Impact of Untransposed 66kV Sub-transmission Lines on Voltage Unbalance

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ABSTRACT

The level of voltage unbalance that exists in some interconnected sub-transmission networks in Australia has been observed to be above the code requirements (e.g. 1% in Victoria). There is a perception that these high levels arise as a result of asymmetrical loads. However, the system asymmetry (of lines which are not normally transposed at 66kV, transformers and capacitor banks) also can play a significant part in the lead up to this situation. This lack evidence is partly due to the fact that analysis of asymmetrical systems require careful modelling of system components and lack of widespread availability and use of proper unbalanced load flow programs. To understand the impact of transmission lines in an interconnected network in relation to voltage unbalance, individual and interconnected behaviour of transmission lines have to be closely investigated under balanced supply and loading conditions. The paper presents the methodology and the results of such an investigation carried out employing an interconnected 66kV sub-transmission system as the study case.

1. INTRODUCTION

Excessive voltage unbalance has become a power quality problem of concern in some networks in Australia, as it leads to problems such as overheating of three-phase induction motors, generation of non-characteristic harmonics by three-phase power converters and additional power losses in the entire power system. System voltages at the point of utilisation can be unbalanced for several reasons. Uneven distribution of single phase loads and asymmetrical transmission line impedances possibly caused by incomplete transposition are the two major causes of voltage unbalance.

There are international and national voltage unbalance limiting codes for transmission and distribution systems. The National Electricity Code (NEC), Australia [1] specifies the average voltage unbalance to be limited at 0.5% for systems operating at or more than 100kV, 1.3% for systems operating between 10kV and 100kV and 2.0% for 10kV and lower voltage systems, when determined over a 30-minute averaging period. Concurrently, Australian electricity distributors are obliged to limit the voltage unbalance at the point of common coupling to a customer's three-phase electrical installation as stipulated in electricity distribution code. As an example, this limit is at or less than 1% with excursions to 2% for a total of 5 minutes in every 30-minute period for Victorian distributors [2].

Some electricity distributors are facing difficulties in maintaining the level of voltage unbalance in their high voltage networks in order to satisfy the stipulated level at customer's three-phase installations. As an example, the 66kV sub-transmission network under study, is experiencing excessive voltage unbalance levels (up to 2%) at various substations, specially during peak demand periods. There is the perception that this occurs purely due to unbalanced loads and not much attention has been given to the possible contributions from untransposed transmission lines, since the effect of transposition is not well established at sub-transmission voltage levels such as 66kV. In addition, the need for careful modelling of system components and lack of widespread availability and use of proper unbalanced load flow programs for analysis of asymmetrical systems have aggravated the situation. Hence the impact of 66kV untransposed transmission lines on voltage unbalance has to be paid due attention.

The paper presents the methodology and the results of an investigation carried out with the objective of examining the effect of untransposed 66kV transmission lines in relation to voltage unbalance, employing an interconnected 66kV sub-transmission system as the study case. Power system components have been modelled in phase domain, and a genelised three-phase unbalanced load flow program incorporating both load and system asymmetry has been developed employing phase co-ordinate reference frame. This unbalanced load flow program has been used to examine the behaviour of individual transmission lines and the interconnected sub-transmission system with balanced supply and loading conditions. This enables the prediction of contribution from untransposed transmission system to the problem and identification of critical transmission lines (which lead up the problem).

The paper is organised as follows: Section 2 describes the proposed methodology of analysing the problem of voltage unbalance in interconnected networks. The three-phase modelling of various power system components together with relevant equations is discussed in Section 3.

The formulation of the generalised three-phase load flow method is presented in Section 4. Results obtained from analysis of the study system are given in Section 5 and Section 6 summarises the results and gives broad conclusions.

2. METHODOLOGY

To analyse the problem of voltage unbalance in interconnected power networks, a three-phase power flow method incorporating three-phase modelling of power system components is needed.

2.1. SPECIAL REQUIREMENTS

Techniques for three-phase power flow analysis cannot be developed by simply extending the well established balanced positive sequence based power flow methods into three phases. Representation of different responses of system components (e.g. three-phase induction motors) to unbalanced excitation, and formulation of three-phase power flow equations in a generalised way in order to allow the user to incorporate numerous component connections (e.g. single phase loads), need to be uniquely addressed in developing a three-phase load flow method [3]. The method used here takes the above two requirements into account in modelling of system components and formulating the three-phase load flow equations.

2.2. SYMMETRICAL COMPONENTS VERSUS PHASE CO-ORDINATES

The available literature proposes [4]-[6] two basic approaches to three-phase load flow analysis based on symmetrical components and phase co-ordinates.

