

The Use of Electric Circuit Simulation for Power Grid Dynamics

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Abstract—Traditional grid models for large-scale simulations assume linear and quasi-static behavior allowing very simple models of the systems. In this paper, a scalable electric circuit simulation capability is presented that can capture a significantly higher degree of fidelity including transient dynamic behavior of the grid as well as allowing scaling to a regional and national level grid. A test case presented uses simple models, e.g. generators, transformers, transmission lines, and loads, but with the scalability feature it can be extended to include more advanced non-linear detailed models. The use of this scalable electric circuit simulator will provide the ability to conduct large-scale transient stability analysis as well as grid level planning as the grid evolves with greater degrees of penetration of renewables, power electronics, storage, distributed generation, and micro-grids.

I. INTRODUCTION

THE scalability of simulation models for a wide range of power systems components has not been explored in significant detail. Dynamic models of the electric power grid (EPG) are divergent from the existing classes of electrical systems problems being solved in electric circuit simulators such as PSpice™. The dynamic analysis of large-scale power grids needs an advancement of high fidelity scalable tools capable of addressing the future architecture of the EPG. Currently, power grid models are either high level aggregated models (e.g. PSLF™, PowerWorld™) or low level high fidelity models (e.g. Simulink™, SimPowerSystems™, PSpice™). The ability to analyze the impact of low level circuits (e.g. photovoltaic arrays) on a large scale is missing.

By using a parallel electric circuit simulator, developed at Sandia National Laboratories, Xyce™, the ability to model individual electric power grid components and group them into successively larger circuits that can replicate a large scale grid has been achieved. This results in a unique analytical capability for the power grid simulation field. Xyce™ has the ability to model highly complex circuits with very large numbers of nodes. This ability is being leveraged to extend Xyce™ to the electric power grid by using electric circuit elements to model the various components of the power grid. The ability to analyze the impact of high levels of penetration of solar PV, wind, fuel cells, and storage can be analyzed with such a tool. This capability is needed to determine the impact of high levels of renewables, distributed generation, and storage in the future EPG.

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The use of electric circuit elements in Xyce™ for the EPG has some distinct advantages:

- The ability to model EPG as a modular scale-up of electrical circuit components.
- The ability to handle a very large scale network via parallelizable solvers.
- The ability to interface with a graphical user interface to display simulation values on a grid map.

Though some of the EPG components (specifically generators) are not easily modeled as electrical circuits, the re-use of models developed in other platforms (e.g. Matlab™) is currently being addressed.

The basic EPG components modeled consist of generators (including the prime mover, governor, and exciter circuit), transformers (three phase and single phase) transmission lines (both AC and DC), and loads (static and dynamic). Constructing a power grid example begins with these basic components. To construct a realistic EPG, some assumptions were made on types of loads to be modeled as well as the size and types of neighborhood transformers, feeders, and substations to be represented.

There are three different load types being modeled: residential, commercial, and industrial. The only difference between the load types are the percentage of the load that is static vs. dynamic. Typically, residential loads are 80% static and 20% dynamic. Commercial loads are approximately 50% static and 50% dynamic. Industrial loads are generally 10% static and 90% dynamic. Static loads are represented as variable resistors. Dynamic loads are represented as induction motors. More sophisticated load models can be designed as well. Within each load type there are 3 residential sub-types: a medium home, a large home, and a medium apartment complex, 3 commercial sub-types: small, medium, and large, and 4 industrial sub-types: small, medium, large, and extra-large. For each of these sub-types, data for typical average power loads is used to determine how large the static and dynamic loads need to be in terms of power draw.

The build-up of the substation circuits progresses from loads to the distribution transformer level to the feeder circuit then to the substation level. For the higher levels, 9 distribution transformer types were defined, 6 feeder circuits were defined, and 7 substation types were defined. Finally, at the grid level, the substations are connected to generators via transmission lines using the circuit models corresponding to these components. A realistic EPG based on the state of New Mexico was constructed using the above procedure. Data visualization was accomplished by developing a Google™ map based graphical user interface (GUI). The GUI can display actual EPG nodes and edges (generators, substations, transmission lines) overlaid on a geographical map while displaying voltage and power time series data for selected nodes.

II. POWER GRID COMPONENT MODELS USING PSPICE CIRCUIT ELEMENTS

A. Generator Equivalent Circuit Models

The basic model to be used for the electric power generators is based on [1]-[2] and depicted in Figs 1-4.

