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# Impact of Distributed Generators on Power Loss in Distribution Systems

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**Abstract:** Load flow is the most fundamental algorithm for the power system analysis and is used in the operational as well as planning stages. Certain applications, particularly in distribution automation and optimization of a power system, require repeated load flow solutions. The distribution systems have some characteristics like radial structure, untransposed lines, large number of nodes and unbalanced loads along with single phase and two phase laterals. In distribution load flow analysis these features need to be taken into account. Hence, the analysis should be done on the three phase basis unlike the transmission system, which can be analyzed on the per phase basis. The objective of this study, is to develop a formulation and an efficient solution algorithm for the distribution power flow problem which takes into account the detailed and extensive modeling necessary for use in the distribution automation environment of a real world electric power distribution system. The modeling includes unbalanced three-phase, two-phase and single-phase branches, constant power, constant current and constant impedance loads connected in wye or delta formations, cogenerators, shunt capacitors, line charging capacitance, switches and three-phase transformers of various connection types.

**Key words:** Transformer model, cogenerator, power flow, system loss, injected current

## INTRODUCTION

Electric power has become a fundamental part of the infrastructure of contemporary society, with most of today's daily activity based on the assumption that the desired electric power is readily available. The power systems consist of three primary components: the generation system, the transmission system and the distribution system. Each component is essential to the process of delivering power from the site where it is produced to the customer who uses it. The objective of this research was to develop a formulation and an efficient solution algorithm for the distribution power flow problem which takes into account the detailed and extensive modeling necessary for use in the distribution automation environment of a real world electric power system.

**Basic system model:** For the purposes of power flow studies, a radial distribution system can be modeled as a network of buses connected by distribution lines, switches, or transformers to a voltage specified source bus (Patil and Kulakarni, 2004). Each bus may also have a corresponding load, shunt capacitor and cogenerator connected to it. The model can be represented by a radial interconnection of copies of the basic building block shown in Fig. 1. The dotted lines from the cogenerator, shunt capacitor and load to ground are to indicate that these elements may be connected in an ungrounded delta configuration.

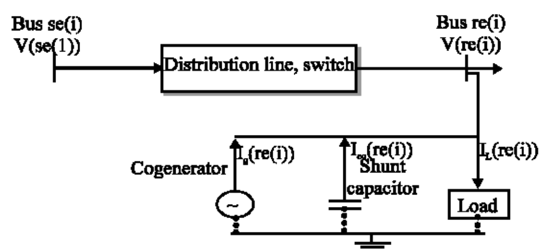

Fig. 1: Generic network branch diagram

## COMPONENT MODELLING

The models used for loads, shunt capacitors, co generators, distribution lines, switches and transformers. These models provide relationships between the relevant voltages, currents and power flows

**Branch model:** A simple circuit model is shown in Fig. 2 and its parameters are shown in Fig. 3 for a three-phase,

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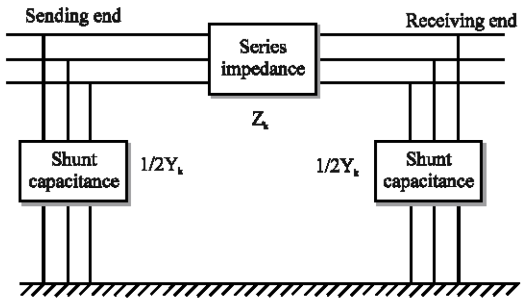



Fig. 2: Representation of a distribution line

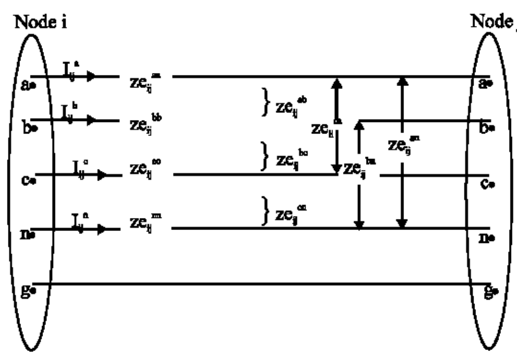



Fig. 3: Three-phase four-wire line model

four-wire grounded star system (Ranjan *et al*., 2004; Carol and Dariush, 1994). Line charging admittance is neglected at the distribution voltage level. For this four-wire system, Carson's equations lead to the development of an impedance matrix of 4×4 dimension. This matrix is used to calculate conductor voltage drop as shown below. Using Kirchoff's voltage law, one may write:

$$\begin{bmatrix} V_i^{ag}\text{-}V_j^{ag} \\ V_i^{ag}\text{-}V_j^{ag} \\ V_i^{ag}\text{-}V_j^{ag} \\ V_i^{ag}\text{-}V_j^{ag} \end{bmatrix} = \begin{bmatrix} ze_{ij}^{aa} & ze_{ij}^{ab} & ze_{ij}^{ac} & ze_{ij}^{an} \\ ze_{ij}^{ba} & ze_{ij}^{bb} & ze_{ij}^{bc} & ze_{ij}^{bn} \\ ze_{ij}^{ca} & ze_{ij}^{cb} & ze_{ij}^{cc} & ze_{ij}^{cn} \\ ze_{ij}^{na} & ze_{ij}^{nb} & ze_{ij}^{nc} & ze_{ij}^{nn} \end{bmatrix} \begin{bmatrix} I_{ij}^{a} \\ I_{ij}^{b} \\ I_{ij}^{c} \\ I_{ij}^{n} \end{bmatrix} \quad (1)$$

Therefore, for phase a, one may write equation as:

$$\begin{bmatrix} V_i^a \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} V_i^a \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} ze_{ij}^{aa} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{ij}^{a} \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

Similarly for phase's b and c, one may write expression as below:

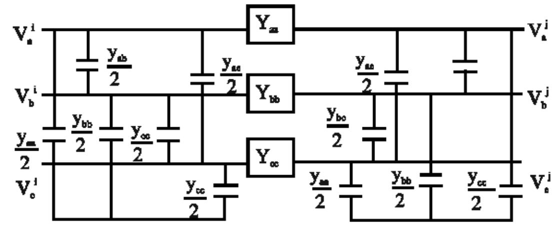


Fig. 4: Shunt capacitances of the line sections

Fig. 5: Representation of the flow of currents due shunt capacitances

$$\begin{bmatrix} 0 \\ V_{ij}^{b} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & Ze_{ij}^{b} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ I_{ij}^{b} \\ 0 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} 0 \\ 0 \\ V_{ij}^{c} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Ze_{ij}^{b} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ I_{ij}^{c} \end{bmatrix} \quad (4)$$

**Shunt-admittance model:** The Fig. 4 represents the shunt admittances connected to each phase and the admittances connected between the phase and ground. The directions of currents injected by the shunt admittances are represented in the Fig. 5.

$$\begin{aligned} I_a &= (-y_{ab}(V_a - V_b) + y_{ca}(V_c - V_a) - y_{aa}V_a)/2 \\ I_b &= (-y_{ab}(V_a - V_b) - y_{bc}(V_b - V_c) - y_{bb}V_b)/2 \\ I_c &= (-y_{bc}(V_b - V_c) - y_{ca}(V_c - V_a) - y_{ca}V_c)/2 \end{aligned} \quad (5)$$

**Shunt capacitor model:** Shunt capacitors, often used for reactive power compensation in a distribution network, are modeled as constant capacitance devices. Capacitors are often placed in distribution networks to regulate voltage levels and to reduce real power loss. The Fig. 6 and 8 represent the capacitors placement in wye and delta connections and Fig. 7 and 9 represent the flow of currents due to this connections, respectively.

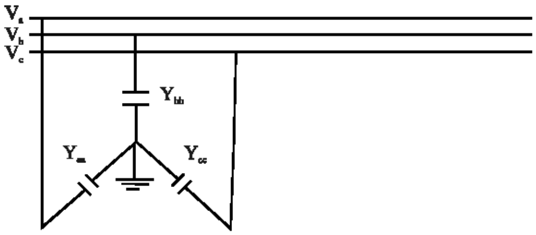



Fig. 6: Capacitors connected in wye connection

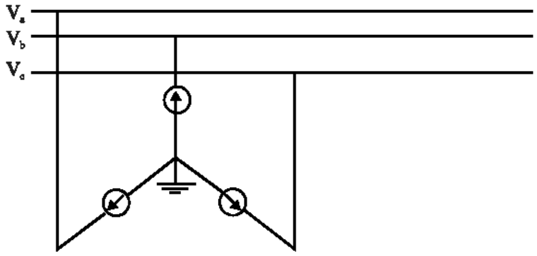



Fig. 7: Representation of flow of currents due to wye-connected capacitors

$$I_a = -y^{aa} V_a$$
$$I_b = -y^{bb} V_b \qquad (6)$$
$$I_c = -y^{cc} V_c$$

$$\left.\begin{aligned} I_a &= \frac{y_{ab}}{3}\left(-2V_a + V_b + V_c\right) \\ I_b &= \frac{y_{bc}}{3}\left(-2V_b + V_a + V_c\right) \\ I_c &= \frac{y_{ac}}{3}\left(-2V_c + V_b + V_a\right) \end{aligned}\right\} \qquad (7)$$

**Load model:** All the loads are assumed to draw constant complex power (S = P+jQ). It is further assumed that all three-phase loads are star connected and all double and single-phase loads are connected between line and neutral. In fact, double-phase and single-phase loads are modeled by setting the values of the complex power of the non-existing phases to zero.

A node in a radial system is connected to several other nodes. However, owing to the structure, in a radial system, it is obvious that a node is connected to the substation through only one line that feeds the node. All the other lines connecting the node to other nodes draw power from the node. The study shows phase a of a three-phase system where lines between nodes i and j feed the node j and all the other lines connecting node j draw power from node j. Following Eq. 8-10 can be written $(P_{ij}^{a} + jQ_{ij}^{a})$, $(P_{ij}^{b} + jQ_{ij}^{b})$, $(P_{ij}^{c} + jQ_{ij}^{c})$ refer to the power at the receiving end node j.

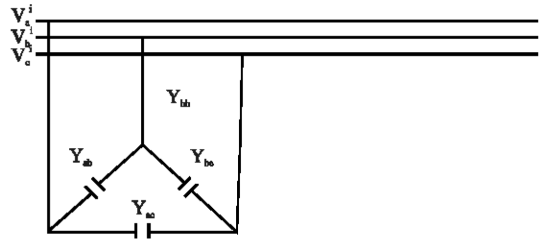



Fig. 8: Capacitors connected in delta connection

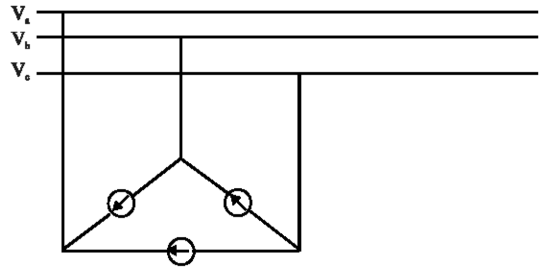



Fig. 9: Representation of flow of currents due to delta-connected capacitors

$$I_{ij}^{a} = \left[\frac{P_{ij}^{a} + jQ_{ij}^{a}}{V_j^{a}}\right]^{*} \qquad (8)$$

$$I_{ij}^{b} = \left[\frac{P_{ij}^{b} + jQ_{ij}^{b}}{V_j^{b}}\right]^{*} \qquad (9)$$

$$I_{ij}^{c} = \left[\frac{P_{ij}^{c} + jQ_{ij}^{c}}{V_j^{c}}\right]^{*} \qquad (10)$$

**Wye-connected loads:** In the case of loads connected in wye are single phase loads connected line-to-nuetral, the load current injections at the $K^{th}$ bus can be given by

$$I_a = \frac{P_m - jQ_m}{V_m^{*}}, m \in [a, b, c] \qquad (11)$$

Where $P_m$, $Q_m$ and $V_m^*$ denote real power, reactive power and complex conjugate of the voltage phasor of each phase, respectively.

**Delta-connected loads:** The current injection at the $K^{th}$ bus for three-phase load connected in Delta are single-phase load connected line-to-line can be expressed by

$$I_a = \frac{P_{ab} - jQ_{ab}}{V_a^* - V_b^*} - \frac{P_{ca} - jQ_{ca}}{V_c^* - V_a^*} \quad (12)$$

$$I_b = \frac{P_{bc} - jQ_{bc}}{V_b^* - V_c^*} - \frac{P_{ab} - jQ_{ab}}{V_a^* - V_b^*} \quad (13)$$

$$I = \frac{P_{ca} - jQ_{ca}}{V_c^* - V_a^*} - \frac{P_{bc} - jQ_{bc}}{V_b^* - V_c^*} \quad (14)$$

All the loads, including shunt capacitors for reactive power compensation are represented by their active ($P_{L0}$) and reactive ($Q_{L0}$) components at 1.0.pu. The effect of voltage variation is represented as follows:

$$P_L = P_{L0}|V|^k \quad (15)$$

$$Q_L = Q_{L0}|V|^k \quad (16)$$

Where,

|V| is the voltage magnitude, K = 0 for constant Power load, K =1 for Constant current load and K = 2 for Constant Impedance load.

The value of K may be different according to load characteristics.

## COGENERATORS

Cogenerator is basically called as Distributed Generator because it is used in the distribution system (IEEE Distribution Planning Working Group Report, 1991). Cogeneration is an effective means of increasing energy efficiency and reduced energy costs. The cogeneration process puts wasted heat to work. It saves energy by using the reject heat of one process as an energy input to a subsequent process, effectively using the same fuel. When a request is made to generate electricity using cogenerators in parallel with a utility system, there is a need to study the impact of the proposed cogenerators will have upon existing system. There are different types of DGs from the constructional and technological points of view. These types of DGs must be compared to each other to help in taking the decision with regard to which kind is more suitable to be chosen in different situations. However, we are concerned with the technologies and types of the new emerging DGs: micro-turbines and fuel cells. The location of distributed generation is defined as the installation and operation of electric power generation modulars connected directly to the distribution network or connected to the network on the customer site of the meter.

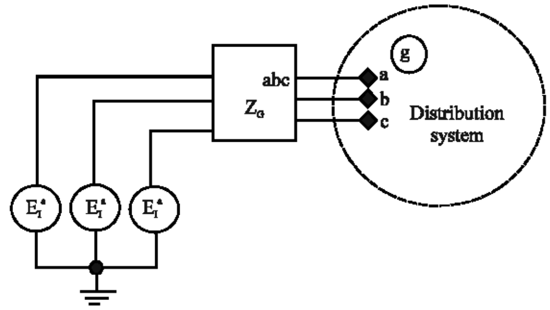



Fig. 10: Thevinen's equivalent circuit of cogenerator

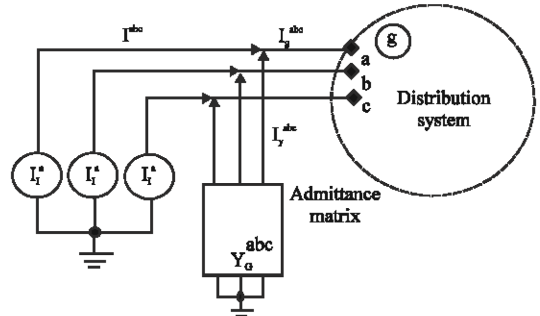



Fig. 11: Norton's equivalent circuit of cogenerator

**Cogenerator model:** A preliminary investigation of typical voltage control systems for synchronous cogenerators was done (Chen and Chen, 1991). According to the investigation results, synchronous cogenerators are not controlled to maintain constant voltage; they are controlled to maintain constant power and constant power factor. The power factor controller must be capable of maintaining a power factor within plus or minus one percent at any set point. As a result, the synchronous cogenerators can be represented approximately as constant complex power devices in the power flow study, i.e. cogenerators can be represented as P-Q specified devices in the power flow calculation. As for induction cogenerators, their reactive power will vary with the terminal voltage change. Thus, the reactive power consumption of the induction cogenerators is not exactly constant

$E_i^{abc}$ are the voltages behind sub transient , $Z_i^{abc}$ is the sub transient impedance matrix. Based on the assumptions discussed above, we have

Total real power = $P_T = p^a + p^b + p^c$ = Constant
Total reactive power = $Q_T = q^a + q^b + q^c$ = Constant

The internal voltage $E_i^{abc}$ is a balanced three-phase voltage in both magnitude and angle, assuming a balanced design of the generator windings. A Norton equivalent circuit of Fig. 10 is used to represent the cogenerator model shown in Fig. 11.

## TRANSFORMER MODEL

The impact of the numerous transformers in a distribution system is significant. Transformers affect system loss, zero sequence current, grounding method and protection strategy. In this study, a transformer model and its implementation method are shown, so that large-scale unbalanced distribution system problems such as power flow, short circuit and system loss studies can be solved.

The conventional transformer models based on a balanced three phase assumption can no longer be considered suitable for unbalanced systems. Recent interest in unbalanced system phenomena has also produced a transformer model adaptable to the unbalanced problem which is well outlined in Dillon (1972). The model developed thus far can be applied directly to distribution power flow and short-circuit analysis. However, it is still not accurate for system loss analysis because the transformer core loss contribution to total system loss is significant (Sun, 1980; Sun *et al.*, 1980). To calculate total system loss, the core loss of the transformer must be included in the model. To solve this problem, this thesis introduces an implementation method in which artificial injection currents are used to make the system $Y_{Bus}$ nonsingular.

**Derivation of transformer models:** A three-phase transformer is presented by two blocks shown in Fig. 12.

One block represents the per unit leakage admittance matrix $Y_T^{abc}$ and the other block models the core loss as a function of voltage on the secondary side of the transformer.

The core loss of a transformer is approximated by shunt core loss functions on each phase of the secondary terminal of the transformer. These core loss approximation functions are based on the results of EPRI load modeling research (Ranjan *et al.*, 2004) which state that real and reactive power losses in the transformer core can be expressed as functions of the terminal voltage of the transformer. Transformer core loss functions represented in per unit at the system power base are Sun (1980) and Sun *et al.* (1980):

$$P\,(\text{P.U.}) = \frac{\text{KVArating}}{\text{Systembase}}\left(A|V|^2 + Be^{c|V|^2}\right)$$

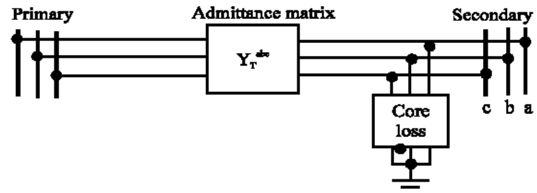



Fig. 12: Overall proposed transformer model

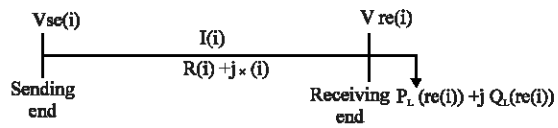
$$Q\,(\text{P.U.}) = \frac{\text{KVArating}}{\text{Systembase}}\left(D|V|^2 + Ee^{F|V|^2}\right)$$

Where, typically,

| | | |
|---|---|---|
| A = 0.00267 | B = $0.734\times10^{-9}$ | C = 13.5 |
| D = 0.00167 | E = $0.268\times10^{-1}$ | F = 22.7 |

|V| is the voltage magnitude in per unit.

**Load flow calculation:** Consider the $i^{th}$ branch of the network




The receiving-end node voltage can be written as

$$V\,re(i) = V\,se(i) + I(i)Z(i)$$

The equation is evaluated for i = 1,2 . . . ln.
where ln is the total number of branches.

Current through branch i is equal to the sum of the load currents of all the nodes beyond branch i plus the sum of the charging currents of all the nodes beyond branch i plus the sum of all injected capacitor currents of all the nodes and the sum of cogenerator currents at all nodes, i.e.

$$I(i) = \sum_{j=1}^{ln} I_L(IE(i,j)) + \sum_{j=1}^{ln} I_C(IE(i,j)) - \sum_{j-1}^{ln} I_{CC}(IE(i,j)) - \sum_{j-1}^{ln} I_G(IE(i,j)) \quad (17)$$

The real and reactive power loss of ith node is given by

$$P_L(i) = \text{real}\ \{V(se(i))\text{-}V(re(i))\}.I(i) \quad (18)$$

$$Q_L(i) = \text{imag}\ \{V(se(i))\text{-}V(re(i))\}.I(i) \quad (19)$$

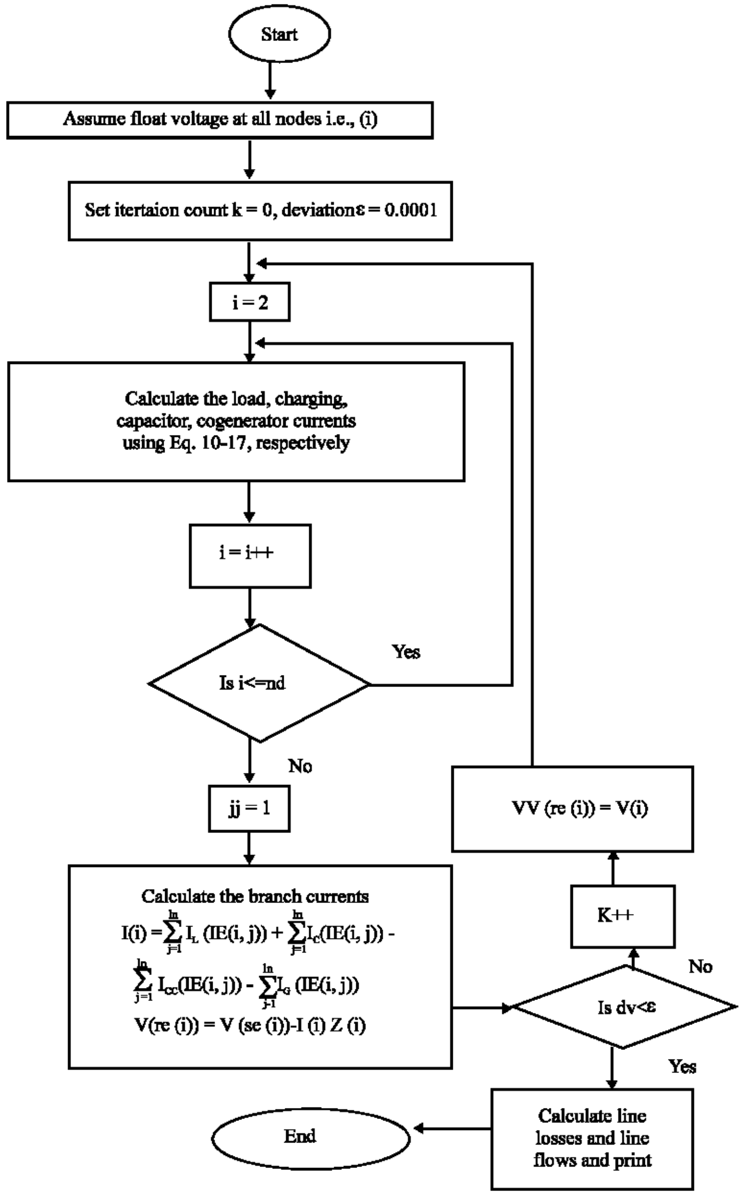



Fig. 13: Flow chart for load flow calculation

Initially, a constant voltage of all the nodes is assumed and load currents, charging currents, capacitor currents and cogenerator currents are computed. After currents have been calculated, the voltage of each node is then calculated. The real and reactive power losses are calculated. Once the new values of voltages of all the nodes are computed, convergence of the solution is checked. If it does not converge, then the load and charging currents are computed using the recent values of the voltages and the whole process is repeated.

The convergence criterion of the proposed method is that if, in successive iterations the maximum difference in voltage magnitude ($D_{vmax}$)is less than 0.0001p.u., the solution has then converged. This solution method is known recursive voltage computation method. The flowchart of the method is represented in Fig. 13.

## RESULTS

The problem is solved on IEEE 13 bus system (Patil and Kulkarni, 2004) and the results are analyzed for four different cases.

**Case 1:** This is the load current calculation with considering load and shunt admittance.

Table 1: Comparision of results for the four different cases for 13 bus system

| Case | Phase A P loss KW | Phase A Q loss kVar | Phase B P loss KW | Phase B Q loss kVar | Phase C P loss KW | Phase C Q loss kVar |
|---|---|---|---|---|---|---|
| 1 | 5.8516 | 29.7653 | 4.6844 | 8.8784 | 15.1915 | 29.8099 |
| 2 | 5.8616 | 29.7851 | 4.6882 | 8.8938 | 15.1972 | 29.8300 |
| 3 | 6.4146 | 26.1100 | 5.7930 | 7.3076 | 12.0394 | 23.3449 |
| 4 | 5.0979 | 21.2511 | 5.7450 | 8.1381 | 10.2045 | 18.3986 |

**Case 2:** This is load current calculation with considering load and shunt admittance and including the transformer core losses current.

**Case 3:** This is load current calculation with considering, load and shunt admittance including the transformer core losses current and capacitor currents.

**Case 4:** This is for load current calculation with the load and shunt admittance considering, including the transformer core losses current, capacitor currents and co-generator currents.

From the test results Table 1, the power loss is minimum when the cogenerator currents are considered (case 4).

## CONCLUSION

Rigid cogenerator and transformer models were shown in this study. Based upon these detailed models, a program was successfully developed. The results show that the cogenerator has a significant impact on the system. The voltage profile, system loss and power factor are totally different. Hence, to analyze the distribution system in detail, the three-phase cogenerator model as well as the three-phase system representation, are important. For the unbalanced transmission and most distribution systems, the transformers must be modeled in greater detail. Core loss, system imbalance and phase shift problems should be taken into account to improve the reliability of the results.

The proposed method has good convergence property for any practical unbalanced radial distribution network. This method is efficient as it solves algebraic recursive equations for voltage phases. The system modeling for the networks with different types of ground connections, unbalanced constant impedance, constant current and constant power loads, cogenerators and capacitors were considered. For several realistic distribution networks the effectiveness of the proposed method is explained with a practical system.

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