4
0.3	0.25	0.22	0.07	0.24	2.4
0.31	0.26	0.22	0.08	0.25	2.4
0.31	0.28	0.22	0.08	0.25	2.4
0.31	0.29	0.24	0.07	0.26	2.4
0.31	0.29	0.25	0.05	0.26	2.4
0.31	0.29	0.26	0.04	0.25	2.4

Table-4: System Voltage & Current during Balanced transmission & Unbalanced Load

I_R (A)	I_Y (A)	I_B (A)	I_{NG} (A)	V_{NG} (V)	R_{GE} (Ω)
0.28	0.25	0.22	0.07	0.24	2.4
0.32	0.25	0.23	0.12	0.25	2.4
0.36	0.26	0.3	0.22	0.26	2.4
0.37	0.32	0.22	0.21	0.27	2.4
0.37	0.34	0.25	0.15	0.28	2.4
0.36	0.34	0.32	0.02	0.28	2.4

Table-5: System Voltage & Current during Unbalance in transmission & Unbalanced Load

I_R (A)	I_Y (A)	I_B (A)	I_{NG} (A)	V_{NG} (V)	R_{GE} (Ω)
0.28	0.25	0.22	0.1	0.24	2.4
0.32	0.25	0.23	0.12	0.25	2.4

0.35	0.25	0.23	0.21	0.26	2.4
0.36	0.25	0.23	0.24	0.27	2.4
0.36	0.26	0.23	0.22	0.26	2.4
0.37	0.28	0.22	0.22	0.27	2.4
0.37	0.32	0.22	0.21	0.27	2.4
0.37	0.34	0.22	0.23	0.28	2.4
0.37	0.34	0.25	0.15	0.28	2.4
0.36	0.34	0.27	0.12	0.27	2.4
0.36	0.34	0.32	0.02	0.28	2.4
0.35	0.34	0.31	0.08	0.36	2.4

5. TRANSFORMATION OF EXISTING THREE PHASE SYMMETRICAL MODEL TO THREE PHASE FOUR WIRE MODEL

Existing PS models assume a balanced system 3-Φ network, and these models are effectively established. In the proposed model, the Three-phase Four-wire system along with a consolidated solutions for balanced and unbalanced system analysis having with categorical neutral voltage representation. Extending many of the presently available three phase symmetrical component models become necessary to equivalent three phase four wire models.

It is convenient to represent the system parameters during unbalance in sequence domine and also support to calculate self & mutual impedance of each line with the available line sequence parameters.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_n \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 \\ 1 & a^2 & a & 0 \\ 1 & a & a^2 & 0 \\ 3 & 0 & 0 & x \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \\ 0 \end{bmatrix} \tag{4.1}$$

$$\therefore\ V_n = V_a + V_b + V_c = 3V_{a0} \tag{4.2}$$

$$\therefore D = \begin{bmatrix} 1 & 1 & 1 & 0 \\ 1 & a^2 & a & 0 \\ 1 & a & a^2 & 0 \\ 3 & 0 & 0 & x \end{bmatrix}$$

$$[V_{abcn}] = [D] * [V_{012x}] \tag{4.3}$$

Similarly current equation written as

$$[I_{abcn}] = [D] * [I_{012x}] \tag{4.4}$$

$$[I_{abcn}] = [V_{abcn}] * [Z_{abcn}]^{-1}$$

Or

$$[I_{abcn}] = [V_{abcn}] * [Y_{abcn}] \tag{4.5}$$

Substituting equation (4.3) & (4.4) in (4.5)

$$[D] * [I_{012x}] = [D] * [V_{012x}] * [Y_{abcn}] \tag{4.6}$$

$$[I_{012x}] = [D] * [Y_{abcn}] * [D]^{-1} * [V_{012x}] \tag{4.7}$$

$$\therefore [D] * [Y_{abcn}] * [D]^{-1} = [Y_{012x}]$$

$$[I_{012x}] = [Y_{012x}] * [V_{012x}] \tag{4.8}$$

The equation 4.1 does not affect the original symmetrical component equations. With the assist of a new transformation matrix ‘D’, it can be converted to any conventional Three phase distribution system component impedance model to equivalent three phase four wire system.

6. CONCLUSION

All the generating stations, distributed sources and loads are interconnected through transmission and distribution systems. All the components are effectively grounded with various methods to provide additional protections. Earth resistance depends on the type of soil, moisture present, temperature and mineral content; this resistance affects the performance of equipment and components. However, the practical approach offers some small current to ground, and it provides a considerable amount of voltage drop. In this work, the entire PS symmetrical components (012) convert into (012x) without affecting existing system components. In future scope, the proposed novel technique will be applied to both balanced and unbalanced distribution systems with or without grid-connected systems to evaluate the effect of ground impedance and improve the protection of individual components and Power Systems.

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