An Object-Oriented Framework for Analysis of MV/LV Distribution Systems

Vijayanarasimha H. Pakka[1], and Richard M. Rylatt[1]

[1] Institute of Energy & Sustainable Development
School of Engineering, Media & Sustainable Development, De Montfort University
The Gateway, Leicester, LE1 9BH, U.K.
Phone: +44 116 2078835, Fax: +44 116 2577977
E-mail: vpakka@dmu.ac.uk

Abstract. The interest of this work is in designing and developing a simulation package for comprehensive analysis of a distribution system based on object-oriented principles. Towards such an objective, we propose a design of a framework based on an object-oriented approach that is capable of handling such features and yet is simple and flexible enough for further extension. Here, we present a novel derivation of an object oriented methodology to firstly model the various components of a present day distribution system, and then to solve for the power flows across the system. Innovative aspects of the implementation of the derived system are how the various components are represented for power flow calculations using a standard backward/forward algorithm. An IEEE test feeder is used to demonstrate the framework. This work is of interest to model developers, distribution network planners, software designers and most importantly to users in the academia and industry.

Key words

Distribution Systems, Power Flow Analysis, Backward-Forward Sweep, Object-Oriented Framework, Component Modelling.

1. Introduction

Distribution networks have unique features with respect to the type of components and the complexity involved in analysing this network. Analysis of such networks would act not only as a conventional planning tool, but also in investigating the robustness of the distribution network to new features such as the introduction of smart meters, new market mechanisms at the distribution level, responsive loads, etc. Towards this end, in this work we develop an object-oriented modelling framework capable of analysing medium to low voltage (MV/LV) distribution systems.

A comprehensive distribution network would ideally comprise of a variety of components and actors that need to be modelled with sufficient accuracy for effective analysis of the system. This work contributes in modelling such components and actors using an efficient object-oriented methodology. The modelling framework is extensible and straight forward to adapt to complex distribution networks. It is capable of performing steady-state power flow and short circuit analysis. The design of the framework is flexible so as to include operations of the electricity market such as auctions and bidding processes. Finally, the advanced operations relating to the distribution system operator such as network congestion management, voltage stability, network reconfiguration, and demand side management are easily implementable using the object-oriented approach. Hence this approach is of interest to distribution system operators who need to keep their software systems up-to-date.

There is a growing need for improved models of the electricity distribution system that can flexibly and efficiently accommodate changes such as the integration of Distributed Generation (DG), automated demand side management strategies and various new technologies associated with the concept of the smart grid. To begin we need to model elements of a distribution network such as transformers, lines, buses and the like. Additional elements to be included in the object oriented model are composite loads, voltage regulators, capacitor banks, switches, DGs and the like that are participative in nature and crucial in the ability of the system operator to manage and control the system. For example, there are situations where the models need to be in line with latest technological advances such as power electronic based devices that are used to compensate for the reactive power in the system in real-time. Whether the models are advanced are novice, using an object-oriented approach [1] is useful in updating the models without affecting the analysis package. This is crucial from the view point of a software developer if the package is to be developed deployed as quickly as possible and without much hassle. The object-oriented approach has found flavour amongst power system software developers and is continuing to do so for investigating new ideas in the smart grid domain [2].

Innovative aspects of the implementation of the derived system are how the various components are represented for power flow calculations, together with an account of how the standard backward/forward algorithm [3], [4] is altered to effectively accommodate these new features. A generic 4.16kV network that is predominantly radial in structure and extending up to and including the 4.16kV/480V secondary distribution transformers is used to assess the algorithm.

The objectives of this work are:

- To model a wide variety of components and actors within a power distribution system, predominantly at a medium to low voltage level.

- To build an object-oriented framework capable of performing steady state power flow and short circuit analysis, market trading and advanced operations relating to the Distribution System Operator (DSO).
- And finally to demonstrate the performance of this framework on an IEEE Test Feeder.

