Decentralized-Inverter Based Reactive Power Compensation of Active Meshed Distribution Network

A Thesis

Presented to

the Faculty of the Department of Electrical & Computer Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Electrical Engineering

by

Prateek Gaure

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Decentralized-Inverter Based Reactive Power

Compensation of Active Meshed Distribution Network

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Abstract

This thesis presents the analysis of voltage control in distribution systems, with the presence of distributed generation (DG). In microgrids, many smaller renewable generators (e.g, wind turbines, photovoltaic, fuel cells, etc.) and energy storage units are interfaced through power electronic inverters. Dynamic response of voltage & frequency under events such as fault or load and/or transmission line switching, may lead to instability in the interconnected micro-grids. These inverters are programmable to work as a source or sink of reactive power. Hence, the dynamic stability can be achieved with the help of localized, fast responding VAR-capable inverters for either providing or absorbing necessary reactive power. The main prospect of injecting reactive power from distributed and localized power sources are to better manage resources, minimize losses, lower costs and offer a better service to the costumers.

An active, low voltage, meshed microgrid which has a complex distribution pattern as well as varying loads and sources will be considered. The thesis will include a local control algorithm for cooperative operation of decentralized and interfaced inverters to achieve voltage regulation and also loss minimization. The test system will be simulated on a Hardware-in-Loop (HIL) OP5600 Real time digital OPAL-RT simulator for a real time experimental set-up.

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1. Introduction

With the advent of evolving smart grids, distribution power networks today are shifting gears from a passive to a more active role in the power system scheme. By the introduction of Distributed Generation (DGs), the distribution networks are changed into a source owned system that has great impact on the characteristic of the conventional power flow. At the same time, it increases the load forecasting uncertainty and may lead to a series of influences on distribution networks voltage profile and losses. Moreover, the microgrid is susceptible to instability caused due to various contingencies such as faults, voltage dip, sudden removal/addition of large loads etc. In particular, any oscillations in power electronics interfaced generators and loads may resonate with other parts of grid and dramatically impact the stability of the interconnected microgrids.

Dynamic stability control of interconnected microgrids becomes very complex problem that needs fast data collection and communications, and also proper preventive and/or corrective actions. The traditional reactive power dispatch approaches compensate for the drop of voltage by using controlled injections of reactive power at few locations.

1.1 Distributed Generation integration to Power Grid

Distributed generation (DG) encompasses any small-scale electricity generation technology that provides electric power at a site close to consumers. The size of DG could range from a few kilowatts to hundreds of megawatts. DG units are rarely directly connected to transmission grid. This is because, compared with traditional central generation, DG has limitation for bulk power production. Despite this, DG technologies promise a great many benefits, including cheaper power supply, higher power quality, less capital investment, improved system performance. The alternatives for connecting DG systems to local distribution system is shown Figure 1.1. The alternatives a, b and c are mostly used by consumers. However, a and b with double power sources provide higher reliability.

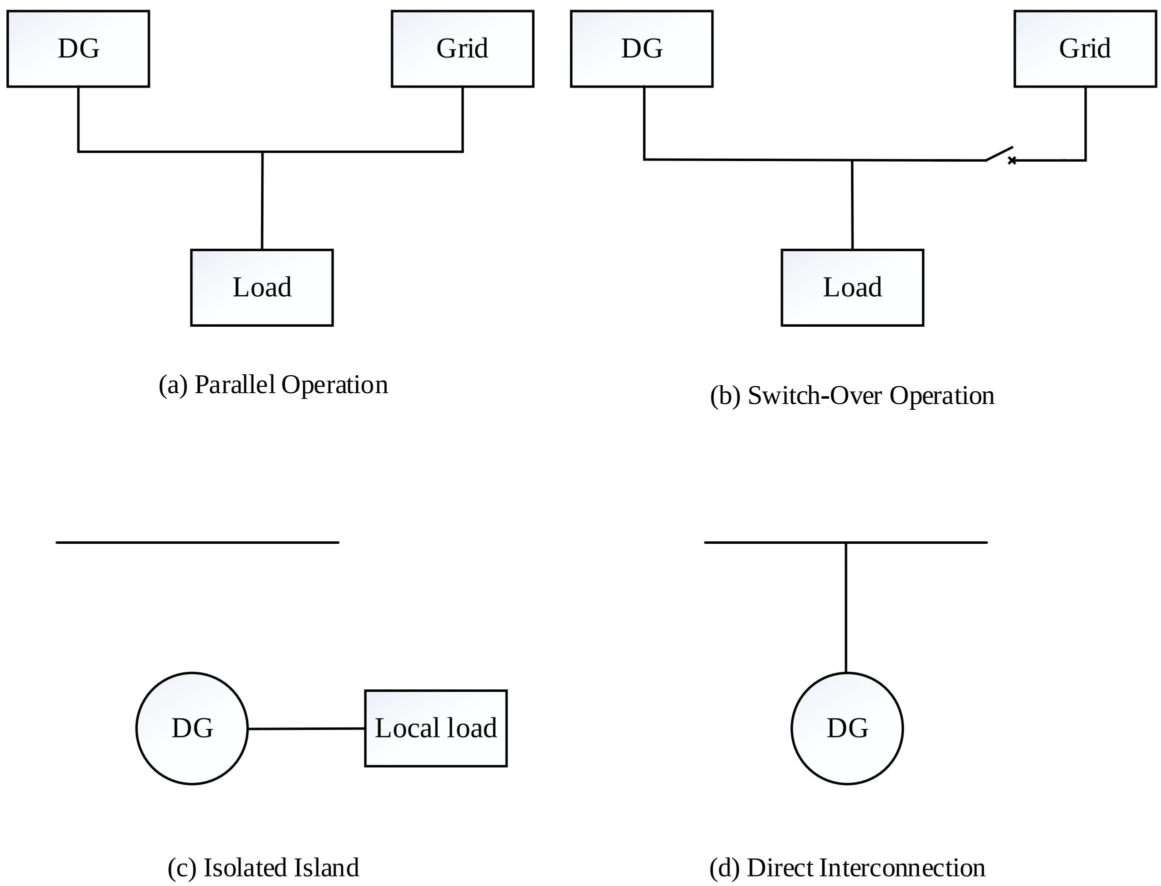

Figure 1.1 Interconnection Fashion
(Courtesy: Wiley-Interscience, IEEE Press)

Moreover, as shown in Figure 1.2, integrating DG into a power grid has two implications. One is the technical integration (i.e., hardware and software) which include issues relevant to power system operation, control and optimization; other is the market integration, which includes the establishment of new market mechanisms that allow DG to participate in a market competition [1].

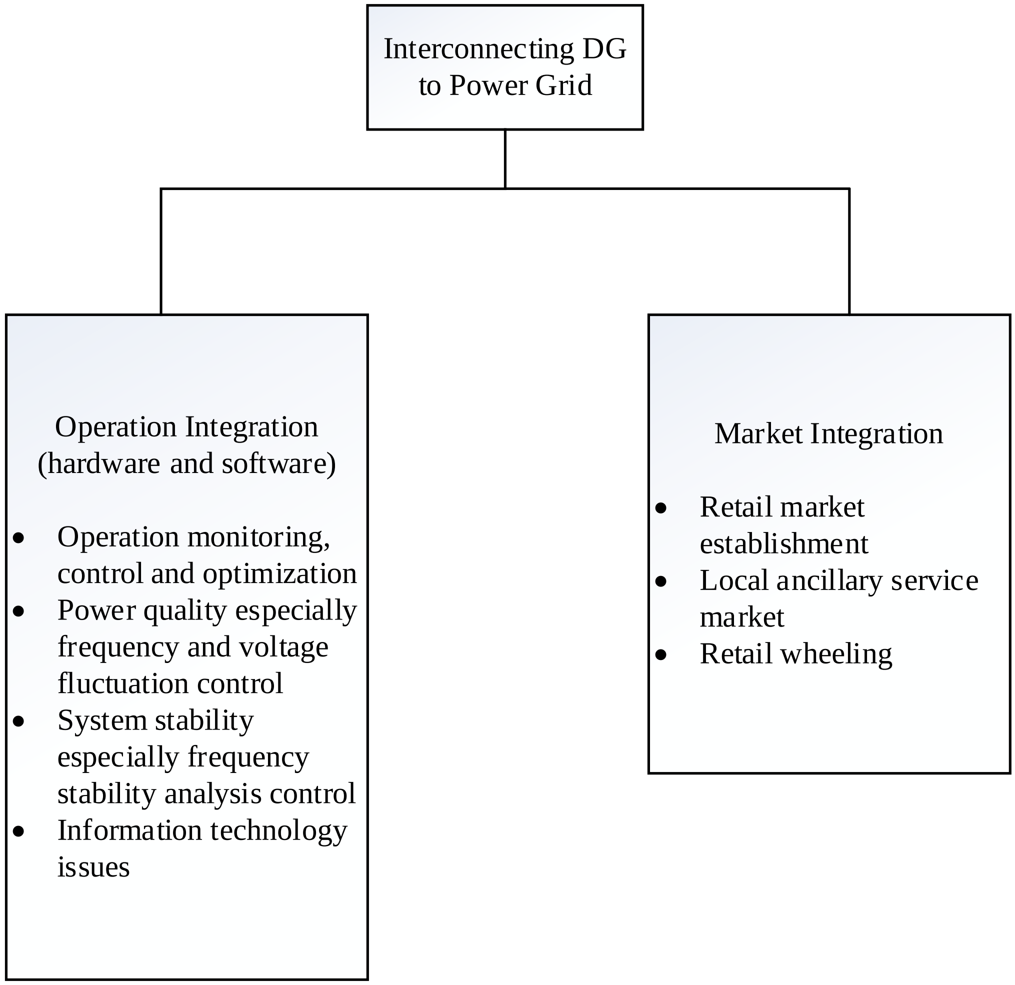

Figure 1.2 Integration of DG into Power Grids
(Courtesy: Wiley-Interscience, IEEE Press)

1.1.1 Transition to More Active System

The distribution system was initially designed to operate with minimal real-time intervention except for responding to faults, allowing routine maintenance and network modification. This philosophy of passive operation has placed a number of limitations on the integration of DG into the power gird. It is envisioned that the active operation of distribution system could accommodate a large number of DG units while improving the performance of the entire distribution system. The active operation of a distribution system refers to its intelligent adaptation to changes in the local loads and DG units. The transit from the present passive mode to a fully active mode can be accomplished in the following three stages:

- **Passive.** The Distribution Network Operator (DNO) would only be reacting to abnormal situations and planned abnormalities or no longer-term restrictions. This can be realized by using existing monitoring and control infrastructure at key nodes.
- **Intermediately active.** In addition to functions of the passive stages, the DNO would provide real-time monitoring of the distribution system, scheduling of DG units, and load management, for parts of the distribution system.
- **Fully active.** In addition to functions of the intermediately active stage, the DNO is equipped with real-time modeling capability for the monitoring and control of the distribution system security. The need for enhanced control and communication systems, as well as appropriate market mechanisms, could develop over time as DNO becomes more actively familiar with a network operation.

1.1.2 Distributed Network Structure and its Monitoring & Control

The distribution network structure could be radial or meshed. The radial network suffers the disadvantage of low degree of reliability. Meshed networks on the other hand, have well known advantages versus radial schemes: a reduction in power losses, a better voltage profile, a greater flexibility and ability to cope up with the load growth, and an improvement of Power Quality due to fault level increases at each bus. A distribution network is usually composed of a number of distribution system. When there are many DG units operating in a synchronized manner, a large distribution system could be divided into a number of control areas for the effectiveness of monitoring and control.

1.2 Centralized vs. Decentralized Control Strategy

A form of distribution network management by gathering system conditions and coordinating the operations of voltage/reactive power control equipment is called Centralized Control. In the centralized control strategy, the communication requirements and additional system vulnerability due to reliance on communication may outweigh the potential performance benefits. In addition, latency in communication and control may degrade performance during rapid changes in cloud cover.

On the other hand, by comparing measured voltages and desired values, voltage and reactive power are regulated independently through the controller of DG units (inverters). This control strategy is called Decentralized Control. That is, without considering the system wide effect from other equipment, only the voltage error at the bus with control equipment is expected to stay within a pre-specified range. This scheme acts on local variables and thus does not suffer from latency. Also they are much less vulnerable as they do not depend upon communication for their operation (communication to its immediate neighbor or other limited communication may be employed).

1.3 Literature Review

The reactive power planning and operation is an optimization problem of nonlinear, non-smooth and non-continuous function. It is one of the most complex problems of power systems because it requires the simultaneous minimization of real power losses to reduce the operating cost and improve the voltage profile, and the cost of additional reactive power sources. Several algorithms for reactive power control especially suited for distribution system with DER's have been developed over the time which discusses over a range of topics like: Co-ordinated voltage and reactive power control schemes, Power flow studies, Optimal sizing and siting of the DGs [8-10[1]].

1.4 Thesis Objective

1.4.1 Problem Definition

The goal of this thesis is to develop & evaluate an algorithm for optimal dispatch of reactive power at each active node of the active (from local inverter) meshed distribution network in a decentralized manner for achieving voltage regulation and minimum distribution losses. After evaluating the algorithm on a test system (simulation), it is emulated with the help of Hardware in loop OPAL Real Time Simulator (OPAL RT-5600).

1.4.2 Background

This thesis work demands good understanding of power flow solution in a meshed distribution network. Moreover, it requires understanding of power converter devices such as inverter for developing an algorithm to integrate optimal power dispatched at each node in the distribution network within the reactive power capability curve of the inverter. The modeling detail of a dynamically controlled decentralized scheme of reactive power compensation for a meshed network has been proposed. The algorithm has been tested on

[1] This research is largely inspired from these works

a small local microgrid example using Power World Simulator and the primary results are verified. Another test system build specifically using OPAL-RT Toolbox in MATLAB Simulink is implemented on Hardware-In-Loop OPAL-RT Simulator.

1.4.3 Existing Solution & Challenges

The most common practice existing today is a centralized method of dealing with a large pool of data. Centralized optimization of reactive power control problem involves constant monitoring of the status of reactive power control equipment, load forecasting, and then solving the optimization problem based on forecasted conditions and ultimately determining the optimal settings for the equipment. But, for large systems, centralized approach becomes tedious and too complex. Moreover, the solution may not be accurate because of varying output power of renewable-energy based DGs. Furthermore, centralized approach demands considerable investment in sensors, communications and control systems hence making it less suitable for massive DG networks.

The challenges involved in distributed generation system, can be listed as below:

1) Large scale integration of decentralized power generating units may lead to instability of voltage profile
2) Bi-directional power flow and complex reactive power management can be problematic and may lead to voltage profile fluctuation
3) DG units are likely to affect the system frequency
4) Bi-directional power flow demands for different protection schemes at both voltage levels

1.4.4 Motivation

The opportunities distribution generation has, can be listed as below:

1) DG open up new opportunities for distributed reactive compensation for the purpose of voltage control, reducing losses and frequency regulation
2) Network performance in terms of flexibility, reliability, speed of operation and efficiency can be enhanced
3) DG’s have direct impact on electric loss due to their proximity to load centers
4) The VAR-capable inverters in the network have the untapped potential of localized support to voltage stabilization
5) DGs can prove to be instrumental in decreasing the vulnerability of the electric systems to external contingencies such as terrorist attacks and other potential catastrophic disruptions owing to the fact that it is localized instead of being centralized

Voltage control in a distribution system is mainly related to the control of VAR. Reactive power control in turn may lead to added advantages such as minimization of real power loss and power factor improvement. Reactive power control has been looked at as an important issue in distribution systems.

1.4.5 Thesis Organization

The thesis is divided into five chapters.

- Chapter 2 includes the background and literature review for this research work. It has a brief overview of Methods of Power Flow Studies. The power flow measurement techniques employed varies for different application, in this chapter we discuss the difference in methodology for conventional power system and more complex distributed power networks. Also, for distributed network itself, there are various methods which could be deterministic or non-deterministic. Further ahead in this chapter, the importance of allocation of DGs in distributed network is discussed.

- The theory behind distribution network modeling, classification of distributed network connections, introduction to reactive power compensation are discussed in Chapter 3. The method of end-user (inverter based) reactive power compensation in a decentralized manner is discussed in length. The construction of the active meshed distribution network and the algorithm proposed to achieve the aim is presented in this chapter.
- Chapter 4 presents the Simulation Methods carried out to validate the algorithm proposed. It includes two sections: one utilizes Power World Simulator for network analysis and the second one is done in MATLAB Simulink in association with the Real Time Simulator OPAL-RT.
- The last chapter summarizes the contributions of this thesis and discusses future work.

2. Background and Literature Review

2.1 Methods of Load Flow

Conventional load flow methods may not converge when applied to distributed system owing to the fact that they are weakly meshed and have a high R/X ratio. These factors lead to an ill-conditioned Jacobian, which eventually results into non-convergent solution. Moreover, iterative methods are tedious and time consuming. The load flow problem in distributed system includes electric loads which have variable dynamic behavior; several voltage levels, whose topology could be radial or meshed, and dispersed and renewable energy sources.

2.1.1 Deterministic Load Flow Studies

Deterministic load flow is solved with fixed value parameters as input. These methods are simple, and a slight modification of some of the techniques results into a quick and accurate methodology. Thus, for distributed network the most common methods are either backward-forward sweep or variants of Newton methods.

a. Backward/Forward Sweep methods

A realistic mathematical single and three phase model to facilitate the inclusion of distributed generators with controlled voltage on power flow studies for distribution systems, using an injection of reactive power from the DG units is proposed in [11]. Another method that includes some important features, such as three-phase systems, PV node, distributed generation, distributed loads, or voltage regulators is elaborated in [12]. Also, three phase four-wire system, including neutral grounding [13] was proposed. A solution for weakly meshed systems in which the loops are broken and the network is converted into radial was presented in [14].

An improved backward/ forward sweep algorithm for three-phase load-flow analysis of radial distribution systems is proposed in [15]. It elaborates two steps:

- Backward sweep: Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) are used to find the calculated voltage for each upstream bus of a line or a transformer branch.
- Decomposed forward sweep: The linear proportional principle is employed to update the voltage at each downstream bus.

Comparison of the execution time and number of iteration between the ladder network, backward/forward sweep and improved backward/forward sweep method suggests that the improved algorithm is quicker and accurate. Up to, 35% more computational efficiency was observed in [15].

b. Newton-Raphson type methods

The backward/forward sweep method cannot reflect the capacities of DGs and load, which caused influence on distributed network losses at different levels of DG penetration. Hence, we look forward to another method that can overcome these shortcomings. Conventional Newton-Raphson or Newton-like methods may fail to converge when solving the load flow problem for ill conditioned systems.

The paper [16] introduces participation factor load flow [17] that reflects the network parameters and load distribution, by applying the concept of power loss sensitivity and rule of equal incremental cost. The improved network based distributed slack bus model is discussed referring to [18], which includes the characteristic of DGs. This algorithm can calculate the distribution power flow with multi-type DGs and different levels of DG penetration. The advantage of this method is that it also reflects the capacity of DGs and the network parameters.

2.1.2 Stochastic Load Flow Studies

Deterministic load flow methods do not take into consideration the uncertainties of power system such as intermittent power generation, variation in load demands, failure rates and network reconfiguration. The stochastic or probabilistic method involves a sequence of random variables and time series associated with these random variables. The stochastic load flow can be solved by using either numerical method or analytical method.

a. Numerical Solution Method

It basically involves solving a deterministic power flow technique repeatedly with inputs of diverse permutations while using the non-linear power flow equations. The results of this method can be used as a reference to the results obtained from other stochastic approach to keep a check on its accuracy because it uses exact load flow equations.

b. Analytical Solution Method

One of the main disadvantages of numerical solution method is the large amount of computational time. Analytical method takes individual probability density function for each random variable and convolves them together according to load flow equation. This method may not converge for distributed system because a number of simplifications are introduced before solving this approach which is not in accordance with distributed network parameters. To practice analytical method in distributed system we first need to linearize the load flow equations around the mean value and also the input power variables should be made completely independent of each other. Moreover, interdependence of power generation and load demand, also in between different DGs poses a difficulty. These unrealistic assumptions of uniformly distributed load in distributed system make this method ineffective. Hence it becomes increasingly complicated and tedious. No matter how promising these methods seem to be, deterministic approach is desirable owing to the fact that it is convergent and more lucid.

2.2 Allocation of DGs in Distributed Network

Some of the challenges that are confronted while designing the embedded generation network are proper location, appropriate size and operating strategies of the distributed generator. Proper allocation and sizing of DGs is vital for reducing losses, improving voltage profiles and increasing reliability. It is noteworthy that, even if the location is optimal but the sizing of DG is improper it would increase the losses in the system.

2.2.1 Analytical approach

Authors in [19] utilize an analytical method to obtain the optimal location and size of a single DG unit. This method is based on an exact loss formula and power flow method and is employed only twice, once with DG and once without DG. Although promising, this method does not account for any constraints such as voltage requirements that the distribution systems must meet. Moreover, this method is limited to DG type capable of delivering real power only.

An improved analytical method [20] which is a modification of [19] which covers three other types, e.g., DG capable of delivering both real and reactive power, DG capable of delivering real power and absorbing reactive power, and DG capable of delivering reactive power only, can also be identified with their optimal size and location.

Generally, the analytical approaches are based on injection of phasor current into a node and they usually consider some unrealistic assumptions in practical sense while implementing them. Such assumptions make this method ineffective and are prone to generate erroneous solution for actual systems.

2.2.2 Meta-heuristic approach

Meta-heuristics make very few assumptions about the optimization problem being solved, and so they may be usable for a variety of problems. Meta-heuristic algorithms are approximate and usually non-deterministic. They do not guarantee a global optimal solution. Out of many examples of meta-heuristic approach; Simulated annealing (SA), Genetic algorithm (GA), and Particle Swarm Optimization (PSO) are briefed here.

a. Particle Swarm Optimization (PSO)

Using a combination of Particle Swarm Optimization (PSO) [21-24] and Newton-Raphson load flow methods further in depth investigate the impact of location and size of distributed generators on distribution systems. Particle swarm optimization (PSO) is a population-based optimization technique which utilizes weight function.

In [25], the application of Particle Swarm Optimization (PSO) technique to find the optimal placement of wind turbine DG in the primary distribution system to reduce the real power losses and improvement in voltage profile. The results are verified with analytical approach which uses analytical expressions of wind turbine characteristics for proper deployment of the DG unit and the effects on system performance are investigated.

b. Genetic algorithm (GA)

Siting and sizing of DG in Smart Grid construction are researched in [26]. A multi-objective optimal model is established and normalized in the DG number, location and individual capacity of uncertainty. The model at length considers the total operation cost of DG, power network loss and maximum capacity of DG. To propose a direct weighing factor, the power network loss is transformed into the cost of purchasing power. The improved adaptive genetic algorithm is used to optimize the siting and sizing of DG.

Optimal location of DGs is obtained by comparing the power losses after injecting the optimal size of DGs at various locations in the distribution network. The case which results in minimum losses is considered to be the optimal location.

3. Proposed Method

3.1 Distribution Network Modeling

Until few years ago, distribution networks were regarded as a passive termination of the transmission network, having the goal of supplying reliably and efficiently end users. According to this scheme, distribution network were radial, with unidirectional power flows and with a simple and efficient protection scheme. A greater penetration of DG has changed completely, this well consolidated environment: definitely, distribution networks are no longer passive and it has been foreseen a gradual, but ineluctable, changing towards a new kind of active networks. Active networks will be strongly interconnected (no radial scheme, no unidirectional power flow) and subdivided into small cells, locally managed by a power controller, which superintends power flow among local generators, loads and adjacent cells.

3.2 Radial and Meshed Network

3.2.1 Passive Radial Distribution Network

Such distribution networks are always operated with a radial arrangement, and are often subdivided into two different levels: trunk feeders and lateral branches. The low degree of reliability obtained with radial network is generally improved by adding emergency ties, which provide alternative routes for power supply in case of outages or scheduled interruptions; these emergency ties end with an open switch so that radial structure is maintained during normal conditions.

3.2.2 Passive Meshed Distribution Network

As discussed earlier, meshed networks have well known advantages versus radial schemes: a reduction of power losses, a better voltage profile, a greater flexibility and ability to cope with the load growth, and an improvement of Power Quality due to the fault level increase at each bus. Moreover, also without DG, the potential is more suitable for power flows sharing, consequent to the passage from radial arrangement to meshed operation, can allow the deferment of investment needed to meet with the growing energy demand.

It is prominent to observe that these advantages can be maximized only by optimizing number and position of the emergency ties. Without careful planning strategies, the adoption of a meshed scheme can also worsen some technical aspect of the network operation: for example, if a weak lateral (generally having smaller sections) is involved in a meshed route, it could turn to a status of excessive exploitation. Obviously, compared to radial arrangement, a meshed network presents also some drawbacks: a more complex planning and operation, which consequently involves a higher cost, and a rising of short circuit current in each node, that could implies the substitution of the existing circuit breakers.

3.2.3 Active Radial and Meshed Distribution Network

The presence of DG on the Distribution System drastically changes the characteristics of the existing radial networks, which are no more passive with unidirectional power flows, but become active. These circumstances alter the well consolidated management procedures applied, and the effects of DG towards the network could be positive or negative depending on the position and the size of the generators installed. Thus, it is more desirable to optimize their allocation, instead of choosing randomly their connection sites, like it is preferable to optimize the position of the additional ties used to mesh the existing radial distribution networks. The case when a medium size generator is installed in a weak lateral, causing higher power losses and virtually requiring additional resizing investment is emblematic.

The same remarks can be made also for the active meshed distribution network, even if the stronger and more flexible architecture reduces the potential negative effects of the presence of DG. If properly allocated, the main benefits introduced by DG on the distribution networks refer to the reduction of power losses, the improvement of voltage profile, and the deferment of investment resulting from a reduced equipment exploitation (conductors and transformers). All these benefits could be potentially higher for meshed networks, because they join with the same benefits introduced by this network arrangement. Moreover, if intentional islanding is permitted, the presence of DG suitable coordinated with network automation can also improve the supply reliability of users connected to some laterals. On the contrary, the main negative aspects associated to the existence of DG are the increase of the short circuit currents and the alteration of the protection system logic, which can prejudice its selectivity. For this reason, currently the majority of the international standards contemplate the instantaneous disconnection of the generators in case of a fault, so that the existing protection system can work properly. On the other hand, this practice prevents the adoption of the intentional islanding, deleting the relative benefit, and prevents the advantage of a power quality improvement, related to the fault level increase.

3.3 Reactive Power Compensation

Traditional power systems are designed vertically. Power is generated at large power plants, it is then delivered to consumers via a hierarchical network of transmission and distribution grids. In distribution systems, the voltage is normally controlled only at the entry point (substation), and then it sags down the distribution lines, mainly because of consumption of reactive power by end consumers and the impedance of the distribution lines. A number of technologies are employed in the modern power systems to compensate for the flux of reactive power and thus to improve the power quality in the system. These technologies compensate for the drop of voltage using controlled injections of reactive power at a few locations. In this section we review the end-user reactive power compensation technique.

3.3.1 End-User Reactive Power Compensation

Inverter-based technologies discussed in this work belong to an emerging class of end-user reactive dispatch technologies. There are several reasons that make them highly promising as follows.

- *Efficiency.* Proximity of reactive power compensation to the reactive load decreases the average magnitude of current flowing through the system and thereby reduces the thermal losses.
- *Flexibility.* Reactive flows generated by distributed compensation systems result from a large number of individual compensators that can combine their reactive injections in multitude of ways, allowing the system to achieve optimal operation.

- *Scalability*. Large-scale capacitor banks constrains the expansion of the distribution systems and require coordination between the capacitor banks upgrades and new renewable generator installations. Local compensation allows easy and on-the fly system upgrades.
- *Reliability*. Relying on large capacitor banks makes the grid vulnerable to equipment failure. Moreover, from the cybersecurity viewpoint, a distributed control system with limited communication between its smaller components is potentially more resilient to cyberattacks in comparison to centralized control systems that control larger equipment.

3.3.2 Decentralized-Inverter based Reactive Power Compensation

The proposed algorithm aims at:

1) Voltage stabilization and regulation;

2) Minimization of power loss in the distribution line;

3) Exploitation of untapped potential of power electronic devices that integrate the microgrid, i.e. inverters;

4) Full utilization of energy storage and renewable energy units. The reactive power is controlled independently of the active power, and depends on the voltage of the feeder near the inverter.

a. Inverter Model

An inverter attached to a PV generator is not an infinite source or sink of reactive power. Its instantaneous reactive power capability is limited by its fixed apparent power capability S and the variable real power generation $p^{(g)}$.

If the rated (instantaneous) active power output of the DC/AC inverter is denoted by $p^{(g)}$, and the minimum power factor is denoted by λ. The maximum apparent power capacity of the inverter is given by

$$S = \frac{p^{(g)}}{\lambda}. \tag{3.1}$$

The instantaneous reactive power generation capability $q^{(g)}$ of an inverter is dependent on its fixed apparent power capability S and variable real power generation $p^{(g)}$. This can be represented as

$$\left|q^{(g)}\right| \leq \sqrt{s^2 - (p^{(g)})^2} \cong q^{max}. \tag{3.2}$$

It can clearly be inferred from the equation that keeping S larger than $p^{(g)}$, the inverter can supply or consume reactive power $q^{(g)}$.

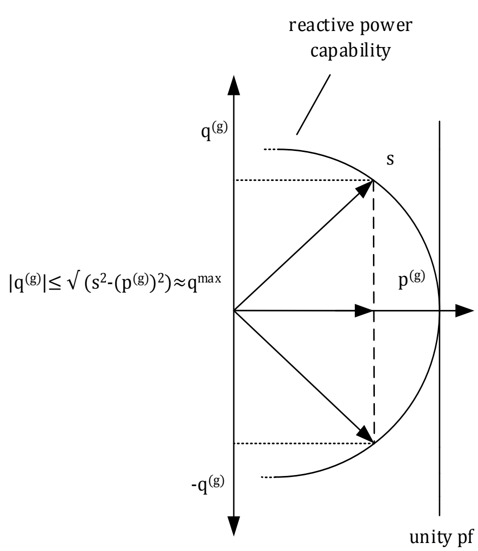

Figure 3.1 Reactive capability curve of inverter

This relationship is also described by the phasor diagram in Fig. 3.1. When S is larger than $p^{(g)}$, the inverter can supply or consume reactive power $q^{(g)}$. The inverter can dispatch $q^{(g)}$ quickly (on the cycle-to-cycle time scale) providing a mechanism for rapid voltage regulation. As the output of the PV panel array $p^{(g)}$ approaches S, the range of available $q^{(g)}$ decreases to zero. On a clear day with the sun angle aligned with the PV array, $p^{(g)} = p_{max}{}^{(g)}$ and the range of available $q^{(g)}$ is at a minimum.

b. Active Meshed Distribution Model

This section analyzes the structure of the distribution path between various *active nodes* (i.e., grid nodes where a Distributed Energy Resource (DER) unit is connected through an inverter). The connecting points of the loads belonging to the path are called *passive node.* The active nodes are the nodes where the reactive power can either sink in or rise out of the inverters connected to it. Whereas, the passive nodes are sink of active & reactive power.

In the following, we represent the currents and voltages by phasor, in the assumption that a common time reference is available through the grid and the node operation can be synchronized.

Considering a generic section of meshed microgrid, schematically shown in Fig. 3.2:

1) active node N connects to surrounding active nodes $N_1, N_2, N_3, \dots\dots, N_K$;
2) connecting paths be $L_1, L_2, L_{3,} \dots\dots, L_K$;
3) voltages of active nodes $\vec{V}_1, \vec{V}_2, \vec{V}_3, \dots\dots, \vec{V}_K$;
4) $\vec{z} = r + jx$ be the impedance per unit length of the distribution line;
5) $\vec{I}_{Lm}$ be the load current absorbed at generic passive node m ;
6) $\vec{I}_{NK}$ & $\vec{I}_{KN}$ are current flowing from node $N\ to\ K$ and $K\ to\ N$ respectively;
7) d_{NK} be the length of path $N - K$;
8) Δ_m be the distance between adjacent passive nodes $m\ and\ m + 1$.

The aim is to accomplish voltage regulation throughout the network in a cyclic manner such that each node voltage $\vec{V}_N$ is within acceptable range and also minimization of distribution loss in the paths $L_1, L_2, L_{3,} \ldots \ldots, L_K$.

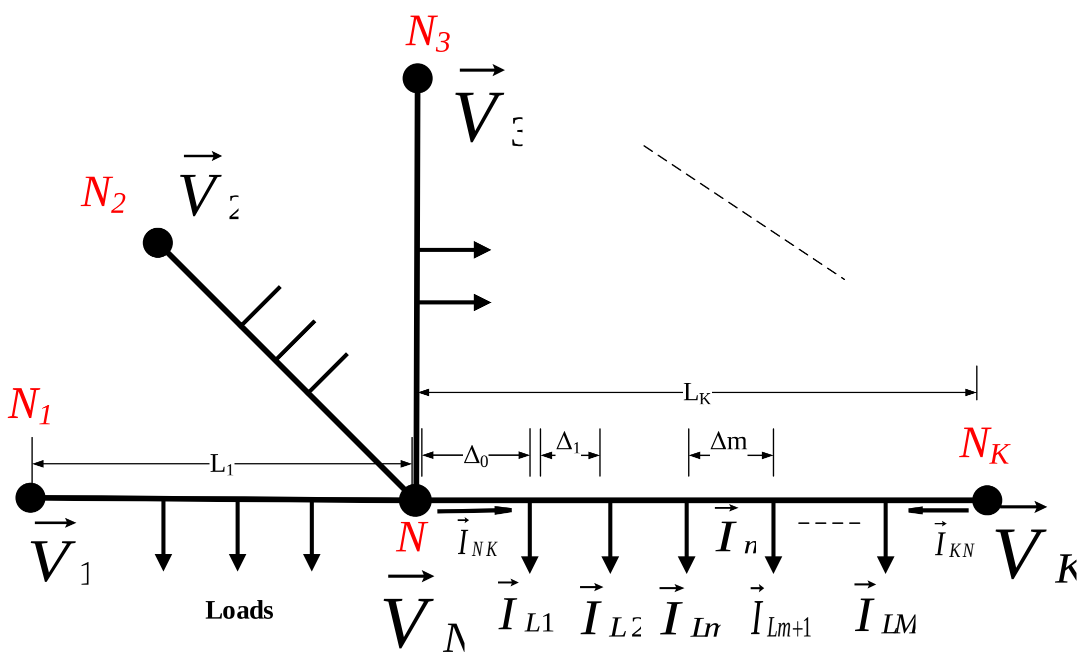

Figure 3.2 Active & passive nodes in a meshed grid

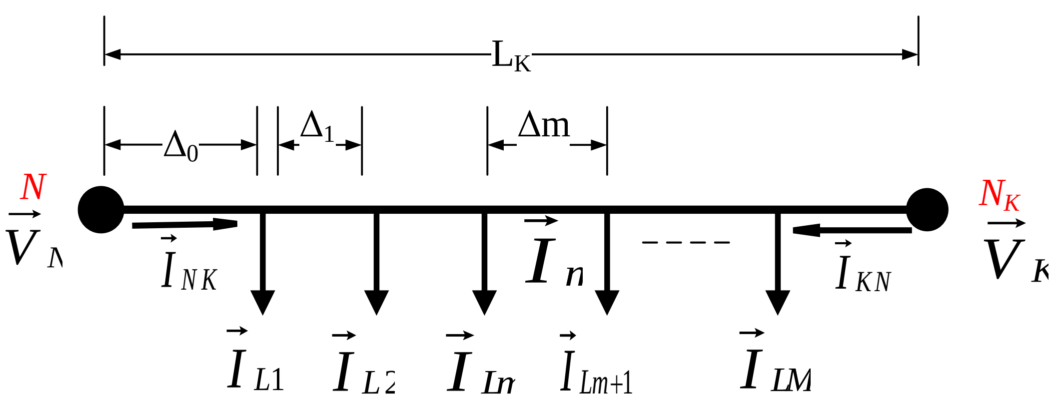

Figure 3.3 N-K branch of the same meshed grid

c. Node Voltage Optimization

Most of the voltage variations in the distributed network are because of a shortage or surplus of reactive power. Motor start up, lightning strikes, fault clearing, power factor switching can be the reason behind voltage fluctuations. The inverters interfaced with DGs can provide continuous real-time voltage regulation service according to the rated capability of the inverters. We assume that no restrictions on power factor are imposed as our aim is flexible reactive power control to support voltage regulation. Moreover, reactive power output is controlled within the current capability of the inverter without compromising the active power output.

1) Inverter provides real-time local voltage regulation by providing variable on-demand reactive power to the system
2) Local voltage regulation is a more effective voltage regulation method for increasing system capacity and reducing system losses
3) Power electronic inverters have fast dynamic response, which can effectively compensate voltage sags and other sudden changes in the system.
4) Integrated voltage regulation (multiple DEs performing voltage regulation together) can increase the voltage regulation capability of multiple DEs and reduce the capital and operating costs
5) Local voltage regulation and the required reactive power are dependent on the electrical distance between the disturbance and the controlled voltage (the impedance between the reactive power source and the controlled voltage)

The voltage variations from reference are fed by reactive power output of each interfaced inverter, which is calculated based on local measurements. We assume that, at every active node there are voltage and current sensors capable of measuring total current leaving the node and the voltage. From Fig. 3.3, we note that current $\overrightarrow{I_m}$ flowing in the path Δ_m can be expressed as

$$\vec{I}_m = \vec{I}_{NK} - \sum_{n=1}^{m} \vec{I}_{Ln}. \quad (3.3)$$

The voltage drop across the path N-K is formulated as follows:

$$\vec{V}_{NK} = \sum_{m=0}^{M} \vec{z}\, \Delta_m \vec{I}_m = \vec{z} d_{NK}\left(\vec{I}_{NK} - \vec{I}_{LM}\right), \quad (3.4.a)$$

$$\vec{V}_{NK} = \vec{Z}_{NK}\left(\vec{I}_{NK} - \vec{I}_{NK}^{opt}\right), \text{and} \quad (3.4.b)$$

$$\vec{I}_{NK} = \vec{I}_{NK}^{opt} + \frac{\vec{V}_{NK}}{\vec{Z}_{NK}} = \vec{I}_{NK}^{opt} + \vec{I}_{NK}^{cir}. \quad (3.5)$$

$\vec{I}_{NK}^{opt}$ is the current required to feed the load while achieving minimum distribution losses; it is called the “optimum current”;

$\vec{I}_{NK}^{cir} = \frac{\vec{V}_{NK}}{\vec{Z}_{NK}}$ is the current flowing to due net effective voltage difference between nodes N and K; it is called “circulation current”;

$\vec{Z}_{NK} = \vec{z} d_{NK}$ is the total impedance of path N-K;

From Fig. 3.1, it is evident that the total current leaving the node N is the vector sum of all the currents towards surrounding paths $L_1, L_2, L_{3,} \dots \dots, L_K$; thus

$$\vec{I}_N = \vec{I}_{N1} + \vec{I}_{N2} + \vec{I}_{N3} + \dots \dots .. \vec{I}_{NK}, \quad (3.6.a)$$

$$\vec{I}_N = \sum_{k=1}^{K} \vec{I}_{NK}, \text{and} \quad (3.6.b)$$

$$\vec{I}_N = \sum_{k=1}^{K} \vec{I}_{NK}^{opt} + \sum_{k=1}^{K} \frac{\vec{V}_N - \vec{V}_K}{\vec{Z}_K}. \quad (3.6.c)$$

Optimum distribution losses occur when the voltages at nodes N and K are the same, meaning they supply optimum current. More precisely, if the circulation current is minimized then the distribution component due to circulation current could be suppressed.

Hence, we aim at minimizing the circulation current by making sure that $\vec{V}_N$ takes the optimum value which is

$$\vec{V}_N^{opt} = \left. \sum_{k=1}^{K} \frac{\vec{V}_K}{\vec{Z}_K} \middle/ \sum_{k=1}^{K} \frac{1}{\vec{Z}_K} \right. . \tag{3.7.a}$$

If we assume that all the paths have the same impedance per unit of length, the above equation becomes a function of distance between neighboring active nodes;

$$\vec{V}_N^{opt} = \left. \sum_{k=1}^{K} \frac{\vec{V}_K}{d_K} \middle/ \sum_{k=1}^{K} \frac{1}{d_K} \right. . \tag{3.7.b}$$

Due to grid distribution linearity, if all active nodes successively control their voltages, they progressively approach same potential.

d. Microgrid network operation optimization strategy

The concept of intelligent information agents is employed in this methodology. An agent essentially carries operative instructions such as prioritized activation signal for specific inverter of the network; instant removal of a node in case of fault or any contingency; P-f or V-Q droop functions etc. These agents are circulated in the distributed network in a cyclic manner. Each inverter processes these agents for a few cycles and then passes the updated information to the adjoining inverter in the microgrid. This is called the control phase, during which the voltage reference is adjusted. It can run for a fixed number of cycles and repeat periodically (synchronous operation) or else last for time needed to execute control action (asynchronous operation). The control phase begins when the inverter receives the agents, which are an information cluster containing references, measurement data and operative instructions. After this, it enters the hold phase, during which the inverter retains the value calculated during control phase and operates till the next control phase is passed on to it. The hold phase helps in stabilizing impedance seen by active nodes, thus preventing risk of instability caused due to unpredictable variations in inverter control loops.

In meshed distribution network, electrical distribution pattern is complex and can change dynamically due to addition or removal of DGs. The activation sequence of grid nodes is thus chosen in a cyclic manner in real time keeping this in mind. Also, generally it is passed on to a grid node which has had the highest hold time.

This network operation optimization strategy demands the following:

1) Narrow band communication between each active node;
2) Active nodes should have a common time reference, such as change of voltage being measured as phasor;
3) Every active node is identified by its unique node address;
4) During control phase the node collects node address and hold time from the adjoining node

Optimization of network operation with the help of voltage regulation can be achieved by following method:

Optimum voltage control is based on the equations (3.7.a & 3.7.b). From figure 3.2, when the node N enters the control phase, it collects voltage information from neighboring nodes $N_1, N_2, N_3, \dots \dots, N_K$ and computes optimum voltage reference using (3.7.b). Then using the current capability of inverter the control minimizes difference between $\overrightarrow{V_N}$ and $\overrightarrow{V_{ref}}$. This voltage control is achieved by regulating reactive current. The algorithm makes sure that if the measured rms voltage at a given grid node is less than V_{min} or greater than V_{max} in (3.7.b), its amplitude is set to V_{min} or V_{max} respectively.

Let, $\vec{V}_N^i = V_N^{i'} + jV_N^{i''}$ be the node voltage;

$\vec{I}_N^i = I_N^{i'} + jI_N^{i''}$ be the node current;

at the start of control phase (which we know from the voltage and current sensors at each node). So, we bring this node voltage more towards $\vec{V}$ref with the help of reactive power compensation of inverter that results in current variation of $\Delta\vec{I}_N$. Hence, the node voltage after this variation becomes:

$$\vec{V}_{ref} = \vec{V}_N = \vec{V}_N^i + \vec{Z}_{eq}\Delta\vec{I}_N, \tag{3.8.a}$$

where $\vec{Z}_{eq} = R_{eq} + jX_{eq}$ is equivalent impedance as seen by the node N

$$V_N' + jV_N'' = V_N^{i'} + jV_N^{i''} + \left(R_{eq} + jX_{eq}\right)(\Delta\vec{I}_N' + j\Delta\vec{I}_N'') \text{ and} \tag{3.8.b}$$

$$V_N' + jV_N'' = V_N^{i'} + jV_N^{i''} + \left(R_{eq}\Delta\vec{I}_N' + jX_{eq}\Delta\vec{I}_N' + jR_{eq}\Delta\vec{I}_N'' - X_{eq}\Delta\vec{I}_N''\right). \tag{3.8.c}$$

Comparing real and imaginary part of the equation:

$$V_N' - V_N^{i'} = R_{eq}\Delta\vec{I}_N' - X_{eq}\Delta\vec{I}_N'' \text{ and} \tag{3.8.d}$$

$$V_N'' - V_N^{i''} = R_{eq}\Delta\vec{I}_N'' + X_{eq}\Delta\vec{I}_N'. \tag{3.8.e}$$

Solving (3.8.d) and (3.8.e);

$$\Delta\vec{I}_N' = {R_{eq}\left(V_N' - V_N^{i'}\right) + X_{eq}\left(V_N'' - V_N^{i''}\right)} \Big/ {Z_{eq}^2} \text{ and} \tag{3.9.a}$$

$$\Delta\vec{I}_N'' = {R_{eq}(V_N'' - V_N^{i''}) + X_{eq}(V_N' - V_N^{i'})} \Big/ {Z_{eq}^2}. \tag{3.9.b}$$

The change in node current that minimizes the difference between $\vec{V}_N$ and $\vec{V}_{ref}$ can be calculated from (3.9.a) & (3.9.b). The voltage support is mainly achieved by controlling the reactive current $\vec{I}_N''$ only. With this provision, all nodes tend to progressively approach reference voltage, while minimizing the distribution losses.

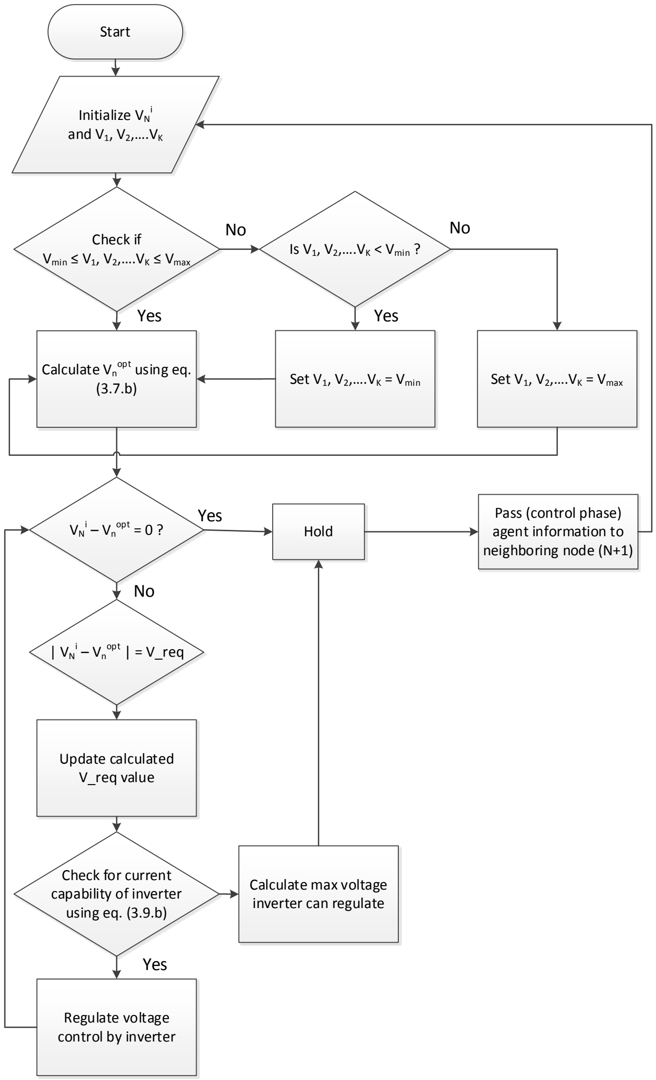

Figure 3.4 Flowchart of algorithm

4. Simulation and Results

4.1 Simulation using Power World Simulator

In order to validate the proposed control algorithm, simulations were done in Power World Simulation Software. For a single-phase local microgrid sketched in Fig 4.1, with nominal voltage of 13.8 kV, a set of loads absorbing variable active and reactive power (110-150 MW, cos θ = 0.7-0.95) with four DERs. This is the primary experiment for proving node voltage optimization, which concerns voltage regulation with loss minimization. Hence, the role of inverter controlling the reactive power flow is replicated by the AVR (Automatic Voltage Regulation) voltage control using the capability curve for respective DER to set the desired regulated bus voltage.

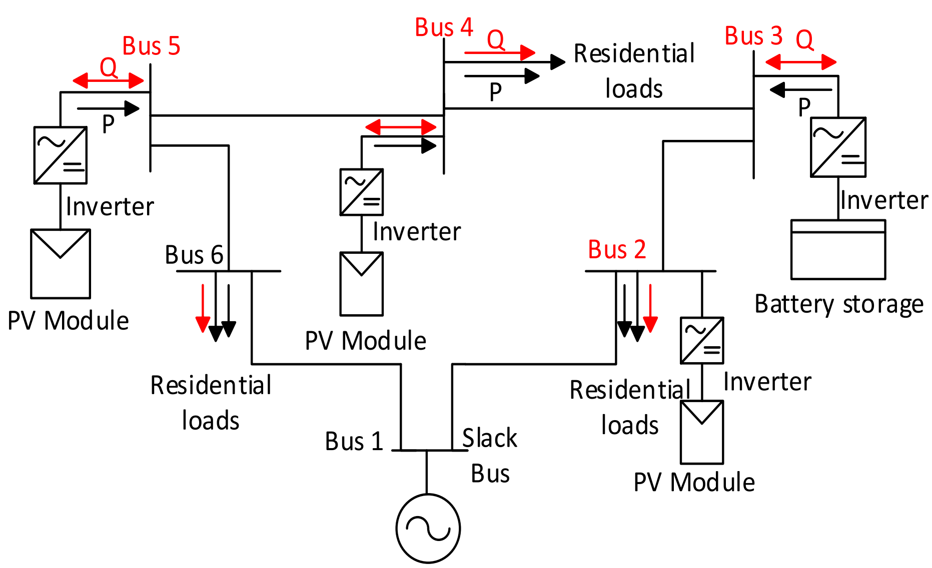

Figure 4.1 Schematic diagram of a microgrid

Table 4.1 Parameters of the distribution line

Per Unit Impedance Parameters (ohm/km)	
Series Resistance (R)	0.017
Series Reactance (X)	0.092
Shunt Charging (B)	0.158

Table 4.2 Length of the distribution lines

From Bus	To Bus	Length (km)
1	2	30
2	3	60
3	4	30
4	5	40
5	6	50
6	1	40

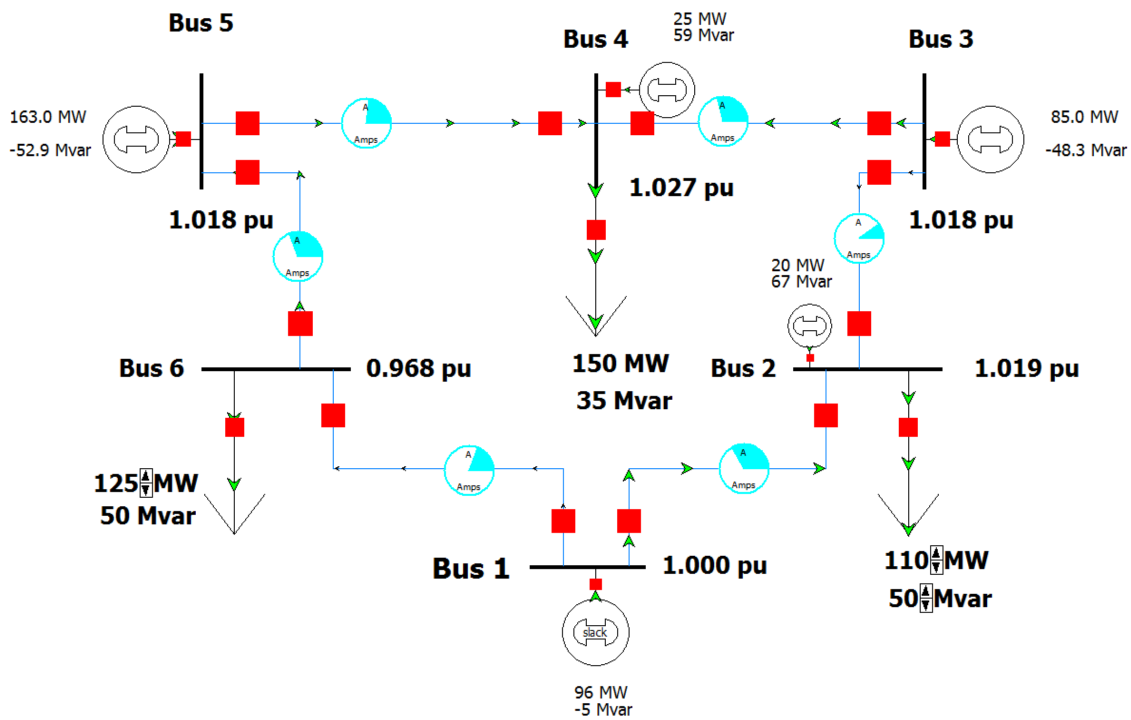

Figure 4.2 Power World Model in Run Mode

Table 4.3 Limit Monitoring Settings (Buses)

Bus Name	**PU Volt**	**Volt (kV)**	**Lower limit PU Volt**	**Higher limit PU Volt**
1	1	13.8	0.90	1.10
2	1.01932	14.067	0.90	1.10
3	1.018	14.048	0.90	1.10
4	1.0265	14.166	0.90	1.10
5	1.01830	14.053	0.90	1.10
6	0.96839	13.364	0.90	1.10

Table 4.4 Limit Monitoring (Lines)

From Bus	To Bus	Limiting Flow used	Limit defined	% of limit used	Unit
2	1	89.9	250	36	MVA
6	1	53.2	200	26.6	MVA
3	2	25.5	250	10.2	MVA
4	3	78.2	250	31.3	MVA
5	4	59.5	250	23.8	MVA
5	6	74.5	250	29.8	MVA

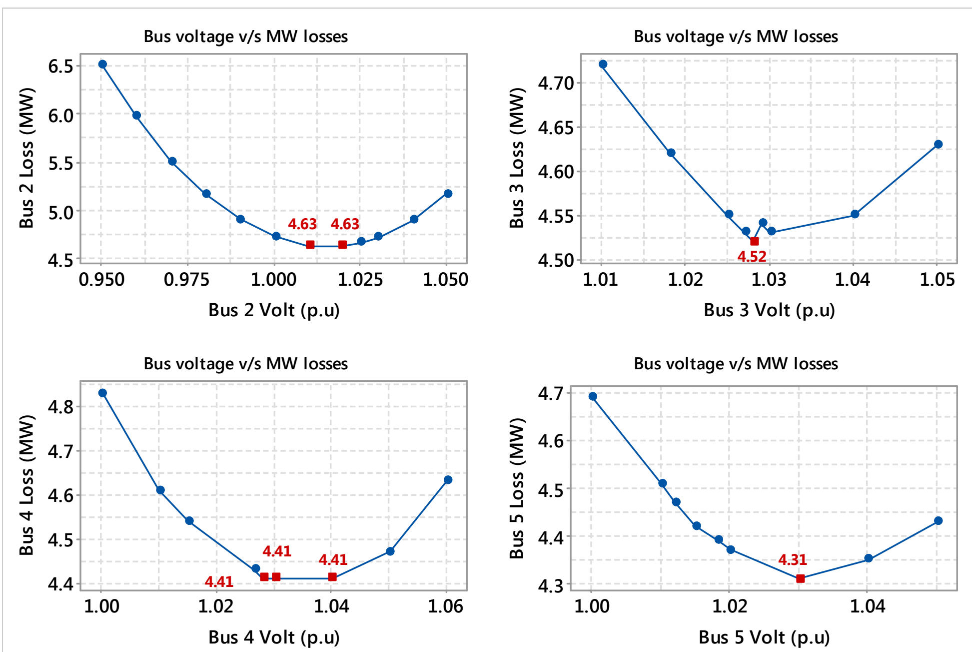

Figure 4.3 Bus Voltage v/s MW Losses

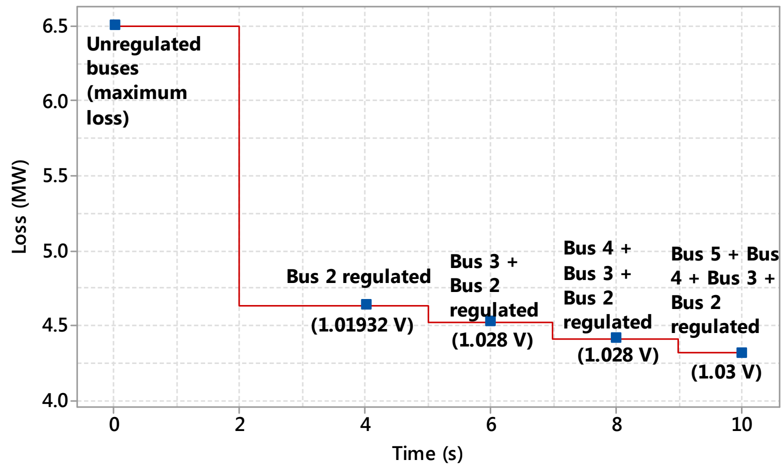

Figure 4.4 Behavior of distribution loss over node voltage optimization

4.2 Hardware-in-the-loop real-time simulation

This section elaborates on real-time simulation of a grid model other than the previous one, but it utilizes the same control algorithm from voltage regulation and loss minimization. Due to the high computational burden of the grid model, parallel distributed computing capability embedded in OPAL-RT's simulator has been utilized to comply with real-time simulation constraints.

Table 4.5 Compatibilities of OPAL-RT Toolbox with MATLAB

MATLAB versions	**Compatibilities**			
	RT-LAB	**eFPGAsim**	**ARTEMiS**	**RT-Events**
2015a (32 bits)	✓ (11.0.8)	✓ (1.4.2)	✓ (7.0.5)	✓ (4.0.2)
2015b (32 bits)	✗	✗	✗	✗
2014b (32 bits)	✓	✓	✓	✓
2014a (32 bits)	✗	✗	✗	✗

The OpComm block could be found in the RT-LAB library. The OpComm block is used in a Console, Master or Slave subsystem to simulate the behavior of the real-time communication link. Any signal entering a Console, Master, or Slave subsystem has to go through the OpComm first. Only double signals can pass through the block. This block serves a number of purposes:

1) Provides RT-LAB with information about the size and type of data coming from other subsystems
2) Defines acquisition groups along with acquisition parameters (only in the Console subsystem)
3) Emulates the behavior of subsystem communication in RT-LAB with models used offline: The block waits until all of its inputs are updated before updating its outputs. Keep this in mind while designing your model

4) Specifies the sample time of the subsystem in which the block is placed

5) Specifies the communication sample time of a calculation subsystem (Master or Slave) with another calculation subsystem

In the Console, there must be one OpComm for each acquisition group. In Master and Slave subsystems, a maximum of two OpComm is allowed: one for signals coming from the Console (non-real-time communication) and one for signals coming from other Master and Slave subsystems (real-time communication). Note that a single OpComm cannot be used to receive from both a Console and a Master or Slave subsystem, since the communication types are not the same.

ARTEMiS, the Advanced Real-Time Electro-Mechanical Simulator, is a simulation toolset that includes the ARTEMiS Plug-in to the SimPowerSystems blockset. The ARTEMiS Plug-in is a performance-enhancing add-on product for the SimPowerSystems blockset. We just have to simply add the ARTEMiS Plug-in block to any Simulink model containing SimPowerSystems blockset blocks and the model runs using the ARTEMiS improved algorithms.

The ARTEMiS Plug-in offers the following advantages to the standard SimPowerSystems Blockset:

- Real-time computational capability. More than simply providing faster simulations, ARTEMiS is designed to enable real-time computation of SimPowerSystems blockset circuits.

The following considerations were taken into account for the design of ARTEMiS:

1) State-Space Nodal (SSN) solver which provides all the advantages of nodal methods such as enabling the real-time simulation of circuit with hundreds of switches and node count approaching 1000

2) Improved modeling of some power system elements such as: Saturable transformer model (which can be simulated at fixed time step in a non-iterative manner in ARTEMiS)

3) Distributed multi-processors simulation capability of complex power systems with ARTEMIS Distributed Parameter Line and ARTEMIS Stubline models

4) Compatibility with OPAL-RT's RT-LAB suite of products for easy integrated parallel simulation design process

5) Higher precision for linear circuits with high frequency components: ARTEMiS improves the SimPowerSystems blockset's precision of simulation compared with the standard fixed-step integration methods such as trapezoidal or Tustin, especially for circuits whose variables have high frequency components.

Less numerical oscillations without the need for artificial stabilizing snubbers: ARTEMiS uses L-stable integration methods that are free from the numerical oscillations that often affect the standard SimPowerSystems blockset fixed-step integration methods such as trapezoidal or Tustin. The ARTEMiS Stubline block, in the OPAL-RT toolbox in MATLAB, implements an N-phase distributed parameter transmission line model with exactly one time step propagation delay. Therefore, it permits decoupling of state-space system equations of networks on its both sides. The principle to do such a modelling is to deduct part of the feeder impedance equally from all three phases such that the deducted part represents a balance line section and it can be modeled by a Stubline.

4.2.1 Model in MATLAB Simulink

The Simulink model is broken down into three subsystems:

1) SM_LVGrid – Computational block (Master Subsystem)

2) SS_Measurement – Measurement block (Slave Subsystem)

3) SC_Console – Console block

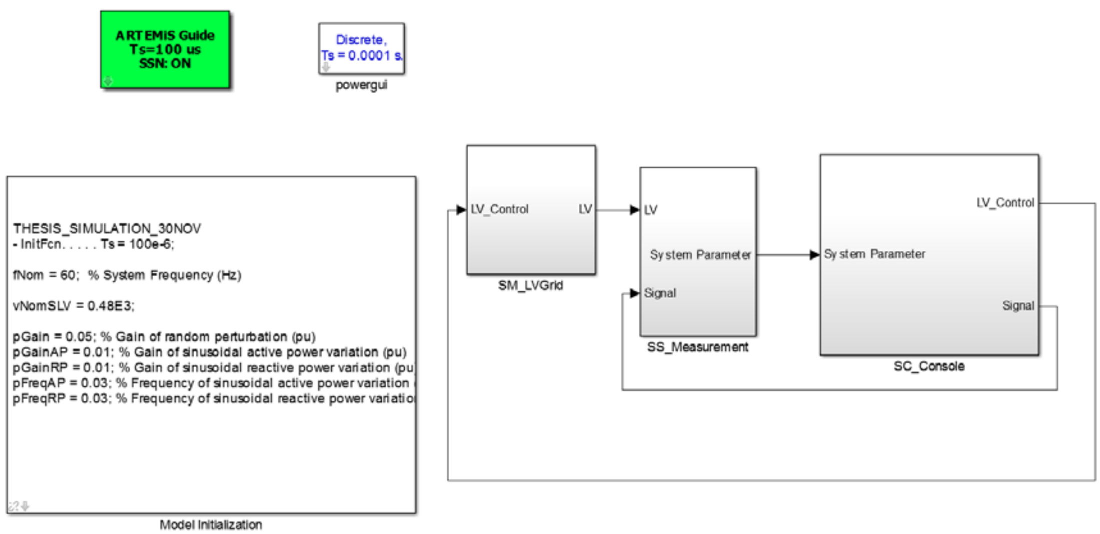

Figure 4.5 Model in MATLAB Simulink

The MATLAB code for node voltage optimization algorithm:

```
%function [V_req1,ph1,V_req3,ph3,V_req6,ph6,V_req16,ph16] = voltage
regulation(V1,Ph1,V3,Ph3,V6,Ph6,V16,Ph16)
%#codegen
% V1=458; V3=478; V6=545; V16=410;
%
% Ph1=30; Ph3=60; Ph6=45; Ph16=-30;
Up_lim = 480+10/100*480;
Low_lim = 480-10/100*480;

Vmag = [V1,V3,V6,V16];
phase =[Ph1,Ph3,Ph6,Ph16];

for k = 1:length(Vmag)
    if Vmag(k)>Up_lim
        Vmag(k)=Up_lim;
    elseif Vmag(k)<Low_lim
        Vmag(k)=Low_lim;
    end
end

d2r = @(V)(V*pi/180);
r2d = @(V)(V*180/pi);
volts = Vmag .* exp(j*d2r(Ph));
V =[abs(volts) r2d(angle(volts))];
Inv_exist = [1,0,1,0,0,1,0,0,0,0,0,0,0,0,0,1];
No_inv = find(Inv_exist==0); %buses whose voltage cannot be controlled
inv_bus = find(Inv_exist==1); %buses whose voltage can be controlled
N = length(volts);
D = 500+(2000-500)*rand(1,16);
Vx=volts.*Inv_exist;
Vx=Vx(inv_bus);
j=0;

for bus = 1:N
    j=j+1;
    if bus~=No_inv;
       v=volts;
       v(No_inv)=0;
       v(bus)=0;
       Vk=v(inv_bus);
           if bus==1;
                d13=D(1)+D(3);
                d16=D(1)+D(5);
                d116=D(1)+D(3)+D(6)+D(7)+D(8)+D(9)+D(10)+D(11);

                 d=[0; 1/d13; 1/d16; 1/d116];

           else if bus==3;

                d13=D(1)+D(3);
                d36=D(3)+D(5);
                d316=D(6)+D(7)+D(8)+D(9)+D(10)+D(11);
```

```
                d=[1/d13; 0; 1/d36; 1/d316];

           else if bus==6;

                d616=D(3)+D(5)+D(6)+D(7)+D(8)+D(9)+D(10)+D(11);
                d36=D(3)+D(5);
                d16=D(1)+D(5);

                d=[1/d16; 1/d36; 0; 1/d616];

               else

                   d116=D(1)+D(3)+D(6)+D(7)+D(8)+D(9)+D(10)+D(11);
                   d316=D(6)+D(7)+D(8)+D(9)+D(10)+D(11);
                   d616=D(3)+D(5)+D(6)+D(7)+D(8)+D(9)+D(10)+D(11);

                   d=[1/d116; 1/d316; 1/d616; 0];
               end
               end
           end

      %d=[0 d13 d16 d116; 0 0 0 0; d13 0 d36 d316; 0 0 0 0; 0 0 0 0;
d16 d36 0 d616; 0 0 0 0; 0 0 0 0; 0 0 0 0; 0 0 0 0;0 0 0 0; 0 0 0 0; 0
0 0 0; 0 0 0 0; 0 0 0 0;d116 d316 d616 0];
      %vk=v.*Inv_exist;
      %vk=vk(inv_bus)

      if j>1
           V_opt(bus) = (V_opt(1)*d(1) + Vk(2)*d(2) + Vk(3)*d(3) +
Vk(4)*d(4));
       else
           V_opt(bus) = (Vk(1)*d(1) + Vk(2)*d(2) + Vk(3)*d(3) +
Vk(4)*d(4));
       end
      V_req = (V_opt(bus))-(Vx);

      V_req_degree=[abs(V_req); r2d(angle(V_req))];

               else

                   V_opt(bus)=volts(bus);

    end
end
```

5. Conclusion

The proposed method of node voltage optimization is efficient in mitigating voltage-control problems with distributed generator. The algorithm can be implemented with the help of power electronic interface, without overrating the power converters. Also it just requires a local measurement unit without the need of a local area supervisor. Control implementation with the help of optimum voltage tracking algorithm aids in achieving full utilization of renewable energy resources while ensuring local support to voltage stabilization in addition to reduction in distribution losses. Present network can be upgraded with minimal investment in control and communication infrastructure. It was found that when only one bus was regulated according to the algorithm there was 28.76% reduction in distribution losses compared to initial value, the losses were further reduced to 30.46%, 32.15% and 33.69% by regulating two, three and four active nodes respectively. This significant reduction in loss is because load power is supplied from sources closer to utilization point and hence the circulation currents are limited.

The hardware-in-the-loop microgrid could be implemented with a various potential:

- Adding a robust communication model to replace the phasor measurement unit and have the data acquisition in synchronism
- Intelligent load shedding using TCP/IP can be incorporated in the microgrid
- Multi-Agent System used for energy management can improve the decentralized scheme of power conditioning

References

[1] Mohammad Shahidehpour, Yaoyu Wang, Communication and Control in Electric Power Systems. (IEEE Press: John Wiley & Sons, 2003)

[2] P. Kundur, Power System Stability and Control. New York: McGraw-Hill, 1994

[3] T.J.E. Miller, Reactive Power Control In Electric Systems (New York: John Wiley & Sons, 1982)

[4] M. Bollen, and Fainan Hassan, Integration Of Distributed Generation In The Power System (IEEE press: John Wiley & Sons, 2011)

[5] L.L. Lai, Intelligent System Applications in Power Engineering (London: John Wiley & Sons, 1998).

[6] IEEE standard 1547.2. IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, 2008

[7] G. Celli, F. Pilo, G. Pisano, V. Allegranza, R. Cicoria, A. Iaria, Meshed vs. Radial MV Distribution Network in Presence of Large Amount of DG. (IEEE 2004)

[8] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Use of reactive power flow for voltage stability control in radial circuit with photovoltaic generation" Proc. 2010 IEEE Power Eng. Soc. General Meeting, Jul. 2010

[9] Paolo Tenti, Alessandro Costabeber, Paolo Mattavelli and Daniela Trombetti, "Distribution Loss Minimization by Token Ring Control of Power Electronic Interface in Residential Microgrids," IEEE Transaction on Industrial Electronics, vol. 59, no. 10, pp. 3817-3826, Oct 2012

[10] Paolo Tenti, Daniela Trombetti, Alessandro Costabeber and Paolo Mattavelli, "Distribution Loss Minimization by Token Ring Control of Power Electronic Interface

in Residential Micro-grids," IEEE International Symposium on Industrial Electronics, pp. 2377-2381, July 2010

[11] Luis A. Gallego, Edgar Carreno, and Antonio Padilha-Feltrin, "Distributed Generation modeling for Unbalanced Three-phase power Flow Calculations in Smart Grids," 2010 IEEE/PES Transmission & Distribution Conference and Exposition: Latin America, pp. 323-328.

[12] C. S. Cheng and D. Shirmohammadi, "A three phase power flow method for real time distribution system analysis," IEEE Trans. On Power Systems, vol. 10, n. 2, pp. 671-679, May 1995.

[13] R. M. Ciric, L. F. Ochoa, and A. Padilha, "Power Flow in Four-Wire Distribution Networks - General Approach," IEEE Trans. on Power Systems, vol. 15, n. 4, pp. 1283-1290, Nov 2003.

[14] D. Shirmohammadi, H. W. Hong, 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, n. 2, pp. 753-762, May. 1988.

[15] G. W. Chang, S. Y. Chu, and H. L. Wang, "An Improved Backward/Forward Sweep Load Flow Algorithm for Radial Distribution Systems," IEEE Transactions on Power system, vol. 22, no. 2, May 2007.

[16] Yang Wenyu, Yang Xuying, Duan Jiandong, Wan Xiaozhonq, and Fan Yue, "Power Flow Calculation in Distribution Networks Containing Distributed Generation," Electricity Distribution, 2008. CICED 2008. China International Conference, Dec 2008.

[17] Xu Guoyu, F.D. Galiana, and S. Low, "Decoupled Economic Dispatch Using the Participation Factors Load-Flow," IEEE Trans. Power App. & Syst. Vol. PAS-104, No.6, June, 1985, pp.1377-84.

[18] Gwang Soo Jang, Don Hur, Jong-Keun Park, and Sang Ho Lee, "A modified power flow analysis to remove a slack bus with a sense of economic load dispatch," Electric Power Systems Research, 2005, 73(2), 137-142.

[19] N. Acharya, P. Mahat, and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network," Int. J. Elect. Power Energy System, Vol. 28, no. 10, pp. 669-678, 2006.

[20] D. Q. Hung, N. Mithulananthan, and R.C Bansal, "Analytical Expressions for DG allocation in primary distribution networks," IEEE Trans. Energy Conversion, vol. 25, no.3, Sept. 2010.

[21] M. S. Arumugam and M. V. C. Rao, "On the performance of the particle swarm optimization algorithm with various inertia weight variants for computing optimal control of a class of hybrid systems," Discrete Dynamics in Nature and Society, vol. 2006, Jan. 2006

[22] S. He, J. Wen, E. Prempain, Q. Wu, J. Fitch, and S. Mann, "An improved particle swam optimization for optimal power flow," Proc. Int. Conf. Power Syst. Technol., pp. 1633–1637, Nov. 2004.

[23] P. Umatathy, C. Venkataseshaiah, and M.S. Arumugam, "Particle swarm optimization with various inertia weight variants for optimal power flow solutions," Discrete Dynamics in Nature and Society, vol.2010, June 2010.

[24] IEEE standard 1547.2. IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, 2008.

[25] Satish Kansal, B.B.R.Sai, Barjeev Tyagi, and Vishal Kumar, “Optimal placement of wind-based generation in Distribution networks”, Renewable Power Generation (RPG 2011), IET Conference 6 Sept 2011.

[26] Xia Lili, Qiu Xiaoyan, Wei Xiwen, and Li Xingyuan, “Research of Distribution Generation Planning in Smart Grid Construction”, Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific March 2010.

APPENDIX-A: OPAL-RT Technologies

A.1 About

OPAL-RT TECHNOLOGIES is the leading developer of open Real-Time Digital Simulators and Hardware-in-the-Loop testing equipment for electrical, electro-mechanical and power electronic systems. OPAL-RT simulators are used by engineers and researchers at leading manufacturers, utilities, universities and research centers around the world.

OPAL-RT produces test systems to help engineers develop, test and validate faster. It offers a full range of engineering and consulting services: design and hardware integration, software development, simulation and modeling, problem solving and training. Its unique technological approach integrates parallel, distributed computing with commercial-off-the-shelf technologies. Rapid Control Prototyping, System Integration, and Hardware-in-the-Loop testing of electric drives, electronic controllers and power distribution networks in a variety of industries including automotive, aerospace, electric ships, power generation, rail, and industrial manufacturing et cetera could be performed using the OPAL-RT.

RT-LAB, enables users to rapidly develop models suitable for Real-Time Simulation, while minimizing initial investment and their cost of ownership. OPAL-RT also develops mathematical solvers and models specialized for accurate simulation of power electronic systems and electrical grids. RT-LAB and OPAL-RT solvers and models are integrated with advanced field programmable gate array (FPGA) I/O and processing boards to form complete solutions for RCP and HIL testing.

A.2 Hardware-in-the-Loop Simulation

Twenty years ago a small engineering team would first build a physical prototype of an engine or sub-system and then write simple code to control the hardware. This first prototype engine would then be used to test all aspects of its required function. The cost related to building the hardware (and possibly destroying it during testing) was understood and accepted as normal business practice.

In many industries this is no longer possible due to the complexity inherent in the design and manufacture of complex hardware. Entire teams of software engineers who are required to control the hardware have been added to a large team of hardware engineers who they themselves are working on sections of these complex machines. In many cases these teams of engineers are working in parallel, designing both the hardware, and the software to control it. In addition the monetary cost of actually building a physical prototype is becoming increasingly prohibitive and in some cases unrealistic in view of time to market considerations.

Consider the complexity of a Boeing jetliner or of a new automobile. If all parts of a new aircraft or automotive design needed to be physically built, tested, assembled, and tested again as part of the greater unit, (and all this before teams of software engineers could even begin to write controllers), the time to market of new jet liners and cars would stretch into decades, and fall well outside the window of opportunity for the product.

The tight development schedules associated with most new automotive, aerospace and defense programs do not allow embedded system design and testing to wait for a prototype to be available. In fact, most new development schedules assume that **HIL simulation** will be used in parallel with the development of the plant. For example, by the time a new automobile engine prototype is made available for control system testing, 95% of the engine controller testing will have been completed using HIL simulation.

A.2.1 Why use Hardware-in-the-Loop Simulation?

This question is an important part of understanding real-time technology. To restate the question using a control systems term: Why not connect the embedded system under test to the "real plant," that is the dynamic system being controlled, to perform development and testing? In many cases, this is the most effective way to develop an embedded system. Increasingly however, HIL simulation is more efficient and or required.

The metric of development and test efficiency is typically a formula that includes the following factors:

- Cost
- Duration
- Safety

Cost of the approach will be a measure of the cost of all tools and effort. The duration of development and test affects the time-to-market for a planned product. The safety factor and duration are typically equated to a cost measure.

Specific conditions that warrant the use of HIL simulation include the following:

- High-burden-rate plant
- Tight development schedules

A.3 Electrical System Simulation Overview

OPAL-RT provides a complete range of real-time digital simulators and control prototyping systems for power grids, power electronics, motor drives and other mechatronic systems. These real-time systems help you perform feasibility studies, develop new concepts, design and test your controllers for a wide variety of applications including small power converters, hybrid electric drives, large power grids and renewable energy systems.

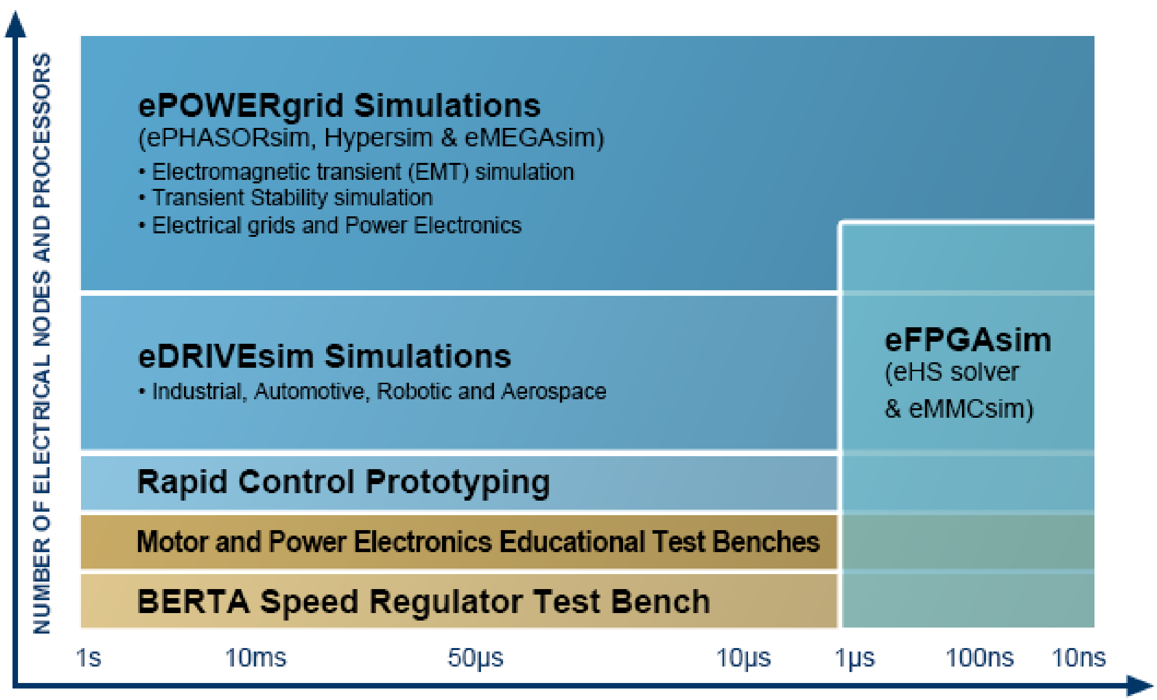

Figure A.1 OPAL-RT solutions for different applications
(Courtesy: www.opal-rt.com)

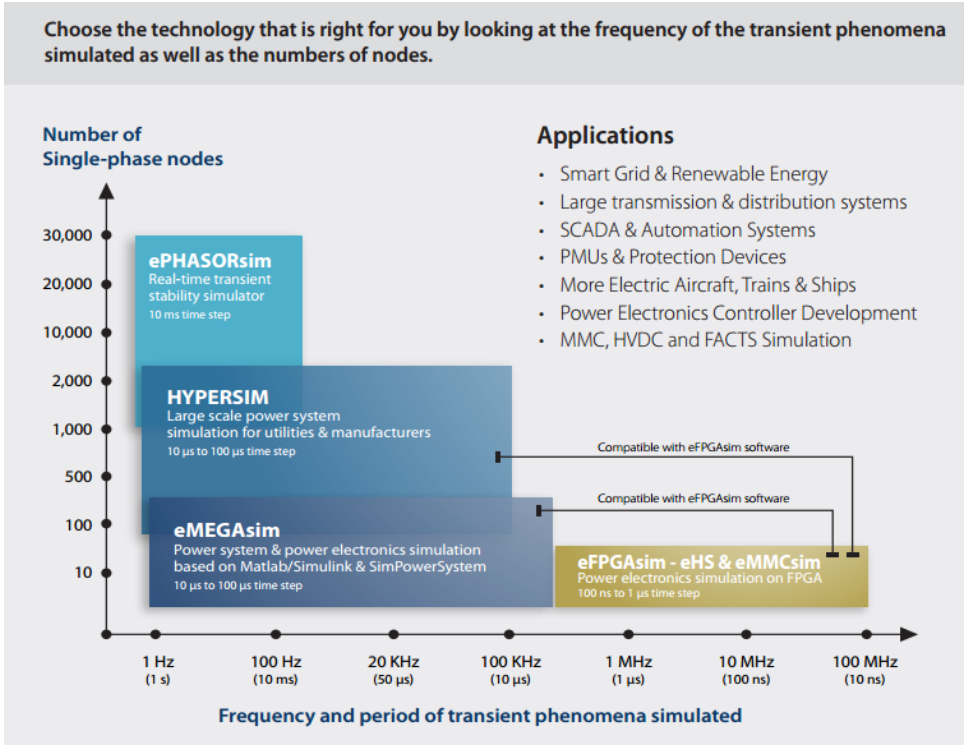

Figure A.2 Real-Time Simulation Tools
(Courtesy: www.opal-rt.com)

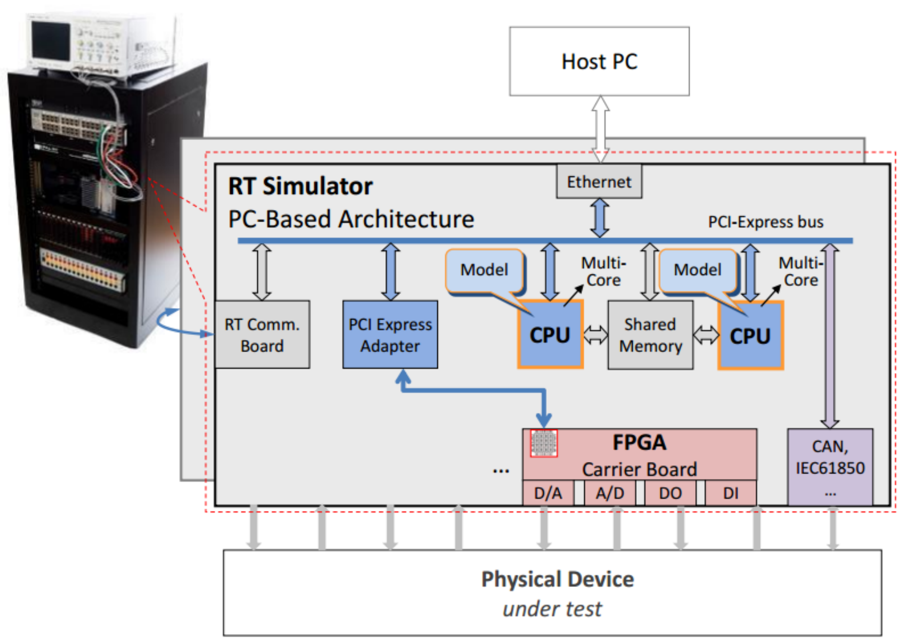

Figure A.3 PC Architecture
(Courtesy: www.opal-rt.com)

A.4 OPAL-RT OP5600 Real Time Digital Simulator

The OP5600 family developed by OPAL-RT are tailored for multiple real-time simulation applications including Hardware-In-the-Loop testing and Rapid Control Prototyping (RCP) for Microgrids, Power Systems, hybrid vehicles and Power Electronic Systems applications.

The OP5600 family are adding advanced monitoring capabilities with scalable I/O and power calculation to OPAL-RT's product line of real-time digital simulator. The OP5600 modular and flexible design can be fully customized to meet specific I/O requirements, and can be easily expanded as needed.

The OP5600 family allows different configurations for specific applications and is designed for the entire OPAL-RT software suite:

- eFPGAsim
- MMC
- eMEGAsim
- HYPERSIM
- ePHASORsim

As the hardware element for eFPGAsim, eMEGAsim, Hypersim or ePHASORsim software suites, the OP5600 Chassis enables you to conduct a number of real-time simulation applications, including hardware-in-the-loop (HIL) testing, rapid control prototyping and FPGA development projects. Complex power grids, micro-grids, wind farms, hybrid vehicles, more electrical aircrafts, electrical ships and power electronic systems can be simulated in real-time with time step as low as 10 microseconds or less than 250 nanoseconds for some subsystem to achieve the best simulation accuracy. Several power electronic manufacturers are now using OPAL-RT real-time digital simulators instead of expensive and less flexible analog test benches.

The OP5600 Chassis consists of an upper section which contains I/O signal modules including converters/conditioning and a bottom section which contains the multi-core processor computer which runs RT-LAB or HYPERSIM, OPAL-RT's real-time simulation software platforms. The OP5600 Chassis can be used either as a desktop system, or rack-mounted as part of a network of OPAL-RT simulators communicating through high-speed PCIe links. It also comes with 6 PCI expansion slots to provide more flexibility to add I/Os and communication devices from other brands (CAN, LIN, FlexRay, ARINC, MIL-STD-1553, RS-232, GPIB, Profibus, reflective memory, etc).

The target computer included in the latest revision of the OP5600, the OP5600 V2, consists of the following COTS components:

- ATX motherboard, Intel Xeon E5 processor, 4, 8, 16 or 32 cores, up to 3.2GHz,
- 10MB Cache Memory per 4 cores and up to 32GB of DRAM,
- 512GB SSD disk,
- PCIe boards (up to 8 slots, depending on the configuration)

Monitoring interfaces and monitoring connectors are accessed through the front of the chassis, while access to all I/O connectors, power cables and the main power switch are accessible on the back of the chassis. The OP5600's design also includes an option to connect up to 16 single-ended signals on Mini-BNC connectors, making it easy to monitor signals using an oscilloscope while the systems is in used and connected to user equipment.

The OP5600 has two user-programmable FPGA options for I/O management, signal processing and fast models:

- A Xilinx ML605 development board, which is based on the Virtex-6 processor, is used for floating-point models and projects requiring the use of large amounts of on-board memory,
- OPAL-RT's OP5142 User-configurable FPGA-based I/O Board based on the Xilinx Spartan-3, and ideal for fixed-point models using no on-board memory.

Both platforms support:

- Standard library of I/O functions (PWM, time stamping, encoder, resolvers …)
- Optional RT-XSG FPGA development systems based on XILINX SG to implement specialized model and signal processing functions

In addition the ML605 platform offers:

- Optional eHS Real Time Power Electronics Simulation Toolbox.
- Optional motor models library such as PMSM, BLDC and finite-element analysis based models.

The FPGA processors are directly connected to 8 I/O converter and signal conditioning modules that can be selected from the following list:

- OP5340 Type B module with 16 16-bit independent analog-to-digital converters, 400 nanoseconds conversion time for all channel converted simultaneously, and equipped with a front end differential amplifier with adjustable resistors to set the input voltage range from +- 1V to +-100V.
- OP5330 Type B module with 16 16-bit digital to analog converter, 1 microsecond update for all channels simultaneously.
- OP5353 Type B module with 32 digital input channel, 4V to 30V, galvanic isolation with fast opto coupler (40 nanoseconds typical delay), differential inputs.

- OP5360-2 Type B module with 32 digital output channel, push-pull type, 5V to 30V, galvanic isolation with fast opto coupler (50 nanoseconds to 100 nanoseconds delay maximum).

Additional signal conditioning modules are also available to cover a wide range of applications.

One OP5600 chassis can then accommodate up to 256 digital or 128 analog I/O. Several OP5607 (OP5600 I/O expansion chassis using Virtex7 FPGA) can be interconnected through a PCI Express expansion chassis to increase the number of channel up to 2048 fast digital signals or 1024 analog signal or a mix or analog and digital I/O. The total round-trip transfer time of all 2048 channels from OP5600 system to the target processor memory is less than 25 microseconds.

Signal interface equipment and accessories such as fault insertion unit, breakout and signal mapping boxes and amplifiers are also available to interface actual electronic controllers to perform HIL tests.

The OP5600 simulator is a high-performance system that can also be interfaced with the powerful and flexible OP7000 multi-FPGA expansion unit.

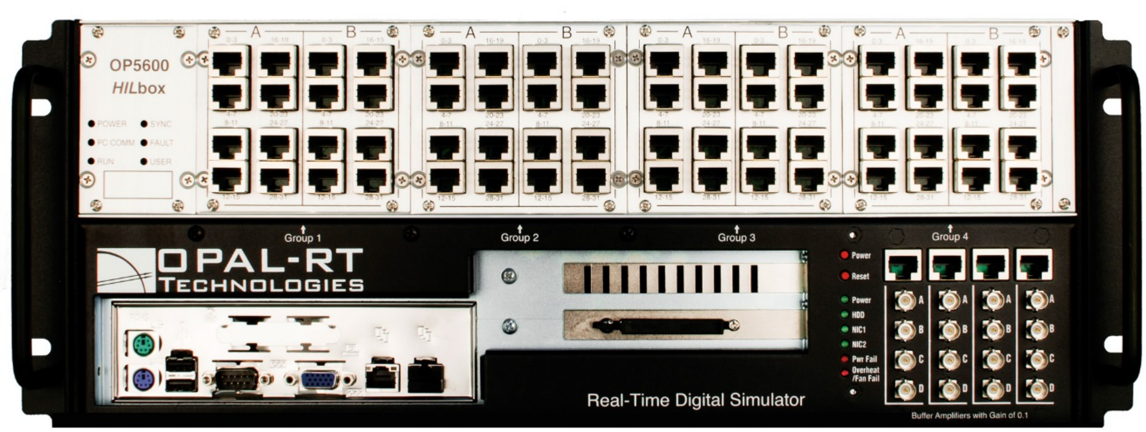

Figure A.4 OP5600 Front View
(Courtesy: www.opal-rt.com)

APPENDIX-B: Simulation and Block Diagrams

B.1 Simulation Block Diagrams

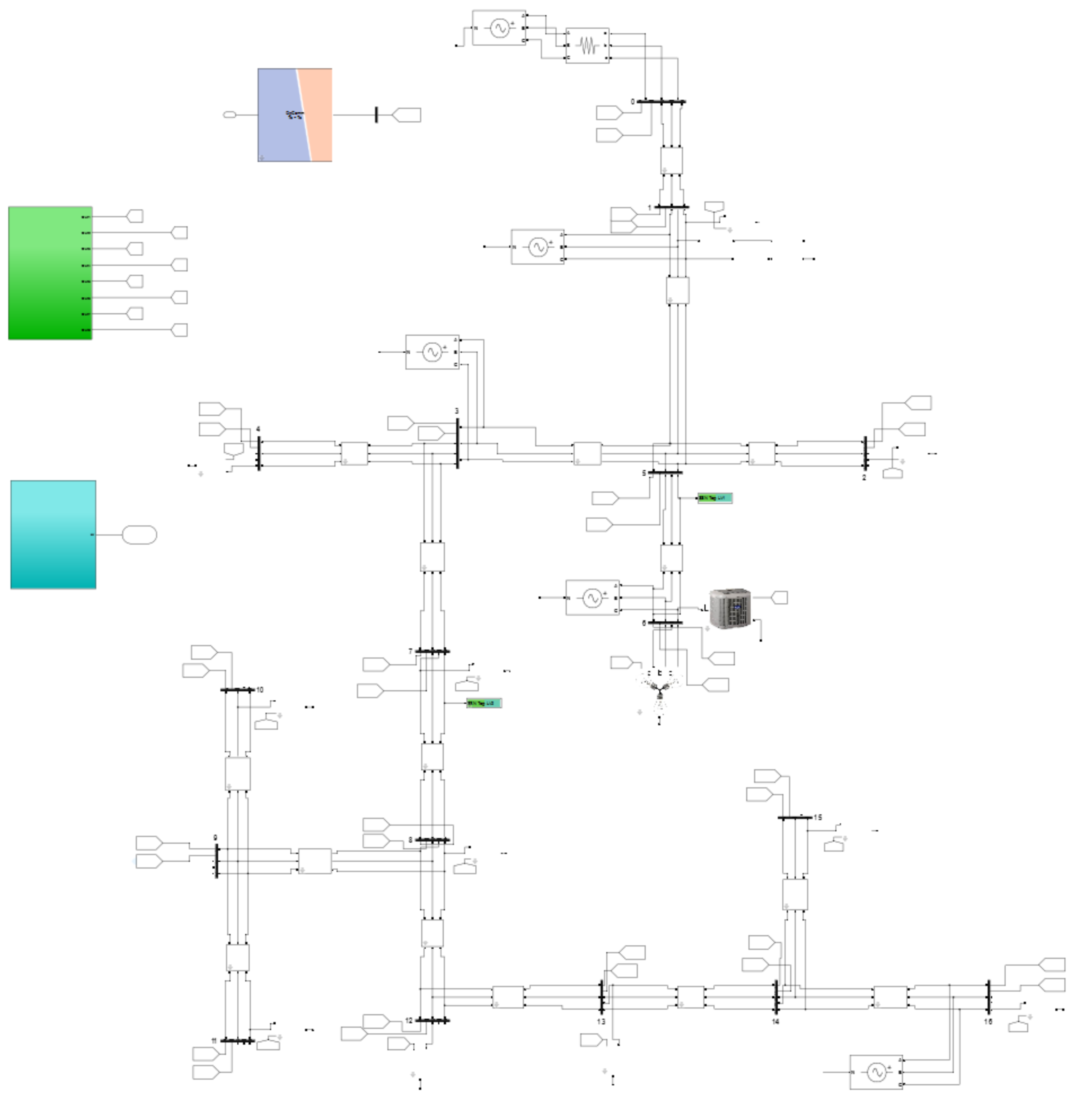

Figure B.1 SM_LVGrid Subsystem

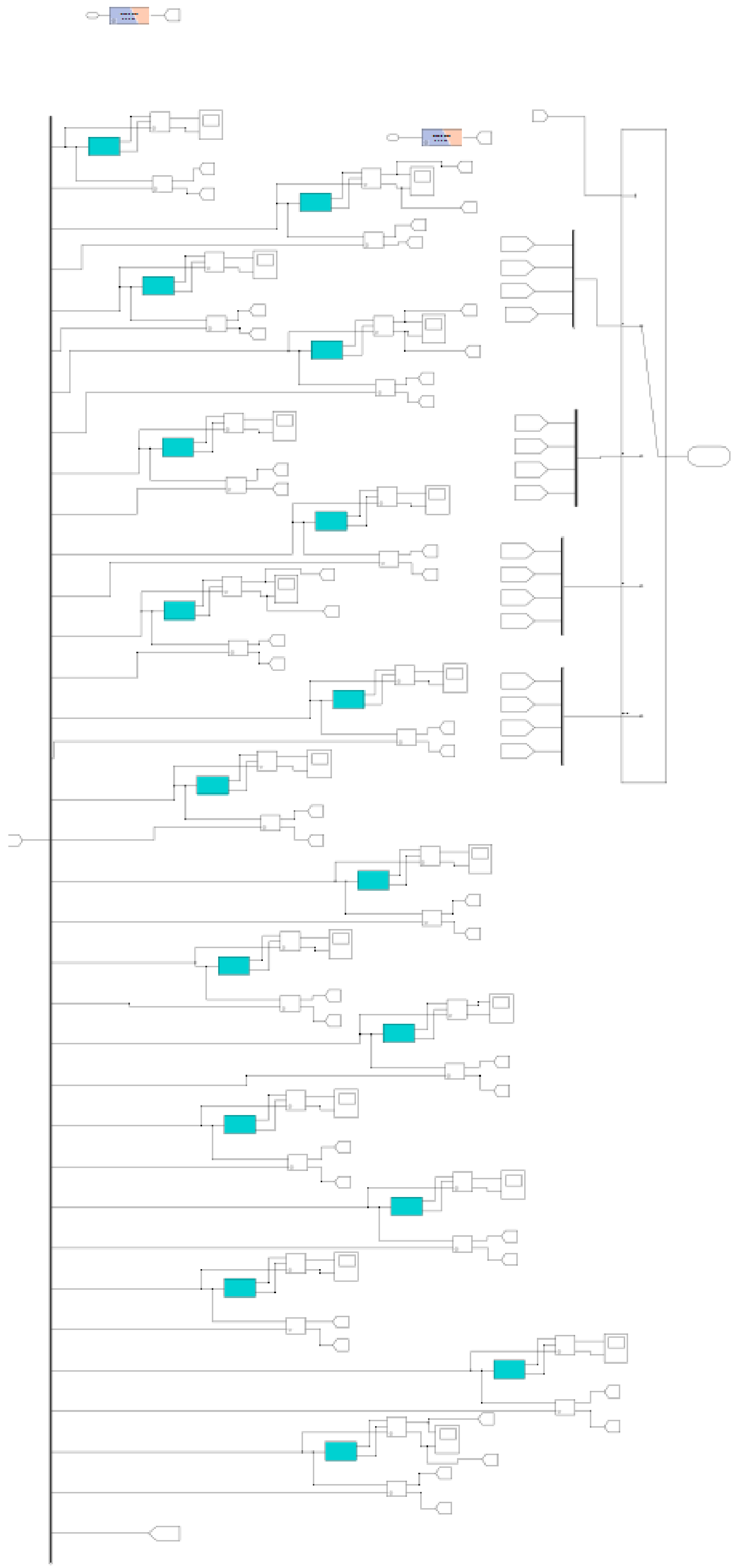

Figure B.2 SS_Measurement Subsystem

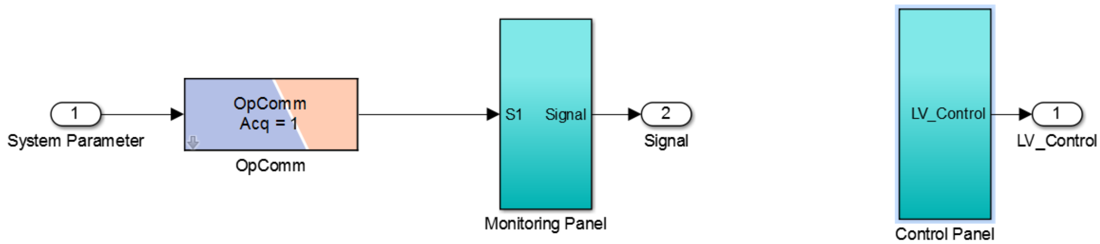

Figure B.3 SC_Console Subsystem