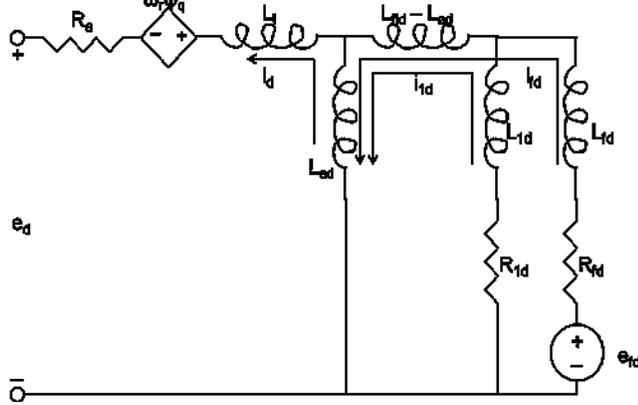


Fig. 1. Equivalent circuit for d-axis of generator.

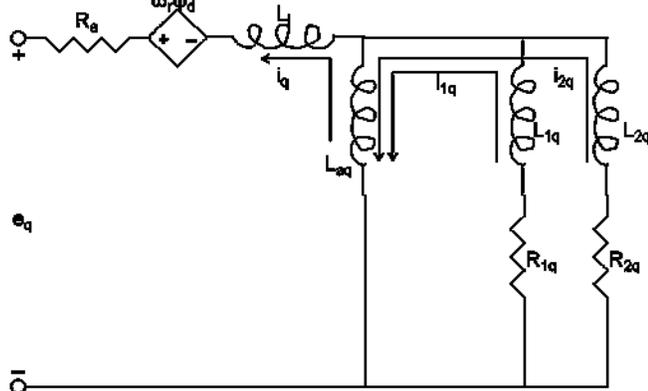


Fig. 2. Equivalent circuit for q-axis of generator.

The inductances and resistances R_a L_1 L_{ad} L_{1d} R_{1d} L_{fd} R_{fd} L_{fd} $-L_{ad}$ L_{aq} L_{1q} L_{2q} R_{1q} R_{2q} will be known *a priori* and are constant.

Note that the currents i_d i_{1d} i_{fd} i_q i_{1q} i_{2q} are defined in the circuit diagrams as loop currents. To determine the values of the dependent voltage sources in the above circuits, the following two equations are needed:

$$\psi_d = -(L_{ad} + L_1) i_d + L_{ad} i_{fd} + L_{ad} i_{1d} \quad (1)$$

$$\psi_q = -(L_{aq} + L_1) i_q + L_{aq} i_{1q} + L_{aq} i_{2q} \quad (2)$$

where ψ_d and ψ_q are the flux linkages of the d and q-axis circuits, respectively and the loop currents and inductances are as defined in Figs. 1-2.

Then, the generator swing equations (equations of motion) must be solved to determine ω_r , the angular swing velocity in rad/s to complete the expressions in the dependent voltage sources:

$$p\Delta\omega_r = (1/2H) (T_m - T_e - K_D\Delta\omega_r) \quad (3)$$

$$p\delta = \omega_0 \Delta\omega_r \quad (4)$$

where

$$\omega_0 = 2\pi 60 \quad (5)$$

$$\Delta\omega_r = \omega_r - \omega_0 \quad (6)$$

with p being the derivative operator d/dt .

Also needed is the generator output power. The active power is given by

$$P_t = e_d i_d + e_q i_q \quad (7)$$

and the reactive power is given by

$$Q_t = e_q i_d - e_d i_q \quad (8)$$

T_e is the electromagnetic torque of the generator and is given by:

$$T_e = \psi_d i_q - \psi_q i_d. \quad (9)$$

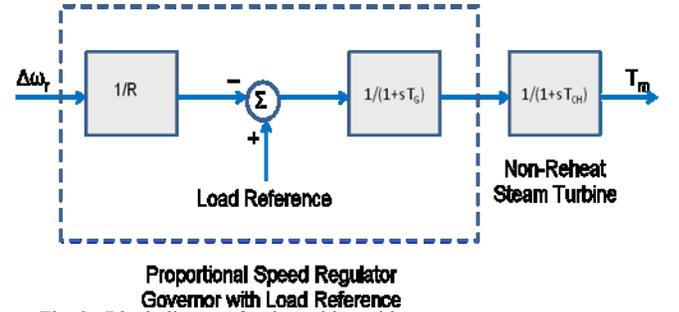


Fig. 3. Block diagram for the turbine with governor.