2. Object Oriented Framework

Object-oriented methodology has its roots in how we perceive entities around us as individual objects. These objects may belong to a type of class which could be abstract, such as a template for a physical object. The attractive feature of this methodology is the ease of representation of the physical world around us, the equal ease of analysing these objects and finally the convenience of altering individual objects without major restructuring to the framework. Crucial to such a design are relationships between objects/class such as associations, aggregations and compositions [5] that are invoked to model the various physical elements. The class diagram in the case of modelling of a distribution system and its components is shown in Figure 1. The methodology supports analysis of 3 phase 4 wire networks with unbalanced loads. The following sections describe in detail the various features and components of the framework. Firstly, we describe the data structures involved in representing the components.

A. Data input and storage and processing

The data corresponding to various components can be classified into predominantly three groups: primary, secondary and tertiary. For example, in the case of distribution lines, the primary data corresponds to the topology or network related information of the objects while the secondary data consists of configuration related data. The tertiary data corresponds to information such as that corresponding to the spacing between conductors, specifically in the case of overhead lines. All the three categories of data are stored as HashMaps, where the keys and values are as shown in Table I below.

TABLE I. – Sample Data Structure relating to Distribution Lines, stored and processed as HashMaps.

Data	Keys	Values
Primary	*lineID*	*fromBus, toBus, length, configID*
Secondary	*configID*	*phasing, phaseSize, phaseStranding, phaseMaterial, neutralSize, neutralStranding, neutralMaterial, conductorDiam, conductorGMR, capacity, resistance, reactance, spacingID*
Tertiary	*spacingID*	*distancePh_AB, distancePh_BC, distancePh_CA, distancePh_AN,* ………

B. Framework Design, Classes and Objects

The framework comprises of Abstract Classes that act as templates for the various components. At the top most level are the two generic abstract classes: *PhysicalElement* and *TopologicalElement*. The mid-level abstract classes that are derived from the *PhysicalElement* are *SeriesElement* and *ShuntElement*. Further sub-classes of the *SeriesElement* are Transformers, Voltage Regulators, Transmission/Distribution Lines and Switches. *Transformer* class is an abstract class from which two concrete classes are derived based on the construction of the transformer. These are the *CentreTappedTransformer* and the *BankConnectedTransformer*. Objects of the transformer type are created out of these concrete classes. Similarly, *TransmissionLine* sub-classes are *OverHeadLine*, *TapeShieldCable* and *ConcentricNeutralCable* from which objects are initialized. The objects of the *SeriesElement* class are identified in the *TopologyProcessor* through *Branch*, which is an Interface, and is processed through primary data such as *fromBus* and *toBus* as shown in Table I.

The sub-classes of the *ShuntElement* class are *DistributedGenerator*, *Load* and *CapacitorBank* which are identified by the *TopologyProcessor* once again through the *Branch* interface. However, the *toBus* for these elements is the ground. A detailed description of the modelling of Load is given in section 3E. The principle of composition is used in the case of Loads, where individual appliances are aggregated under a single *Load* object and lumped under a single *Bus*.

C. Topology Processor

The topology of a distribution network guides the method adopted for calculating the power flows on the network. Additionally, components such as switches and circuit breakers are crucial in determining whether network reconfiguration is feasible or not. Hence any distribution network analysis package needs an efficient and robust topology processor. In the present framework, we make use of object-oriented data analysis and storage for better data retrieval during power flow analysis and other distribution system analysis such as optimal reconfiguration of networks for loss minimization and optimal placement of distributed generating sources.