Analysis of unbalanced power system problems has been traditionally based on symmetrical component quantities because of the advantages of the availability of sequence impedances for power system components and decoupled nature of most of power system components in symmetrical component reference frame [4]. However, the use of phase co-ordinates has been identified as the best way to represent three-phase power system components since 1960s [5], as it maintains the initial physical identity of the system with regard to line parameters and variables such as nodal voltages and line currents. The only drawback of this approach is that the size of the problem is significantly large compared to which uses symmetrical components [6]. In this study, three-phase power flow technique uses phase co-ordinates, disregarding the computational advantages associated with the symmetrical component approach.

3. MODELLING OF SYSTEM COMPONENTS

This section describes the modelling of various components that exist in the study network.

Generalised modelling of power system components (e.g. model for a synchronous machine with no predetermined connection form) in phase domain is needed in order to support a generalised three-phase power flow method. In addition, the different responses of power system components to positive, negative and zero sequence voltage or current are to be considered in modelling of system components.

3.1. THREE-PHASE SYNCHRONOUS MACHINES

The model used here is based on [7] which takes different machine responses for positive, negative and zero sequence current injections into account. It is a positive sequence voltage source behind the generator admittance matrix ($[Y_g]$) with no pre-determined connection form as illustrated in Figure 1.

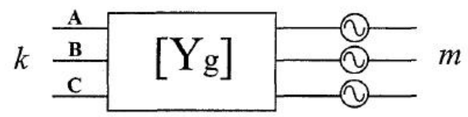

Figure 1: Three-phase generator model

For the system in Figure 1,

$$[I_{km}] = [Y_g]([V_k] - [V_m] - [E]) \tag{1}$$

where,
$[V_k] = [V_{ka} \;\; V_{kb} \;\; V_{kc}]^T$, voltages on side k
$[V_m] = [V_{ma} \;\; V_{mb} \;\; V_{mc}]^T$, voltages on side m
$[E] = [E_p \;\; a^2E_p \;\; aE_p]^T$, internal voltages
$[I_{km}] = [I_{km-a} \;\; I_{km-b} \;\; I_{km-c}]^T$, currents from side k to side m
$[Y_g]_{self} = \frac{(Y_0+2Y_n)}{3}$, generator self admittance
$[Y_g]_{mutual} = \frac{(Y_0-Y_n)}{3}$, generator mutual admittance
$a = e^{\frac{j2\pi}{3}}$
subscripts/superscripts:
a, b, c - three phases
p, n, 0 - positive, negative and zero sequence components respectively
^{T} - transposed matrix

3.2. PASSIVE LOADS

The exponential load model [8] which takes voltage (V) dependency of active (P) and reactive (Q) power into account is used here. This is specified as a single phase branch between two nodes as shown in Figure 2, allowing representation of different load configurations.

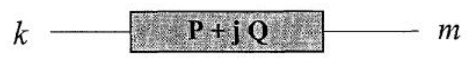

Figure 2: Single-phase load model

$$P = P_0 \left(\frac{V}{V_0}\right)^{\alpha} \tag{2}$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{\beta} \tag{3}$$

where,
α - voltage index for active power
β - voltage index for reactive power
subscripts:
0 - referred to rated conditions

The α and β parameters of this model can be set to represent the aggregate effect of different types of composite loads (e.g. resistive loads, lighting).

3.3. Transmission Lines

Overhead transmission lines are modelled as electromagnetically coupled impedance matrices in phase coordinates. Phase impedance matrix ($[Z_{pq}]_{(3\times3)}$) for a three-phase transmission system with earth return is derived starting from Carson's formula [9].

$$Z_{pq} = R_d + R_s + k\ ln\left(\frac{D_e}{D_{pq}}\right)\ \Omega/m,\ when\ p = q \quad (4)$$

$$Z_{pq} = R_d + k\ ln\left(\frac{D_e}{D_{pq}}\right)\ \Omega/m,\ when\ p \neq q \quad (5)$$

where,
$R_d = 9.869 \times 10^{-7} f\ \ \Omega/m,$ earth resistance
$D_e = 658.376 \times \sqrt{\frac{r_o}{f}}\ \ m$
$k = 2 \times 10^{-7}\ \ H/m$
$D_{pq} - \begin{cases} \text{conductor GMR } (m)\text{, when } p = q \\ \text{GMD between } p \text{ and } q\ (m)\text{, when } p \neq q \end{cases}$
R_s - ac resistance of the conductor (Ω/m)
f - operating frequency (Hz)
r_o - earth resistivity (Ωm)
subscripts:
p and q = a, b, c

Since individual lines of the study system consist of number of sections with different tower configurations and conductor material, the phase impedance matrix is obtained for each section and the resultant impedance matrix for the entire line is derived by combining the sectional impedance matrices.

3.4. Capacitor Banks

Three-phase capacitor banks are considered as passive elements and are modelled as a diagonal impedance matrix. This allows reactive power injection by capacitor banks to be determined by the nodal voltage.

4. Formulation of Three-phase Power Flow Equations

4.1. Concept of Component Level Power Flow Constraints

A unique problem in three-phase power flow analysis is the need to model numerous component connections, such as the phase to phase or delta connections of loads, and impedance grounded star or delta connections of generators. The concepts of specifying power flow constraints for each bus or each phase of a bus cannot take component connections into account. It is therefore not suitable for generalised power flow analysis. In view of the fact that the power constraints such as specified generation (or consumption) of real power are the properties of components instead of buses [7]. Therefore the load flow constraints for each power system component are expressed in component level here, instead of constraints on nodal quantities which have been used in traditional power flow methods.

Since each component can be connected in any form using node renaming, arbitrary component connections with power flow constraints can be easily represented. Furthermore, the approach allows the connection of different load types into the same network bus, thus providing the capability to model a wide variety of unbalanced bus loading conditions.

4.2. Component Constraints

Components with power flow constraints such as loads and generators are represented by their respective component models and the associated power flow constraints, as follows:

(a) Slack generator: The specified constraints are the magnitude and the phase angle of the positive sequence voltage($V_{specified}$) at the machine terminals.

$$[T]([V_k] - [V_m]) = V_{specified} \quad (6)$$

where,
$[T] = \frac{1}{3}[1\ \ a\ \ a^2]$

(b) PV generator: The specified constraints are the three-phase active power output ($P_{3\phi,\ specified}$) and the magnitude of the positive sequence voltage ($V_{specified}$) at the machine terminals.

$$Real\big(-[I_{km}]^H([V_k] - [V_m])\big) = P_{3\phi,\ specified} \quad (7)$$

$$\mid [T]([V_k] - [V_m]) \mid = V_{specified} \quad (8)$$

where,
superscripts:
^{H} - denotes conjugate transposed

The machine internal voltage (E) in (1) is unknown and must be adjusted to satisfy the above machine power flow constraints.

(c) Loads: The specified constraints are the single phase active and reactive power ($(P + jQ)_{1\phi,\ specified}$) consumption.

$$I_{km}^H(V_k - V_m) = (P + jQ)_{1\phi,\ specified} \quad (9)$$

The network (transmission lines and capacitor banks) which does not have power flow constraints is represented by their respective impedance/admittance matrices.

4.3. Power Flow Equations

With representation of system components as described in Section 4.2, the interactions between the network and the system components with power flow constraints (loads and generators) are obtained by the component branch currents using (10). These branch currents are unknowns and are to be determined by the load flow.

$$[Y][V] + [I_u] = 0 \quad (10)$$

where,
$[Y]$ - network nodal admittance matrix
$[V]$ - nodal voltage vector
$[I_u]$ - vector of unknown currents (associated with power flow constraints) leaving each node

Collecting all the related equations together, the three-phase power flow problem can be formulated as:

Generator model:

$$f_1 = [I_{km}] - [Y_g]([V_k] - [V_m] - [E]) = 0 \quad (11)$$

Generator constraint:

$$f_2 = G([I_{km}], [V_k], [V_m]) - K_{specified} = 0 \quad (12)$$

Load constraint:

$$f_3 = I_{km}^H (V_k - V_m) - (P + jQ)_{1\phi,\ specified} = 0 \quad (13)$$

Network:

$$f_4 = [Y][V] + [I_u] = 0 \quad (14)$$

The general form of these equations can be written as:

$$F([x]) = 0 \quad (15)$$

where,
$[I_u] = [I_{generator} \quad I_{load}]^T$
$[x] = [V \quad E_p \quad I_{generator} \quad I_{load}]^T$
$F = [f_1 \quad f_2 \quad f_3 \quad f_4]^T$
$[I_{generator}]$ - vector of generator currents
$[I_{load}]$ - vector of load currents

Equation (15) is a set of nonlinear algebraic equations, which is solved employing the well established Newton-Raphson iterative technique.

5. Case Study

The 66kV sub-transmission system under study as shown in Figure 3 is energised at A (bulk entry point) where the voltage unbalance is known to be negligible. In addition, there are generators connected at B and C where the generator at C operates during limited time periods only. Further, capacitors are present at each substation to support the VAR requirement and a SVC is available at C to support the network. Most of the transmission lines of the network are more than 50km long and are not systematically transposed. The network is supplying for low voltage customers, including three-phase customers such as water boards and irrigators.

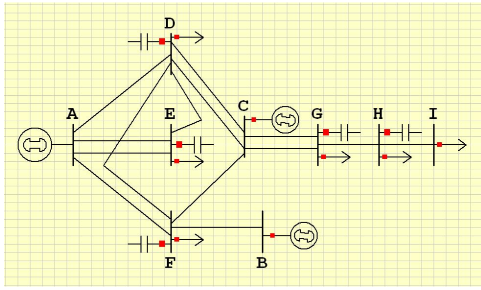

Figure 3: Study network

Despite the fact that the voltage unbalance at A is negligible, the level of voltage unbalance that exists at down stream load buses (G, H and I) exceeds 2% while there is a significant level of voltage unbalance (1.2%) at D and F during peak demand periods. Initial studies have revealed that significant load unbalance existed at G and H. The voltage unbalance in the network has reduced significantly after balancing the loads at G and H, although the subsequent levels are still excessive.

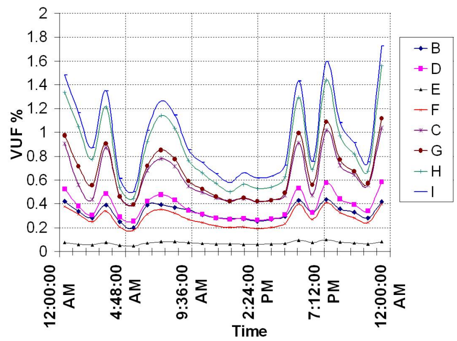

Figure 4: Variation of VUF (%) at different nodes with time

Table 1: VUF at different load substations during peak demand periods

Sub -station	Predicted VUF (%) with balanced loads	Measured VUF (%)
I	1.3	-
H	1.2	2
G	0.9	1.8
D	0.5	1.2
F	0.4	1

The work is carried out to understand the impact of untransposed 66kV transmission lines on the problem in hand. The behavior of individual lines and the interconnected system in relation to voltage unbalance is analysed under balanced loading conditions employing the developed three-phase load flow program as the analytical tool.

The Figure 4 shows the variation of voltage unbalance factor (VUF) at different substations over a 24-hour period using load flow analysis that synthesises the actual network operation. This was done by applying loads (constant power) that are similar to what exists, however applied as balanced loads. It is clear that the asymmetry of the network (due to untransposed lines) itself produces excessive levels of voltage unbalance at G, H and I load buses and considerable levels at D and F as shown in Table 1. The VUF levels caused only by system asymmetry at G, H and I down stream load buses are out of the the code requirements, and the situation will be aggravated when the load unbalance comes into account, as depicted by the measured VUF values given in Table 1.

Figure 5 illustrates the variation of VUF (at receiving end) with respect to line current (as a percentage to line's rated current) for individual lines under balanced supply (66kV) and loading (constant power loads with 0.9 power factor) conditions. It is evident from Figure 5 that some lines (F-C, H-I, A-F, A-D and E-D) behave adversely in relation to voltage unbalance when they are heavily loaded. Among these F-C, A-F, A-D and E-D are significantly loaded under operating conditions and thus can have a significant impact on the problem (Table 2).

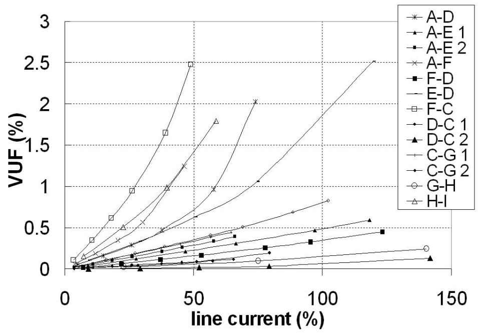

Figure 5: Variation of VUF (%) with line current (%)

Table 2: Maximum loading level and respective VUF (at recieving end) for individual lines

Line	Maximum loading level (%)	VUF (%)
F-C	26	1
A-F	30.5	0.6
A-D	39	0.5
E-D	56	0.75

6. Conclusions and Future Directions

Investigations were carried out to examine the impact of 66kV untransposed transmission lines on voltage unbalance. An Interconnected 66kV sub-transmission network and its individual lines were analysed under balanced loading conditions, employing a three-phase power flow program. It is seen that the level of voltage unbalance at some load substations of the interconnected system is out of the code requirements during peak demand periods, even when the loads are completely balanced. Analysis of individual line behaviour enabled identification of critical transmission lines, which make significant contribution to the problem. Hence, untransposed lines even at lower transmission voltage levels such as 66kV, are investigated as a primary cause of voltage unbalance.

In relation to unbalanced load flow analysis it is crucial that advanced load modelling be undertaken. This is due to that fact that loads such as induction machines behave differently when subjected to unbalanced supply voltages. This is in contrary to the behaviour exhibited by static loads such as resistive loads.

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