T_m is the generator input power and is the output of the prime mover model (e.g. turbine and governor). It is being modeled as a non-reheat steam turbine with a proportional speed regulator governor and optional load reference setting as shown in Fig. 3 where

$$(T_{CH}T_G)p^2T_m + (T_{CH} + T_G)pT_m + T_m = -(1/R)\Delta\omega_r - (1/R)(LoadRef). \quad (10)$$

Parameters and initial conditions for the above equation include:

$$R=0.05, T_{CH} = 0.3 \text{ sec}, T_G = 0.2 \text{ sec}, LoadRef = 0.0, T_m(0) = 0.0, pT_m(0) = 0.0.$$

Finally, e_{fd} is the generator field voltage and is the output of the excitation system as shown in Fig. 4. We'll use an automatic voltage regulator (AVR) to determine e_{fd} . In many large electric power generators, a power system stabilizer (PSS), may be incorporated, but we omit that here. The following equations describe the excitation system:

$$pV_1 + (1/T_R)V_1 = (1/T_R)E_t \quad (11)$$

where $E_t = \sqrt{e_d^2 + e_q^2}$ and

$$E_{fd} = K_A (V_{ref} - v_1) \quad (12)$$

subject to saturation, e.g., if $E_{fd} \geq E_{FMAX}$ then $E_{fd} = E_{FMAX}$ and if $E_{fd} \leq E_{FMIN}$ then $E_{fd} = E_{FMIN}$. Then

$$e_{fd} = (R_{fd}/L_{ad})E_{fd}. \quad (13)$$

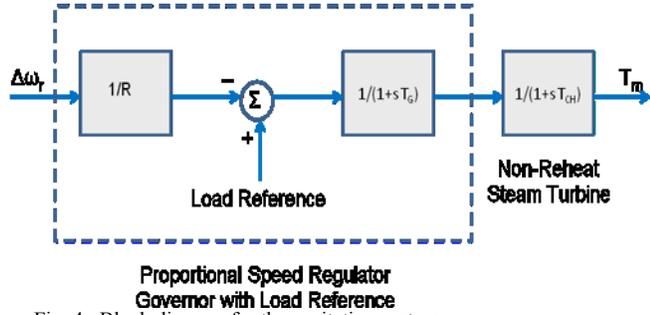


Fig. 4. Block diagram for the excitation system.

For this exciter, the following parameters and initial conditions are used:

$$V_{ref} = (1/K_A)(L_{ad}/R_{fd}) e_{fd}(0) + v_1(0), T_R = 0.015 \text{ sec}, K_A = 200, E_{FMAX} = 7.0, E_{FMIN} = -6.4, e_d(0) = 0.631, e_q(0) = 0.776, e_{fd}(0) = 0.000939, v_1(0) = E_t(0) = \sqrt{e_d^2 + e_q^2} \text{ at } t=0.$$

The following are parameter values used in the testing of the generator equivalent circuit model, assuming a 60 Hz 3-phase round rotor (2 pole) synchronous generator rated at 555 MVA at 24 kV, with a power factor of 0.9. All of these values are in per unit, $H = 3.5$, $K_D = 0.3$, $R_a = 0.003$, $R_{1d} = 0.0284$, $R_{fd} = 0.0006$, $R_{1q} = 0.00619$, $R_{2q} = 0.02368$, $L_1 = 0.15$, $L_{ad} = 1.66$, $L_{1d} = 0.1713$, $L_{fd} = 0.165$, $L_{aq} = 1.61$, $L_{1q} = 0.7252$, $L_{2q} = 0.125$, $L_{fld} = L_{ad} = 1.66 \implies$ the inductance in the d-axis subcircuit, $L_{fld} - L_{ad} = 0$ (which is a typical assumption).