The parent-child relationship between buses is extracted through a *TopologyProcessor* class which helps in restricting the power flow algorithm to the *TopologicalElement* class. The *TopologyProcessor* reads the location of buses, series elements, shunt elements and their connected buses respectively. It also reads the normal position of series elements such as switches, being “open” or “closed”. For switches that are closed, the *SeriesElement* is typecast as a “*DummyLine*” such that the end buses are effectively the same. Next the voltage regulator is processed and depending on where it is located, an additional bus is created. Figure 2 depicts the

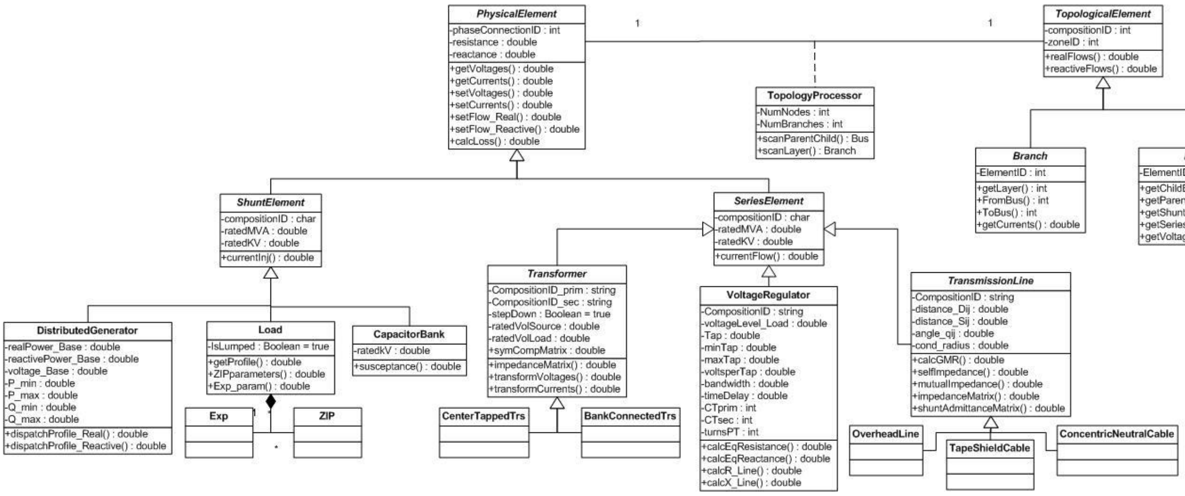

Fig. 2. A Simplified Class Diagram of the Distribution System Analysis Framework.

representation of how the *TopologyProcessor* processes a closed switch and a regulator located towards the end of a line.

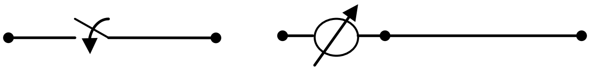

Fig. 2. On the left is a closed *Switch* between two buses. On the right is a representation of a *Voltage Regulator* that is located towards the end of a line with an additional Bus created.

The consequence of processing the topology of the network is that a comprehensive data is built that forms the basis for the power flow algorithm, especially the backward/forward sweep method, to preform efficiently. The Parent-Child relationship of Buses in a predominantly radial network is made use while generating such data. A *Layer* is made up of Buses and hence is useful in power flow methods such as the sweep techniques. A typical Parent-Child Data block consists of the following fields some of which are ArrayLists:

- *bus_ID*
- *layer_ID*
- *parentBus_ID*
- *childBus_ID_List[]*
- *parentBranch_ID*
- *childBranch_ID_List[]*
- *childBranch_Category_List[]*
- *shuntElement_ID_List[]*
- *shuntElement_Category_List[]*

D. Power Flow Methodology

Power flow methods are tools for analysing the electricity networks in steady state, whether transmission or distribution systems and whether radial or meshed in structure. Methods for solving set of non-linear equations such as Newton-Raphson and Gauss-Seidel are well known is solving for the power flows on transmission networks. However these methods are of little use in distribution networks especially those which are predominantly radial in structure. This is due to the specific feature of distribution lines such as their R/X ratio and being untransposed. Additionally, the highly unbalanced nature of the loads means that the power flow algorithm needs to be rigorous and specific for the kind of networks [6]. The algorithm that we employ is largely based on the well-known backward/forward sweep strategy [3], [4] that makes effective use of the Parent-Child topology of radial networks. The algorithm is as follows:

1. Initialize Voltages at each individual *Bus.*

2. Go through the backward-forward sweeps till power mismatch at each bus is within tolerance.

Backward Sweep:
The backward sweep begins from the last *Layer* and the *Buses* in this layer and ends at the top most layer that has the Root Bus, such as a substation or a generating source.

a. Bus currents:

$$I_j^p = \left(\frac{S_j}{V_j^{p-1}}\right)^* + \left(\frac{k\,\mathrm{var}_{cap}}{kv^2_{cap}}\right)V_j^{p-1}$$

The appropriate method, within the *ShuntElement* Class, for calculating the current injections is called depending on whether the object is an instance of *CapacitorBank* or *Load.*

b. Branch currents:

$$I_{i-j}^p = I_j^p + \sum_{k \in ChildBusList} I_{j-k}^p$$

The appropriate method, within the *SeriesElement* Class, for source-side line currents on the branch is called depending on whether the object is an instance of *Transformer, VoltageRegulator,* or a *Line.*

Forward Sweep:
The forward sweep begins from the top most layer and proceeds towards the buses in the last layer. The three phase voltages of buses in each layer are updated.

c. Child bus voltages:

$$V_j^p = V_i^p - Z_{i-j} I_{i-j}^p$$

The appropriate method, within the *SeriesElement* Class, for load-side line currents on the branch is called upon depending on whether the object is an instance of *Transformer, VoltageRegulator,* or a *Line.*

d. Bus power withdrawals:

$$S_j^p = V_i^p \left(I_j^p\right)^* - \left(\frac{k\,\mathrm{var}_{cap}}{kv^2{}_{cap}}\right)\left|V_j{}^p\right|^2$$

Real and reactive power mismatches of all the buses are evaluated between consecutive iterations and the procedure is terminated if within a prescribed tolerance limit.

3. Component Models

In this section we provide a detailed account of the classes within the model. The richness of these models can always be increased or altered based on the requirements of the user of the simulation package.

A. Transmission/Distribution Lines

Distribution lines are not usually transposed. Therefore the mutual coupling between phases is unequal resulting in an unsymmetrical impedance matrix. Neglecting such features results in inaccurate voltage and current levels getting magnified and resulting in erroneous results in power flow calculations. To eliminate these errors we model the lines from first principles, *i.e.,* calculate the individual elements of the impedance matrix through the composition data of the cables and wires used on each line segment of the feeder. The spacing between wires in the case of an overhead line is also taken into account. A 4-wire system results in a 4x4 primitive impedance matrix which is reduced to a 3x3 standard impedance matrix via Kron’s reduction. Carson’s equations are employed for deriving the primitive phase impedances of these lines [7]. We model overhead lines as well as underground distribution cables of various types such as tape shield and concentric neutral.

B. Distribution Transformers

Distribution transformers of different configurations such as $\Delta - \mathrm{Y}_G$ and $\mathrm{Y}_G - \Delta$ are modelled in three phase [8]. Two types of step-down transformers are modelled for the test feeder case. The type of connection of the source and load-sides of the transformer determines the [a], [b], [c], [d] matrices (as derived in ref. [8]) for transforming the voltages and currents from one side to the other. The sample parameters for the transformers of the test case are as given in Table II.

TABLE II. – Transformer Data for IEEE 123 bus test feeder.

Name	Rating (kVA)	Source (kV)	Load (kV)	R (%)	X (%)
Sub	5,000	115 - Δ	4.16 - Y_G	1	8
XFM - 1	150	4.16 - Δ	0.480 - Δ	1.27	2.72

C. Voltage Regulators

Voltage regulators are used as a means to regulating the voltage such that the customer voltage levels are kept within reasonable limits. There have been limited attempts at modelling step voltage regulators in view of their significance in distribution networks [9]. These devices are nothing but autotransformers with a load tap-changing mechanism. The change in voltage is obtained by switching the tap positions up or down by prescribed levels, usually in 32 steps with a regulation of ±10% giving 5/8% or 0.00625 p.u. change per step. This is equivalent to 0.75 volts on a 120 V base. V_{set} is the desired voltage level around which are prescribed the Lower Band (*LB*) and Upper Band (*UB*) voltage limits as follows: $V_{LB} = V_{set} - 0.5BW$, $V_{UB} = V_{set} + 0.5BW$. A Line Drop Compensation (LDC) circuit is used to control the changing of taps. Since the regulator is located at the end of a distribution line, the LDC is used to estimate the drop in the line voltage beyond regulator such that $\Delta V = I_{comp}\left(R_{set} + jX_{set}\right)$ and $V_{LDC} = V_{reg} - \Delta V$. The following protocol is then applied to change taps at each p^{th} step.

$$\begin{Bmatrix} t^p = t^{p-1} & & V_{LB} \le V_{LDC} \le V_{UB} \\ t^p = t^{p-1} + \left(V_{set} - V_{LDC}\right)/0.75 & \text{if} & V_{LDC} < V_{LB} \\ t^p = t^{p-1} - \left(V_{set} - V_{LDC}\right)/0.75 & & V_{LDC} > V_{UB} \end{Bmatrix}$$

D. Distributed Generation

Generating sources at the distribution level such as renewable and hybrid DGs are modelled based not only on their physical characteristics but also on their operational features. This allows for the study of smart grid concepts such as real-time generation dispatch for demand management. A DG node is considered either as a PV (where Real Power and Voltage are the known variables) or a PQ (where Real and Reactive Power are the known variables) bus, depending on the type of technology employed. For a PV bus, in addition to the reactive power output, we derive the equivalent current injection through an iterative procedure.

E. Loads

Finally, we adopt the concept of component-based load aggregation predominantly at the 4.16kV/480V transformer, which will support the increasing adoption of demand management strategies by utility companies that require time-step analysis of appliance models. Appliances that form a part of the *Load* class are modelled as individual elements of either the *Exponential* or the *ZIP* type (Z-constant impedance, I-constant current, P-constant power). These are then aggregated to define a composite load model for use in the algorithm. ZIP models are of the form, $P = P_0(a_1\overline{V}^2 + a_2\overline{V} + a_3)$ and $Q = Q_0(b_1\overline{V}^2 + b_2\overline{V} + b_3)$ with a and b values depending on the type of the load/appliance. Here, we consider a combination of loads that is best represented by a ZIP model with aggregated parameters. This is done by clustering a combination of appliances in each of the three phases downstream to the transformers. This not only induces unbalance across the phases but also allows for changing the composition of loads at each time step. The parameters of the aggregate load model are calculated as the weighted average of the respective parameters of the n appliances in the group. For example:

$$a_{1-agg} = \sum_{j=1}^{n} \frac{KVA_j}{KVA_{agg_j}} a_1$$

The aggregated load model is now:

$$P_{agg} = \frac{P_0}{(a_{1-agg} + a_{2-agg} + a_{3-agg})} (a_{1-agg} \overline{V}^2 + a_{2-agg} \overline{V} + a_{3-agg})$$

$$Q_{agg} = \frac{Q_0}{(b_{1-agg} + b_{2-agg} + b_{3-agg})} (b_{1-agg} \overline{V}^2 + b_{2-agg} \overline{V} + b_{3-agg})$$

where, P_{agg} is the real part of the aggregated load and Q_{agg} is the reactive part that participate in the power flow algorithm.

4. Results

We test the effectiveness of our object-oriented approach on a 3-phase unbalanced radial test feeder having 123 buses with predominantly 4.16kV feeder line [10]. The substation transformer steps down 115kV MV level to 4.16kV. Additionally, there is a secondary distribution transformer which further steps down the feeder voltage of 4.16kV to 480 volts 3-phase. The feeder is unbalanced in the composition of the loads and capacitors on different phases of the system. These loads are supplied either by 3-phase, 2-phase or single phase lines. The IEEE test feeder is shown as a single line diagram in Figure 3 below.