III. DESIGN OF EXAMPLE POWER GRID

In order to build up an example power grid from basic electric circuit components, the following four elements will form the basic building blocks of our example grid: loads, transformers, transmission lines, and generators as shown in Fig. 5. Generators have already been defined from basic circuit elements in Sec. II. Transmission lines are often defined as basic circuit elements in circuit modeling software such as PSpice™. More sophisticated transmission line models can be developed but are omitted here. The basic three-phase transformer is modeled using the Y-Y connection as shown in Fig. 6 [3]-[4]. The loads are built up from static and dynamic load elements. A static load is modeled here as a voltage controlled current source using PSpice™

$$\text{gload n1 n2 value} = \{1/(R_{MIN}/v(n1,n2) + v(n1,n2)/PLOAD)\} \quad (14)$$

which behaves like a resistor of value R_{MIN} at low voltages and a constant power load of $PLOAD$ at high voltages. A very high percentage of industrial loads behave like induction motors, thus we model a dynamic load as an induction motor depicted in Fig. 7 [5]-[6].

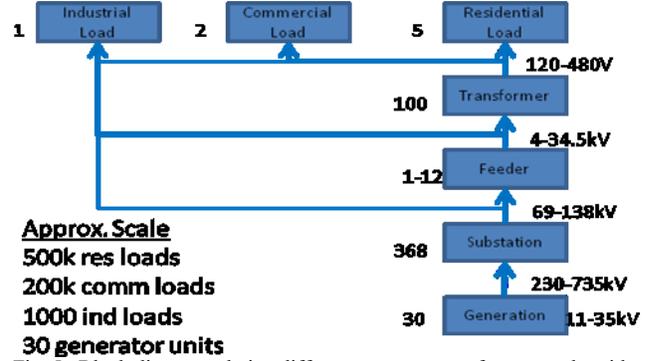


Fig. 5. Block diagram relating different components of an example grid.

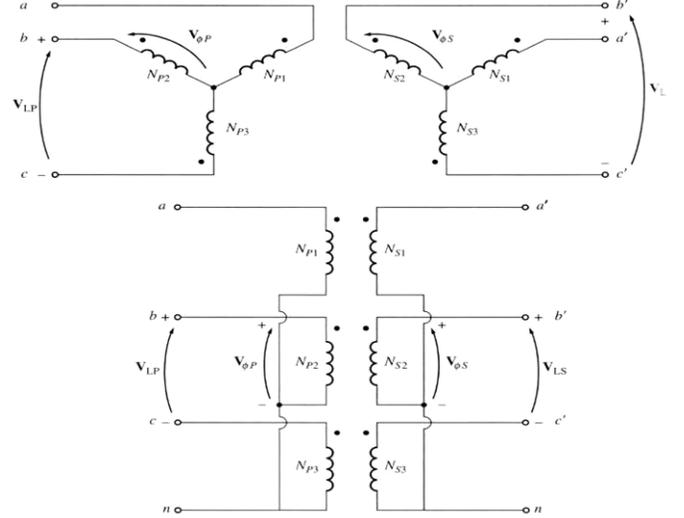


Fig. 6. Circuit diagrams for a Y-Y three phase transformer.

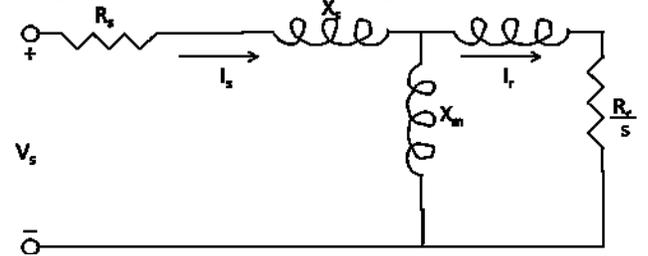


Fig. 7. Equivalent circuit of an induction motor used to represent dynamic load elements.

From (14) and Fig. 7, three different load types are defined: Residential, Commercial, and Industrial. Subtypes are also defined within each type. For instance, residential loads are defined as 20% dynamic and 80% static with an average power factor of 0.95. Subtypes within the residential load include a medium-sized home (2300 sq. ft. with 1.75kW average power load), large-sized home (3000 sq. ft. with 2.25kW average power load), and a medium-sized apartment complex (75000 sq. ft. with 56.25kW average power load). Commercial loads are defined as 50% dynamic and 50% static with an average power factor of 0.9.

Subtypes within the commercial load include a small load (1500 sq. ft. with 0.675kW average power load), a medium load (50000 sq. ft. with 22.5kW average power load), and a large load (200000 sq. ft. with 90kW average power load). Examples of these sub-types include a gas station (small), a grocery store (medium), and a big box store (large). Industrial loads are defined as 90% dynamic and 10% static with an average power factor of 0.85. Subtypes within the industrial load include a small load (200kW average power load), a medium load (500kW average power load), a large load (1MW average power load), and an extra-large load (3MW average power load). The advantage of using circuit elements for these loads is that the only difference between the load types is the % of the load that is static vs. dynamic.

The build-up of the substation circuits proceeds from load level to the distribution transformer level to the feeder level to the substation level as shown in Fig. 5. In order to build up realistic power grids, we define multiple types for each level similar to what was done with loads. That is, there are nine distribution transformer types, DTR1, DTR2, DTR3, DTC1, DTC2, DTC3, DTI1, DTI2, and DTI3, and six feeder types, Residential, Commercial, Industrial 1, Industrial 2, Industrial 3, and Mixed, and seven substation types, A, B, C, D, E, F, and G. Details of how each of these levels is assembled from the lower levels are addressed in the Appendix.

IV. DATA VISUALIZATION

A graphical user interface (GUI) was developed using a graph structure with the edges representing transmission lines and the nodes representing substations, switching stations, and generators. Fig. 8 depicts a screen shot of the GUI with node and edge data corresponding to power grid data from the State of New Mexico.

To differentiate node types, generators are denoted as red squares, switching stations are depicted as blue triangles, and substations are drawn as yellow diamonds. Each node has longitude and latitude coordinates allowing the nodes to be overlaid on a map application. In this case, a Google™ map based application is employed. The topology information is input separately from the simulation variables, which will vary with different runs. The simulation variables consist of 4 or 5 variables over time, with the duration being a couple of minutes sampled at sub-second intervals (potentially at much shorter sampling times). The simulated variables at each node include real and reactive power, voltage magnitude and phase angle, and frequency.

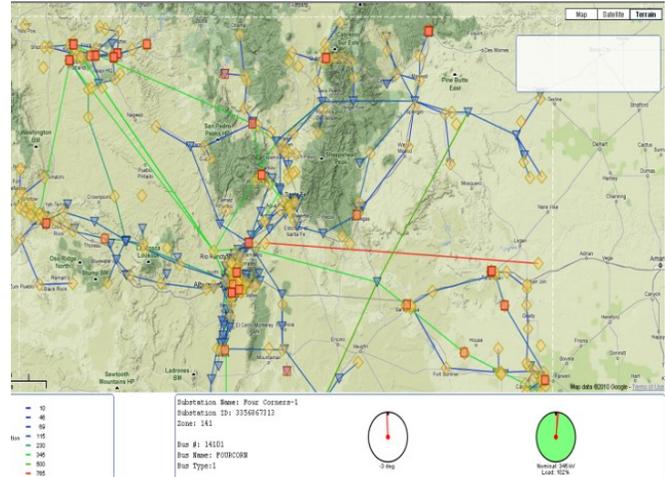


Fig. 8. Screen shot of graphical user interface displaying power grid data for the State of New Mexico.

In the screen shot of Fig. 8, the lower left portion of the GUI contains a legend for the nodes and for the transmission lines. The transmission lines are color coded according to voltage category (e.g. 115 kV, 230 kV, 345 kV, etc.). In addition, if the screen cursor hovers over an edge of interest, the voltage rating for that transmission line will be displayed on the screen. The nodes are selectable, allowing one to display the time series plots in a control panel at the bottom of the screen. In Fig. 8 above, nominal values for voltage magnitude and phase angle are displayed in a console format representing a nominal base case simulation. The GUI is still in a state of further development. In the future, animation controls to view simulation values dynamically change over time will be added. In addition, some of the simulation runs may want to remove edges and nodes and evaluate the impact of a transmission line outage or a generator failure. Further, since the simulation captures detail down to the electric circuit level, a drill down capability will be added to the GUI allowing for time series values of individual loads and transformers.

V. CONCLUSION

A modeling technique that combines the high fidelity of electric circuit models with the scalability of grid level elements is presented as a tool for the use of transient as well as steady state simulation of electric power grids. Circuit simulation for electric power grid networks has some distinct advantages:

- 1) Ability to model grid as a modular scale-up of electrical components.
- 2) Ability to handle a very large scale network via parallelizable solvers using Xyce™ [7].
- 3) Ability to interface with GUI to display simulation values on a grid map.

Some disadvantages of using circuit simulation include:

1) Some of the components (e.g. generators) are not easily modeled as electrical circuits.
 2) Re-use of models developed in other platforms (e.g. differential/algebraic equations or Matlab™) can be done but is non-trivial -- this is currently being addressed.
 The developed graphical user interface not only allows the representation of data over a geographic display but can also display time series values of selected nodes. Further development will include the ability to run simulations with the user specifying which nodes and edges are to be removed (e.g. generator failure, transmission line outages, and substation blackouts).

APPENDIX

The construction of the scalable levels that comprise substations begins with the residential, commercial, and industrial load building blocks. From these, higher levels of complexity are assembled as described in Sec. III. Figs. 9-20 illustrate this process.

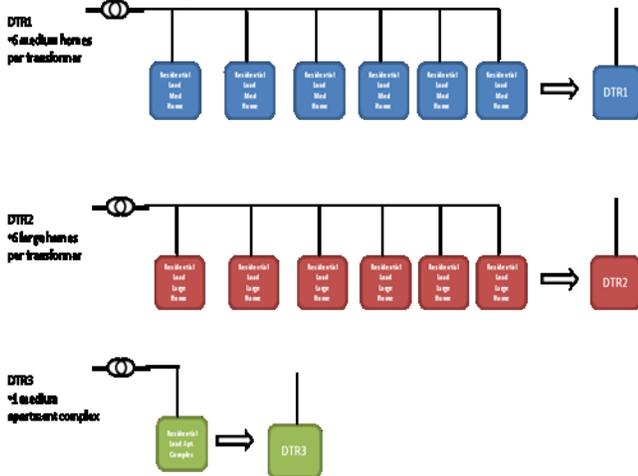


Fig. 9. Block diagrams for the DTR1-3 type distribution transformers.

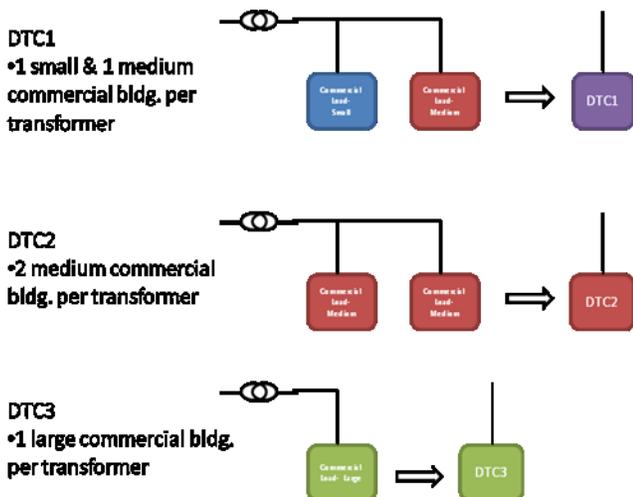


Fig. 10. Block diagrams for the DTC1-3 type distribution transformers.

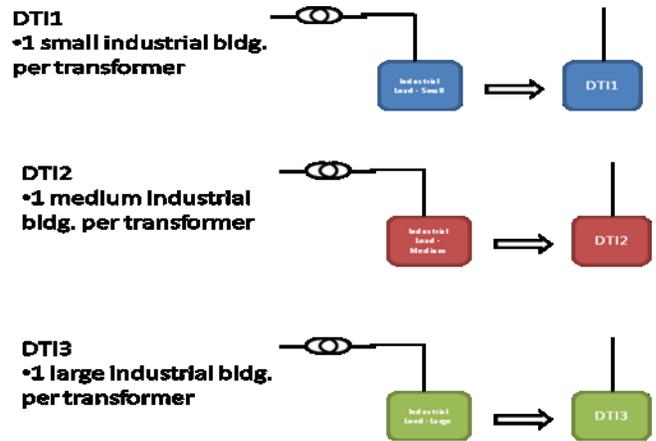


Fig. 11. Block diagrams for the DTI1-3 type distribution transformers.

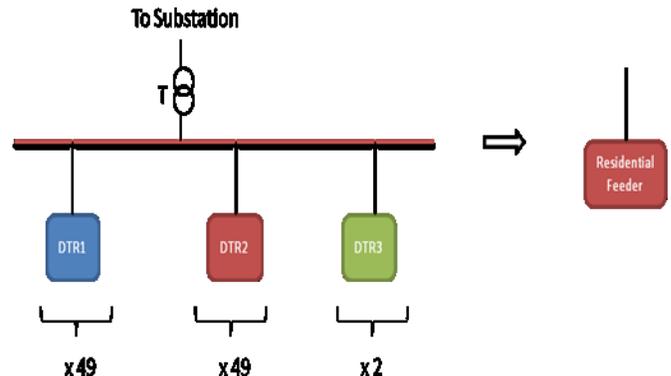


Fig. 12. Block diagram for the residential feeder.

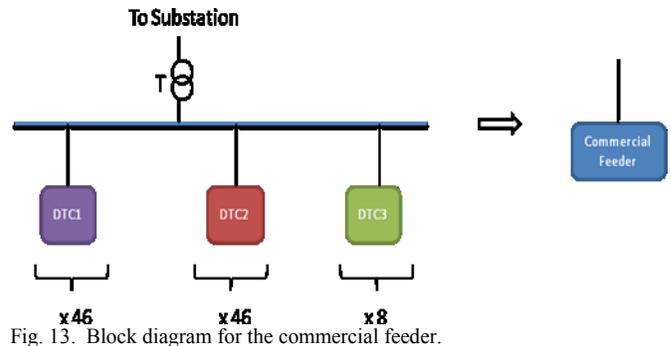


Fig. 13. Block diagram for the commercial feeder.

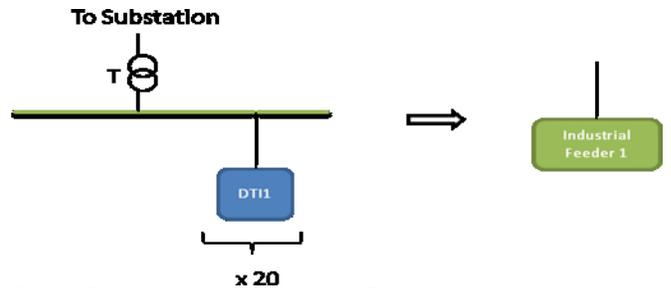


Fig. 14. Block diagram for the industrial feeder 1.

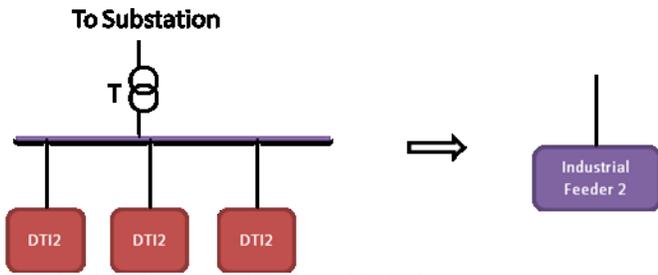


Fig. 15. Block diagram for the industrial feeder 2.

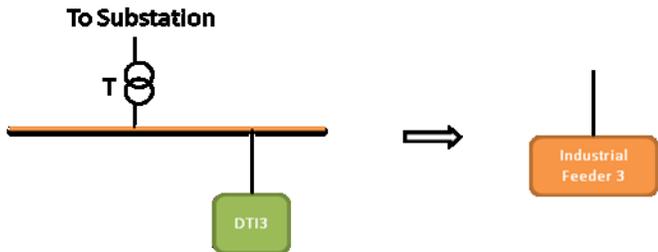


Fig. 16. Block diagram for the industrial feeder 3.

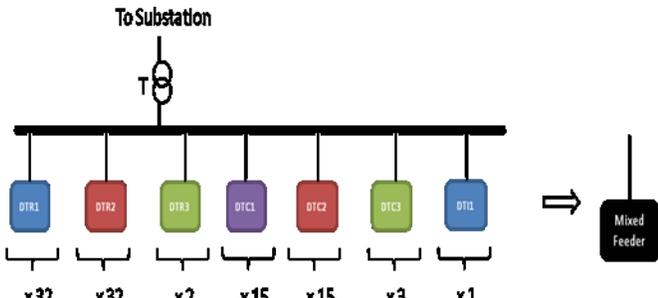


Fig. 17. Block diagram for the mixed feeder.