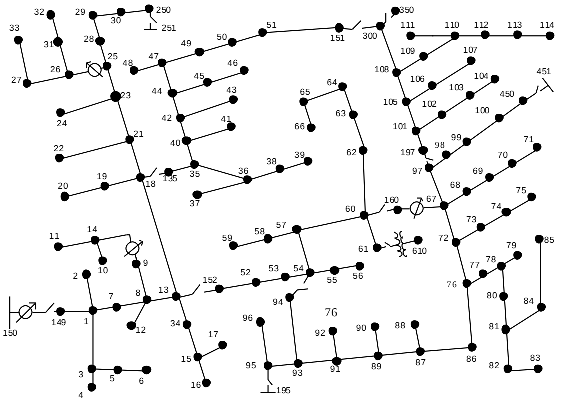

Fig. 3. IEEE 123-bus test feeder.

The voltages at each bus are initialized appropriately and the power flow methodology appropriate for radial topologies such as the one described earlier in section 2D is employed. Variables such as voltages and currents are derived in per unit fashion. Voltages of phase “A” on various buses are shown in Figure 4. We notice that voltage levels are increased by the action of step voltage regulators. The buses are numbered on the X-axis in an increasing level of distance of the bus from the substation, which is at bus number 150. Noticeable regulation on all the three phases is accomplished by the regulator at the substation between buses 150 and 149, and by the regulator located at bus 160. The results show the effect of unbalanced loads and the action of voltage regulators on the voltages along the distribution feeder. Analysing such complex systems for voltages and power flows is paramount for distribution network operators and other stakeholders such as generating companies at the distribution level.

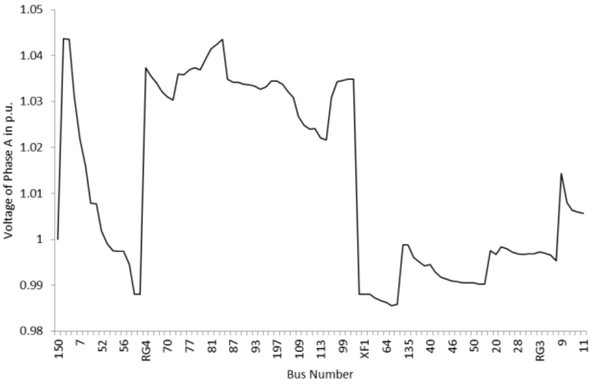

Fig. 4. Voltages on phase “A” at various buses on IEEE 123-bus test feeder. Voltages are in per unit.

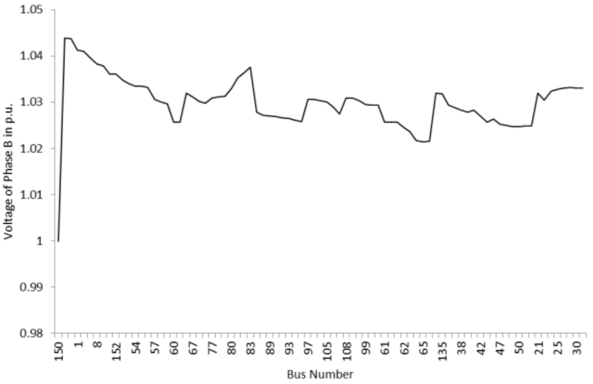

Fig. 5. Voltages on phase “B” at various buses on IEEE 123-bus test feeder. Voltages are in per unit.