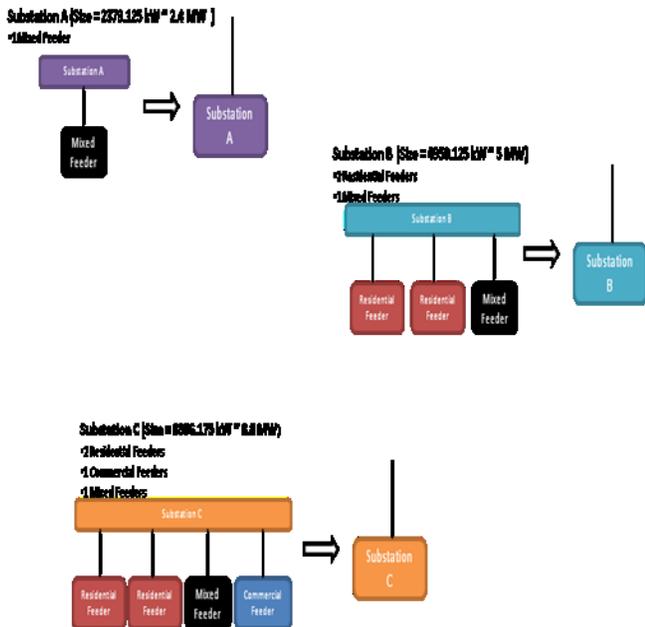


Fig. 18. Block diagrams for A,B,C type substations.

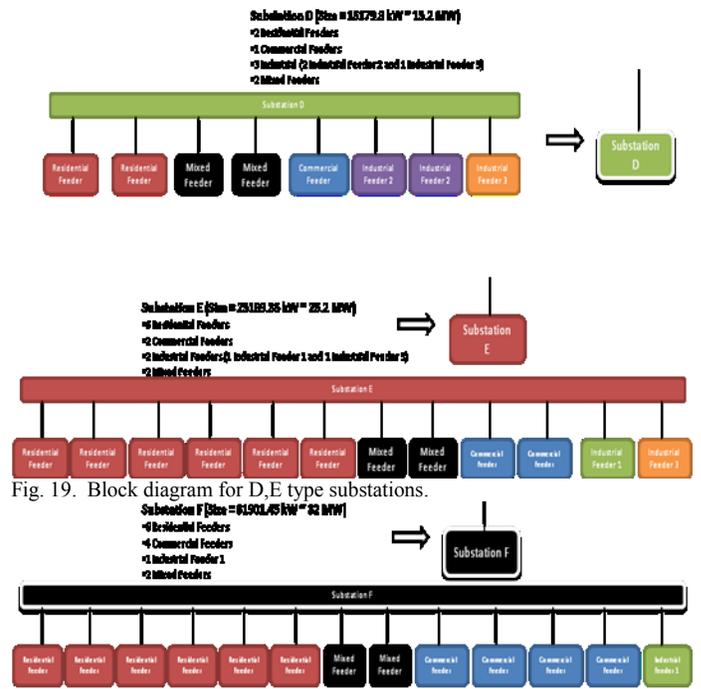


Fig. 19. Block diagram for D,E type substations.

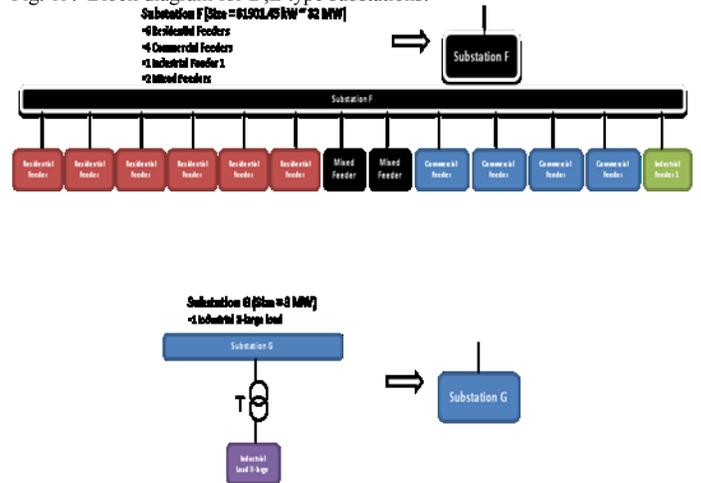


Fig. 20. Block diagram for F,G type substations.

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