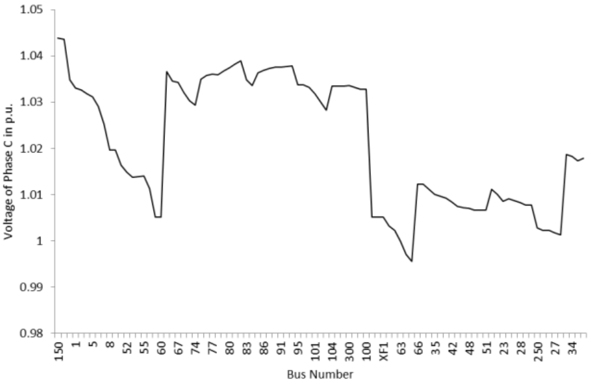

Fig. 6. Voltages on phase “C” at various buses on IEEE 123-bus test feeder. Voltages are in per unit.

5. Conclusions

In this paper we have presented an object-oriented framework for modelling a distribution system along with a variety of components. The object-oriented approach is appropriate in analysing the power distribution system in a sense that it supports a smooth and seamless adoption of power flow techniques such as the backward/forward sweep method. An appropriate power flow methodology that is specifically designed for such unbalanced distribution systems is invariably required to avoid the computational and mathematical pitfalls involved in power flow calculations of distribution systems. However the effective use of object-oriented framework and design for the various components of the system goes a long way in making effective and economical use of such methodologies. Finally, an IEEE test feeder having a range of components was used to test the effectiveness of the framework.

The above framework enables one to assess the power flows within a distribution system on a minute-by-minute basis, which allows for a detailed planning of the MV/LV voltage distribution system and prediction of its behaviour during fault conditions. Optimal placement of DGs and their effect on the LV network can be easily assessed within the framework. Additional components such as current limiters, shunt reactors, STATCOMs etc. can be easily included within the model with minimal changes to the *TopologicalElement* class.

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References

[1] A. Losi and M. Russo, “Object-Oriented Load Flow for Radial and Weakly Meshed Distribution Networks”, IEEE Trans on Power System, Vol. 18, No. 4, pp 1265-1275, Nov 2003.
[2] J. Durana, and O. Barambones, “Object oriented simulation of Hybrid Renewable Energy systems focused on Supervisor Control”, IEEE Conf on Emerging Tech & Factory Automation, Mallorca, Sep 2009.
[3] D. Shirmohammadi, H. W. Wong, A. Semlyen, and G. X. Luo, “A Compensation-Based Power Flow Method For Weakly Meshed Distribution and Transmission Networks”, IEEE Trans on Power Systems, Vol. 3, No. 2, pp 753-762, May 1988.
[4] A. Augugliaro, L. Dusonchet, S. Favuzza, M. G. Ippolito, and E. R. Sanseverino, “A backward sweep method for power flow solution in distribution networks”, Electrical Power and Energy Systems, Vol. 32, pp 271-280, 2010.
[5] M. P. Selvan, and K. S. Swarup, “Modelling and analysis of unbalanced distribution system using object-oriented methodology”, Electric Power Systems Research, Vol. 76, pp 968-979, 2006.
[6] D. R. R. Penido, L. R. de Araujo, S. Carneiro Jr, J L R Pereira, and P. A. N. Garcia, “Three-Phase Power Flow Based on Four-Conductor Current Injection Method for Unbalanced Distribution Networks”, IEEE Trans On Power Systems, Vol. 23, No. 2, pp 494-503, May 2008.
[7] W. H. Kersting, and R. K. Green, “The Application of Carson’s Equation to the Steady-State Analysis of Distribution Feeders”, IEEE/PES Power Systems Conf. and Expo. pp 1-6, March 2011.
[8] W. H. Kersting, W. H. Phillips, and W. Carr, “A new approach to modeling three-phase transformer connections”, IEEE Trans On Industry Applications, Vol. 35, No. 1, pp 169-175, Jan 1999.
[9] L. A. Gallego, and A. Padilha-Feltrin, “Voltage regulator modeling for the three-phase power flow in distribution networks”, IEEE/PES Transmission and Distribution Conf and Expo: Latin America, Bogota, Aug 2008.
[10] IEEE Distribution Test Feeders –
http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders/