

# **Design and Control of FACTS-based high Performance Microgrid**

By

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### Abstract

The current power grid introduces many limitations and challenges in a world that is heavily dependent on electricity. Many government agencies, utility companies, researchers and engineers in the electric power industry have envisioned of transforming the existing grid into MicroGrid. To facilitate domestic consumers' ratings and needs, a microgrid has been developed that includes Distributed Energy Resources (DER). It is expected to be an intelligent, sustainable, resilient and reliable power grid suitable for the 21st century economy. Some of the main concerns for any grid are power quality and efficiency as well as reactive and active power reliability for consumers. To manage active and reactive power Flexible AC Transmission System (FACTS) technology is used to improve power quality and efficiency. Since FACTS technologies have been developed, much research has been done to acquire more accurate and reliable techniques and algorithms to implement FACTS in the power system. The current microgrid scheme implemented with FACTS, produces a highly efficient response monitored with different KPI indicators of the microgrid. A newly developed AC/DC microgrid design with FACTS technology includes DER, which consist of DC batteries, wind Turbines, PV systems (Solar photovoltaic system) and diesel generators. Modulated Power Filter Compensators (MPFC) for AC and Green Plug Filter Compensators (GPFC) for DC are used as FACTS controller. Optimization based on genetic algorithms and intelligent control through fuzzy logic, are defined to optimize the performance of the microgrid. Optimization and intelligent control are accomplished by self-adapting the controller gains and converters gains to achieve the best microgrid energy utilization, stabilization of voltage and reduction inrush current conditions. Key performance indicators are as follows: bus voltages stabilizing, feeder losses reduction, power factor enhancement, improvement of power quality and reduction of the total harmonic distortion at AC interface buses that are compared with and without FACTS criterion. The AC/DC microgrid is modeled in both grid and islanded connected modes.

**List of Abbreviation:**

<b>AVR</b>	Automatic Voltage Regulator
<b>DVR</b>	Dynamic Voltage Restorer
<b>FACTS</b>	Flexible AC Transmission System
<b>FL</b>	Fuzzy Logic
<b>GA</b>	Genetic Algorithm
<b>GTO</b>	Gate Turn-Off (Thyristor)
<b>HVDC</b>	High Voltage Direct Current
<b>IGBT</b>	Insulated Gate Bipolar Transistor
<b>IGCT</b>	Integrated Gate Commutated Thyristor
<b>LPF</b>	Low Pass Filter
<b>LP</b>	Low Pressure (turbine)
<b>PSS</b>	Power System Stabilizer
<b>PWM</b>	Pulse Width Modulation
<b>PQ</b>	Power Quality
<b>SSR</b>	Subsynchronous Resonance
<b>SSSC</b>	Static Synchronous Series Compensator
<b>STATCOM</b>	Static (Synchronous) Compensator
<b>SVC</b>	Static Var Compensator
<b>TCBR</b>	Thyristor Controlled Braking Resistor
<b>TCR</b>	Thyristor Controlled Reactor
<b>TCSC</b>	Thyristor Controlled Series Capacitor
<b>UPFC</b>	Unified Power Flow Controller
<b>VSC</b>	Voltage Source Converter
<b>VSI</b>	Voltage Source Inverter

**FACTS (Flexible AC Transmission System):**

Alternating current transmission system incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability [85].

FACTS is defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability."

According to Siemens "FACTS Increase the reliability of AC grids and reduce power delivery costs. They improve transmission quality and efficiency of power transmission by supplying inductive or reactive power to the grid.

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## 1 Introduction

### 1.1 Objectives

The main goal of this study is to design and control a hybrid AC/DC micro grid with FACTS to enhance performance, efficiency, and quality. In order to achieve main target, the following objectives are identified:

- Study advanced designs and controllers of MG
- Study advanced types/designs and controllers of FACTS within MG
- Define performance indicators (KPIs) of FACTS design, controller, and MG
- Evaluate overall MG performance using different FACTS designs / controllers, and their application to building energy conservation

### 1.2 Approach

Firstly, several researches, journal papers that are related to microgrids and FACTS are studied and reviewed. Literature reviews are completed on different designs and controllers of FACTS in microgrid, control strategies for FACTS in microgrid, key performance indicators of microgrid, and simulation of FACTS devices in microgrid. Based on literature review, SIMULINK simulation model for defining FACTS in microgrid with fuzzy control are used to analyze simulation of control and design strategies. Steady state and transient performance of the system are observed using Matlab/Simulink simulation. Defining KPI for system that differ with and without FACTS comparisons. Fuzzy logic will be implemented for defined control strategy and optimized using Genetic algorithm as an intelligent algorithm.

### 1.3 Research Tasks

The following are expected research tasks that will be completed in this thesis:

- Literature reviews of microgrid modeling, control and operation
- Literature reviews on FACTS modeling, control and operation
- Literature reviews on Key performance indicators for microgrid with and without FACTS
- Designing and modeling comprehensive microgrid case studies
- Designing and modeling different types of FACTS within a microgrid
- Control of power quality and stability through FACTS device in a microgrid
- MATLAB/Simulink simulation model for the FACTS control in a microgrid
- KPI comparison with/ without FACTS in a microgrid

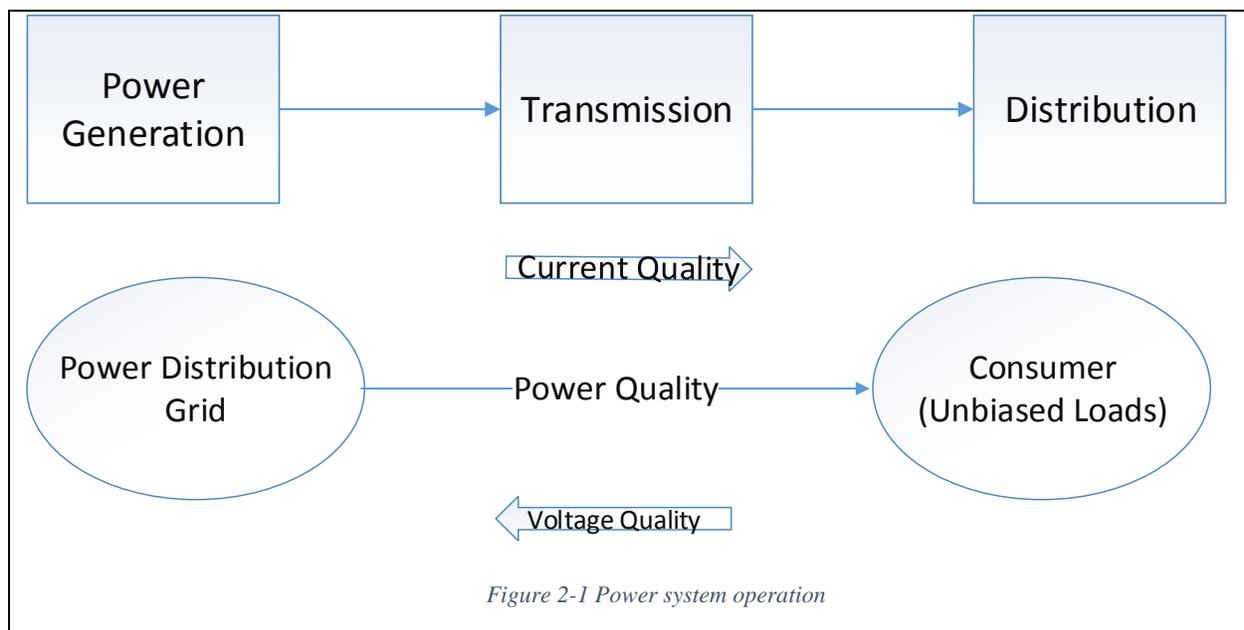
### 1.4 Motivation

The use of renewable energy in the world is increasing gradually. Economical, technological and environmental issues are shaping the characteristics of energy generation and transmission in the power industry. Distributed energy resources (DER) include a wide range of technologies for example; micro gas turbines, photovoltaic, fuel cells and wind-power. These technologies have initial lower cost that can lead to benefits in economies and trade. Recent market of oil and gas has variable and dynamic prices. Developing countries are facing economic challenges due to energy crisis every year. These countries uses several energy generation techniques to meet country energy consumption. In small communities, group of houses uses DERs to build local microgrid. This microgrid can fulfill small community energy solution and in utility grid is off, microgrid works as an islanded mode using DER to generate energy.

## 2 Literature Survey

This chapter provides overview on FACTS and microgrid concept. Later in the chapter different published papers are summarized to present literature survey on microgrid controls, FACTS modeling and control with different optimizing techniques.

FACTS (Flexible Alternative Current Transmission System) has a real purpose which is to control high voltage side of power system through electronic devices. Modern technologies and researches had increased many unreliable resources to the power systems. Unbiased and nonlinear loads results in poor quality, poor utilizations, low power factors and feeder over loading. These problems can be solved through FACTS devices, can minimize many of these problems.



Some of these power quality problems are associated with voltage quality such as “voltage sags, voltage swells, blackouts, voltage transients, frequency deviations. Also these power quality

problems can be caused by current quality such as “harmonics distortions, waveform distortions” that results in over current, voltage flickering.

### 2.1 FACTS Concept

The main purpose of using FACTS in power system is to use power electronic techniques and algorithms to make high voltage power flow electronically controllable. FACTS (Flexible Alternating Current Transmission System) is a term for devices that increase power flow, security, flexibility and capacity of power transmission system. It is an integral technology that is a novel concept that was put into development during the 1980s at the Electric Power Research Institute (EPRI) for applications of North American army tasks [5].

FACTS are flexible alternating current transmission systems that incorporate power electronics based and other static controllers to enhance controllability and power transfer capability [15].

FACTS can relate to many breakthroughs developed in the area of high-voltage, high-current power electronics devices. FACTS also increase the control of power flow in a grid during steady-state or transient conditions. Current innovation of controlling power systems electronically made power systems equipments and technologies efficient enough to help operation of transmission system. These changes had also affect the way energy consumption are conducted, as high-speed control of the path of the energy flow is now available. FACTS by itself have many promising benefits which backed up by the help of electrical system manufacturers, utilities, and research organizations throughout the globe [6].

The main objectives of FACTS controllers are following [15]:

- Power flow regulation in defined transmission lines.
- Loading of transmission lines with saving from their thermal limits.
- Adding feature to emergency control by prevention of cascading outages.
- Oscillation damping to secure from line capacity or security.

Many different types of FACTS devices are installed in various sections of the world. The most popular are: inter-phase power controllers, load tap changers, phase-angle regulators, static VAR compensators, thyristor-controlled series compensators, static compensators, and unified power flow controllers. If any grid has Angular, thermal, voltage and transient stability, then no breakdown to transmission lines and electric devices will occur. FACTS controllers gives systems many benefits such as reduction of operation, transmission investment cost, increased system security and system reliability, maximize power transfer capabilities, and an overall enhancement of the quality of the electric energy delivered to customers [16]. FACTS technology gives the strength to control in an adaptive manner. The high speed controlling in directions of the power flows throughout the network was minimum. The ability to control the line impedance, the buses voltage and phase angles at both the sending and the receiving ends of transmission lines, has directly increased the transmission capabilities of the network. Also considerably enhancing the security of the system is achieved.

### 2.2 Microgrid Concept

The U.S. Consortium for Electric Reliability Technology Solutions (CERTS) has published a White Book [1] where a microgrid is defined as:

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*“The Consortium for Electric Reliability Technology Solutions (CERTS) MicroGrid concept assumes an aggregation of loads and microsourses operating as a single system providing both power and heat. The majority of the microsourses must be power electronic based to provide the required flexibility to insure operation as a single aggregated system. This control flexibility allows the CERTS MicroGrid to present itself to the bulk power system as a single controlled unit that meets local needs for reliability and security.”*

The US Department of Energy (DOE) in [12]:

*“a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.”*

Apart from US, microgrid grid considered as by [13] and [14] as follows:

*“a cluster of loads and relatively small energy sources operating as a single controllable power network to supply the local energy needs.”*

*“Microgrid is a small grid in which distributed generations and electric loads are placed together and controlled efficiently in an integrated manner. It contributes to utility grid’s load levelling by controlling power flow between utility grid and Microgrid according to predetermined power flow pattern. Also, it contributes to an efficient operation of distributed generations by operation planning considering grid economics and energy efficiency.”*

From Hatziaargyriou [11], microgrid can be defined as:

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*“Microgrids are defined as low voltage or in some cases, e.g. Japan, as medium voltage networks with distributed generation sources, together with storage devices and controllable loads (e.g. water heaters, air conditioning) with total installed capacity in the range of few kW to couple of MWs.”*

Micro grid is a distribution network which a group of small generators provides power for a small neighbourhood such as local houses, parks, and office settings. Centralized control works as supervisory control for all network. Large sources to several small utilities, power is transmitted through distribution line that result in reliable power system. The main benefit of using microgrid is to isolate the loads from disturbance during disturbances in the system, hence maintaining the efficiency and reliability of the supply without effecting the main microgrid [1]. In microgrid several micro sources (<100KW) are used with power electronics controlling placed at customer interface. These low cost, low voltages sources assure flexible and efficient control of microgrid through power electronics devices. In [1] some microgrid characteristics are defined as;

- Not controlled by utility
- No central dispatching
- Smaller rating 50-100 MW
- Mostly interfaced with distribution system

Modern micro grids defined by small power grid that uses generating sources from both renewable energy sources and conventional synchronous generators and customer loads are controlled with respect to generated electric energy [2, 3]. Microgrid can be connected to main supply grid or can be operated in islanded connected mode where on site sources provide basic electric power [3]. Using renewable energy sources as an input power generation sources, local consumption will be

more efficient and cause less environmental problems. By using renewable sources enables performances of microgrid optimized and enhanced the input reliability [4]. Microgrid sources are to be on or near the grid, to supply that result in losses due to distribution electricity is minimized [5]. Since using renewable sources for example wind, solar, enhanced microgrid generation and reduce environmental issues but they also constraints economic and stability issues due to their unpredictable outputs [6]. Distribution companies has obligation to customer that to supply voltage in defined designated limit. These limit defines the configuration and durability of circuit used in distribution system, several researches happened throughout the year to use maximum use of circuitry to provide customer required voltage [1]. Some of distribution companies use controlling of on load of distributing transformer through regulators and also use along with voltage measurement current signal compounding at the switching capacitor throughout the feeder [7]. In result of using distribution generator for power feeding cause bad impact on the distribution voltage. In this case, the feeder demands are not fully read through regulator rather it measured small values [8].

Power quality are mostly concerned on [1]:

- Voltage variation in transient state
- Harmonic distortion of the distribution voltage

Microgrid will undergo transient voltage disturbance on distribution network if huge current spikes added to the system during connection or disconnection of generators [9]. Microgrid will cause transient voltage variation at the local consumer power grid, these variation can be caused by the changes in the outputs of microgrid units, quick variations or by voltage controlling device interaction with microgrid in feeder [7]. Improperly modeling of power electronics devices to specific microgrid system can cause harmonic voltages and currents that can result in voltage

distortion in the network. How much dangerous or what type of harmonics added to the system depends only what type of power conversion technology, the configuration of interface and mode of operation used in the microgrid [10]. Recent researches in semiconductor devices developed the usage of higher frequencies on carrier wave that can output in accurate waveform [8]. These problems are reduced mainly through recent technology of insulated gate bipolar transistor (IGBT) that generate sine wave through Pulse width modulation (PWM) [7]. Different policies of microgrid protection can be initialized by [1]:

- Generation equipment protection from internal problems
- Distribution network faults protection from current provided by microgrid
- Main grid or islanded protection
- Microgrid protection on distribution system

In [18], the modeling of FACTS devices for power flow studies and the role of that modeling in the study of FACTS devices for power flow control are discussed. Three essential generic models of FACTS devices are presented and the combination of those devices into load flow analysis, studies relating to wheeling, and interchange power flow control is explained. The determination of the voltage magnitude and phase angle of the FACTS bus is provided by solving two simultaneous nonlinear equations. These equations are solved with a separate Newton-Raphson approach within each iteration of the large load flow analysis. Therefore, another set of mismatch equations must be met for each iteration of the larger study. It is possible that this smaller Newton-Raphson study will not converge, particularly when voltage magnitudes are significantly less than rating. Therefore, the resultant solution may not converge due to divergence of the internal search. The disadvantage of this model is that the firing angle corresponding to such a compensation level should be calculated by reordering to an iterative process, in addition to the

load flow solution. Moreover, it is not possible to evaluate within the load flow solution whether or not the solution is occurring near of a resonant point of a TCSC. The only indication would be a divergent iterative process.

In [17], a novel method for optimal allocation of SVC is determined to enhance the voltage stability of power systems. Using second-order of the Taylor's series expansion, the nonlinear bus voltage participation factor is calculated. This method uses the nonlinear parts of power systems into the process. Following advantages can be viewed using presented method;

1) Using normal forms of the method, more information about the nonlinearity of the power system can be used. Hence, it is more efficient in analyzing complex nonlinear properties of power systems.

2) For the power systems operating under the light loading condition, as the nonlinearity of the system is not very high, the results from both the nonlinear bus voltage PF and the linear bus voltage PF lead to well outputs. When the power networks are working under stressed conditions, the nonlinearity has an essential role in the power system response. In this condition, the nonlinearity of the system cannot be ignored. The nonlinear bus voltages PF will lead to results that are more accurate related to the steady-state voltage stability index.

In [18], the modeling of FACTS devices for power flow studies and the role of that modeling in the study of FACTS devices for power flow control are discussed. Three essential generic models of FACTS devices are presented and the combination of those devices into load flow analysis, studies relating to wheeling, and interchange power flow control is explained. The determination of the voltage magnitude and phase angle of the FACTS bus is provided by solving two simultaneous nonlinear equations. These equations are solved with a separate Newton-

Raphson approach within each iteration of the large load flow analysis. The resultant solution may not converge due to divergence of the internal search. The disadvantage of this model is due to the firing angle corresponding to a compensated level that can be calculated by reordering in an iterative process. Either way, it is not easy to evaluate in the load flow solution whether or not the solution is occurring near of a resonant point of a TCSC. The only solution will be a divergent iterative process.

In [19], the problems of UPFC modeling with the reference of optimal power flow solutions is presented. The UPFC model is presented to control active and reactive power flow through sending and receiver end of the buses. The UPFC model suitable for optimal power flow solutions is presented for the first time in this study.

In [20], there is a proposal for a new optimal routing algorithm to minimize power loss and to maximize the voltage stability in power systems. The resultant characteristics of this research can be presented as follows.

- An powerful a voltage stability index (VSI) is applied to evaluate the voltage stability, which is well suited for frequent switching features. As shown in the case studies, the voltage stability of a radial system can be rapidly evaluated by the proposed VSI. Furthermore, information of all buses along the critical transmission path (CTP) and the critical bus can be automatically determined through the BE procedure. Therefore, operators can prepare a preventive action scheme in a sudden contingency or disturbance environment that may cause the voltage variation in a regional distribution system.

- An improved branch exchange (IBE) approach is presented to decrease the computational time. The IBE method depends on the loss calculation index. The index can be applied as an

efficient judge to evaluate the change of power loss without solving the iterative load flow during the BEs in a loop network. For calculation of the new tie-branch power flow resulting from load transfer during the BEs, the newly derived TBP equation is used with reasonable accuracy.

- The optimal routing algorithm (ORA) also has used the GA as a global search algorithm to look for an initial radial network. As indicated in numerical results, this hybrid method is very powerful in large-scale systems.

In [21], a new method to determine the power flow control of FACTS for the optimal active power flow problem is presented. The linearized network (DC) model is used. Main types of FACTS devices; TCPS, UPFC and the TCSC, are studied. The proposed new method decomposes the solution in such way that it modified optimum power flow (OPF) problem in iteration of two different problems. The first is a power flow control and the second is a normal OPF problem. Further research work is needed for other OPF algorithms with an AC network model.

In [22, 23], a new load flow model for the UPFC and TCSC is presented. The state variable in the TCSC is firing angle that is linked with the nodal voltages and angles of the grid for a combined iterative process using a Newton-Raphson method. Under different operation of the TCSC models, this load flow model presented in the loop current that exists in the TCSC for both partial and full conduction modes. Also, the model provides usage of the resonant points characterized by the TCSC frequency impedance. A series of analytical equations is derived to make best UPFC initial parameters. Specific guidelines are proposed for a reliable control of two or more UPFCs that are operating in series or parallel.

In [24], using the steady state configurations of FACTS devices, the control limits and control ranges of the power flow on distribution line occupied by one FACTS device are researched. That

paper mainly concerns with the commitment of several FACTS devices. To handle this issue, a novel method using genetic algorithm (GA) has been presented. In this presented technique, how many number of FACTS can used to maximum range of the power flow control is analyzed. It is found that the controllability of the power flow is consisted on the number of FACTS devices used in the system and power flow control range with multiple FACTS devices is larger than that with only one such device. Therefore, the commitment of control performances of various devices is a very essential issue for future power system planning and operation.

A linear optimal controller is proposed [25] to enhance the system dynamics and to coordinate three SVCs depending on two control levels, the local control to insure optimum Performance at the local level and the global control to make the coordination by decoupling the state equation for each area. Also a state observer is suggested to obtain the unmeasured states. PSCAD/MTDC is used to simulate the system. The problem of coordination is also handled in [26], a coordinated controller is designed according to the linear quadratic problem; the gain matrix is modified to allow the controller to depend on output feedback. In addition, the system states are reduced since the controller is concerned with the range of frequencies of the inter-area modes.

A methodology to obtain the robust locations ranges and feedback signals of FACTS controllers is proposed in [27]. In proposed criterion is to insure good performance for the controller not only at the designed operating condition but also at the different operating conditions of the power system. An eigen-free index is introduced to evaluate the performance of the controller.

Reference [28] proposed the application of a Takagi-Sugeno (TS) fuzzy controller to provide regulation of UPFC with the series voltages and shunt voltage source inverters, to damp the inter-

area and local modes in a several staged machine power system. The UPFC injection model, which consists of two controllable loads, was used and the dynamics of the DC voltage was expressed by a differential equation. The reactive and active power deviations, which were feedback signals to the reactive and active components of the series voltage source respectively, were fuzzefied using two fuzzy sets, positive and negative. By applying Zadeh's rules for AND operation and the general defuzzifier, the output of the controller was obtained. In [29], it proposed a conventional lead-lag controller for UPFC to reduce the oscillation damping of a single-machine system with infinite buses. The generator speed deviation control is the controller input signal. Based on the linearized model, the damping function of the UPFC is investigated.

A robust fixed-structured power system damping controllers using genetic algorithm is indicated in [30]. The designed controllers have a classical structure structuring from a gain, a washout stage and two lead-lag stages. The GA searches for an optimum solution over the controller's parameter space. The approach is applied to design SVC and TCSC damping controllers to improve the damping of the inter-area modes. Local voltage and current measurements are used to synthesis remote feedback signals.

In [31], different control strategies for damping inter-area oscillations by using SVCs, STATCOM and PSSs are presented. The oscillation problem is studied from Hopf bifurcations perspective. It is analyzed that the damping added by the STATCOM and SVC devices that have only voltage control possess lower damping as compared by the PSSs and the STATCOM. The reason is these controllers are manage to internally move their active power within the system.

Reference [32] concerns with minimizing the active losses in the power systems by adding UPFC in the system. UPFC used in that paper as series element to work as a series compensator

and/or to work as a phase shifter. To find optimal phase angles, optimal values of series reactance genetic algorithms is used, the simulations are applied on IEEE 30-bus system.

Reference [33] focuses on optimal power flow with presence of UPFC in the system. And then it applies Genetic Algorithm (GA) to find the optimal dispatch of the generation powers of the generating units in the network to achieve the minimum total cost (\$/hr). The model, which is used in modeling, is the injected model of FACTS device. The simulations are applied on IEEE 14-bus system. The results show that FACTS device not conclude to a specific reduction for the cost of the generating power. It can be used in controlling and increase the feasibility of the power network.

In [34], a design of fuzzy damping controller of UPFC through genetic algorithm is presented. It applies a fuzzy controller as external controller provides supplementary damping signal to UPFC. The design includes the shape and the number of membership functions for the input and the output variables. The genetic algorithm is used to optimize the scaling factors, which are used in the scaling portion of the fuzzy controller. The simulations are applied on four machines interconnected power system, which used as a test system. A comparison between the fuzzy controller and the conventional controller and also without presence of controller is performed.

Reference [35] presented the optimal location of FACTS controllers. It compares between the simulated annealing method, genetic algorithm method and Tabu search method. Main objective is to find the optimal location for some FACTS controllers for example TCSC, TCVR, TCPST, SVS and UPFC. The study is performed on the steady-state models, and the simulations are occurred on IEEE bus system. The problem is that, this paper represents UPFC as two separated

devices, without modeling the UPFC itself as stand-alone device. It presents a limitation of the number of FACTS devices. It states that GA is better in the simulations.

Reference [36] studies the harmony search algorithm and genetic algorithm in optimal installation of FACTS controllers related to voltage stability and losses issues. It concerns with determining the optimal location of FACTS controllers. The applied devices, which are used in that paper, are TCPAR, UPFC, and SVC. The concerning criteria are the loss and the voltage stability. The used mathematical model of FACTS controllers is the injected power model. The simulations are applied on IEEE 30-bus system.

Reference [37] presents a control method on UPFC based on genetic algorithm, but applied on a single-machine infinite-bus system. The aim of UPFC installation on that system is to damp the system oscillations. The UPFC voltage sources are converted into three power injections at the receiving and sending buses. The applied controller is an external genetic algorithm PI controller trying to return the response deviation to zero. The fitness function is termed on the real and imaginary parts of the dominant eigenvalues.

Reference [38] proposes a micro genetic algorithm based fuzzy logic controller to coordinate between TCSC and UPFC in the system. The micro genetic controller is designed to operate to reach the optimal criteria as fast as possible without enhancing the performance. The micro genetic algorithm is applied when it available to use small size and value of population not more than 10. These characteristics direct the simulations to be executed on three-machine power system. The genetic algorithm search for the optimal membership functions. In [39], it studies the same application, in addition to use parallel micro genetic algorithms to speed up the initialization

process covering the search-space, also it uses neuro-fuzzy technique to escape from dropping in the local minimum.

Reference [40] concerns with enhancement of voltage stability and reduction in investment cost by installing multi-type FACTS devices using genetic algorithm. The fitness functions is termed by the FACTS devices cost functions and the system losses. Three different FACTS devices are used: TCSC, SVC, and UPFC. The paper uses the decoupled model for UPFC, which it less complex but it lacks to the modifications in Jacobian matrix. Multi.-type FACTS devices can achieve the required criteria but the economic aspects must be considered.

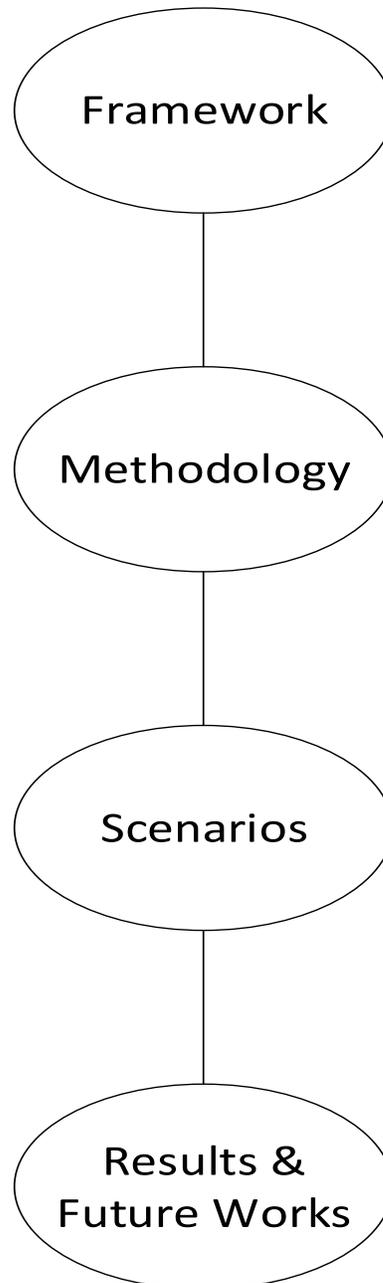
In [41], a genetic algorithm using interior point method is derived for optimal reactive power flow. A new technique in for optimal reactive power flow (ORPF) applications is presented by combining a genetic algorithm (GA) with non-linear Interior Point Method (IPM). New techniques has two sections, first is to solve ORPF using IPM by reducing discrete characteristics variables. Second section is consists on distributing original ORPF into two sub-problems, that is continuous and discrete optimization. The optimal solution can be achieved by solving separately the two sub-problems. Genetic algorithm is use to accomplish discrete optimization with variables are kept fixed and IPM solve continuous optimization with variables are kept constant.

In [42, 43], they present a new method for optimal location of UPFC to improve the load ability by using genetic algorithm. The analysis studies the comparison of installing one, two or three UPFC in the system. The objective function concerns with maximizing the load ability of the transmission lines, and that is the only technical benefit is taken into consideration. The objective function is termed by exponential mathematical formula to describe the required criteria. The process depends on increase the number of UPFC installed in the system. The simulations are

occurred on high loading operating conditions for the transmission lines. The simulations are applied on IEEE 14-bus system. Specially [43], it takes the same area and analysis with some more case studies for improving the reactive and active power. In [44], it concerns with a hybrid genetic algorithm for determining UPFC optimal control setting. The injected-power model is the static modeling of UPFC, which is the used in the simulations. The objective function is related to optimal power flow to minimize the operating cost especially for the power of the generating units. The optimization process searches the control setting of UPFC to minimize the cost of the operation. The results is achieved by first finding the optimal setting of UPFC using genetic algorithm, then simulate the system and UPFC with that setting to get the objective. The simulations are applied on IEEE 14-bus system.

### 3 Thesis Overview

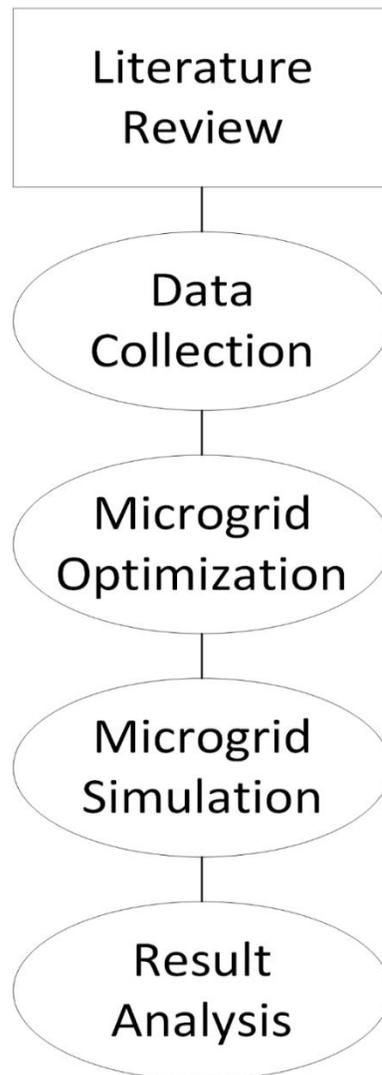
In this chapter an overall thesis overview is represented which includes work frame, methodology, different scenarios and overall summary.



*Figure 3-1 General Thesis Overview*

### 3.1 Proposed framework

This section gives on review on thesis framework which conclude by review different papers and journals about microgrid, FACTS, Key Performance Indicators (KPI) of microgrid and modeling of microgrid. A flowchart on thesis framework is mention below:



*Figure 3-2 Thesis Framework*

### 3.2 Proposed Methodology

The proposed methodology, with respect to the thesis framework, is as follows:

Microgrid Modelling: Develop model libraries of MEG technologies and identify design and operation parameters and state variables. This includes voltage profile, power factor, and active and reactive power, and the associated operational constraints such as voltage limits, line flow limits, and heat balance constraints.

FACTS modeling: Developing microgrid with FACTS, performance analysis through microgrid can achieve good reactive power control, voltage and current profile.

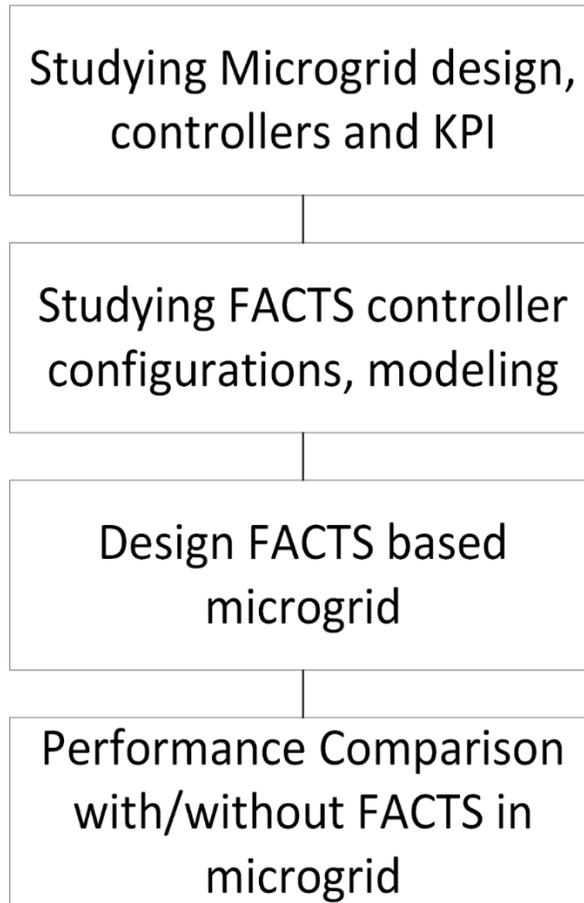
Performance KPI Modelling: Detailed key performance indicators (KPI) modelling to evaluate MEG design, control, operation, installations, and maintenance, in view of lifecycle engineering.

Intelligent heuristic/control System: Design intelligent heuristic/control system for optimized MG based on Key Performance Indicators and parameters specific to MG installations to meet AC/DC energy demands, and cogeneration capacities, in view available distributed generation, storage, and grid inputs. The proposed control will ensure stability to meet acceptable performance of MG systems.

Integrated Simulation: Design and develop integrated simulation for the MG integration and infrastructures, with all identified KPIs to evaluate different design and operation scenarios,

## Design and Control of FACTS-based high performance Microgrid

including the evaluation of the proposed MG control with self-healing and resiliency based on overall performance, and tuning of the control design.

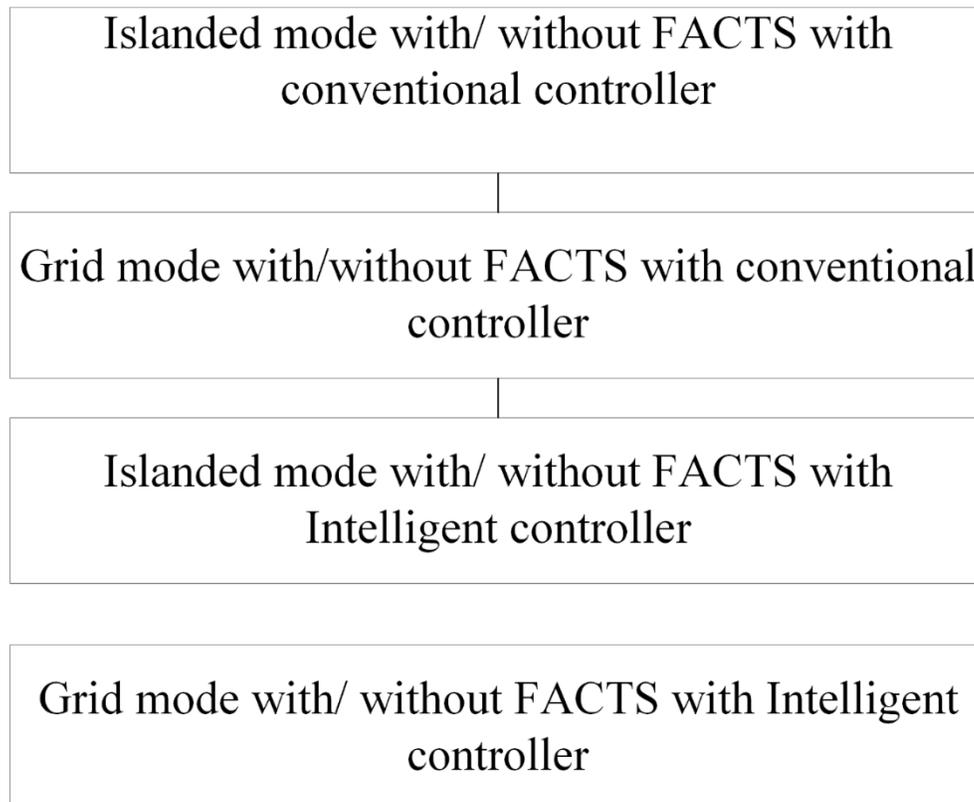


*Figure 3-3 Thesis Methodology*

### 3.3 Proposed Microgrid Scenarios

For checking the proposed microgrid design, configuration and verification, different scenarios are tested that are:

- Islanded mode with/ without FACTS with conventional controller
- Grid mode with/without FACTS with conventional controller
- Islanded mode with/ without FACTS with Intelligent controller
- Grid mode with/ without FACTS with Intelligent controller



*Figure 3-4 Thesis Scenario*

## 4 Modeling of FACTS Devices

### 4.1 Introduction

This chapter presents systematically review of the most FACTS devices that currently are using in the industry. Their characteristics, modeling, control, voltage regulation, active and reactive power flow control, and power quality enhancement are described in this chapter. All FACTS controllers are modeled in both phasor and time domain, while their steady state operation are observed.

### 4.2 FACTS devices

FACTS techniques are divided into four different categories:

1. Series devices
2. Shunt devices
3. Combined Series-Series devices
4. Combined Series-Shunt devices

#### 4.2.1. Series Devices

These devices consist of variable source with main frequencies, sub-synchronous frequencies and harmonic frequencies. Fundamentally, all series devices inject voltage in series to the system. Main purpose is to inject voltage in phase that result in reactive power to supply or consume that results in real power will used.

#### 4.2.2. Shunt Devices

Shunt devices consist of variable impedance, variable source, or combinations of these elements. Shunt devices inject current into the system at the point of connection. Variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of

current into the line. Same as series devices if injected current is in phase reactive power will be used either way real power will be supplied or consumed.

#### **4.2.3. Combined Series-Series Devices**

Series-Series devices also known by interline power flow controllers, which are a combination of separate series devices controlled in a coordinated manner. They have the ability to balance both real and reactive power flows in the lines

#### **4.2.4. Combined Series-Shunt Devices**

Series-Shunt devices are a combination of shunt and series devices, which are controlled in a coordinated manner. In principle, shunt-series devices inject current into the system with the shunt part of the controller, and voltage in series in the line with the series part of the controller.

### **4.3 Thyristor Controlled Reactor (TCR)**

Figure 4-1 gives a schematic block diagram of a TCR where the controllable component is the parallel thyristor pair, (Th1 and Th2), that leads to substitute half cycles of input frequency. The other main component is inductor L. Practically for significant value, many thyristors (generally more than 10) are associated in series to meet the required blocking voltage levels [30, 31]. Thyristor are controlled through gate pulse, gate pulse also termed by firing angle  $\alpha$ . Firing angle is not connected to the gate, it naturally blocked valve from conduction, as percentage of the reactive power. In this way, from [32]. For modeling a supposition made that is resistance of the inductor be disregarded. The terminating point  $\alpha$  is defined by the angle in electrical degrees between the positive going zero intersection of the voltage over the inductor and the positive going zero intersection of the current in it. The thyristors can be let go with most extreme conceivable firing angle of  $180^\circ$ . Full conduction can be accomplished with an angle of  $0^\circ$ ; fractional

conduction can be accomplished with firing angle between  $90^\circ$  and  $180^\circ$  with zero current at  $180^\circ$ . Firing angle, under  $90^\circ$  are not fit for produce unsymmetrical currents with a high DC part [8]. The fundamental part of TCR current have an aberrant association with firing angle, i.e. reduce in current result in firing angle increment. That means an increase in the reactor inductance, reducing both of its reactive power and its current. In Figure 4-2a, the voltage over the TCR inductor and the current through it are appeared at full conduction. The proportional reactance of the TCR is equivalent to the inductor reactance. In Figure 4-2b, the present waveform is appeared for a firing angle of  $100^\circ$ . Just section of the sinusoidal voltage is connected to the inductor, the current and the voltage are not sinusoidal any longer. The essential part of the current is not as much as that the present at a  $90^\circ$  firing angle, bringing about an identical reactance of the TCR higher than the inductor reactance. Figure 4-2c and 4-2d demonstrate the TCR current waveform for a firing angle of  $130^\circ$  and  $150^\circ$ . The central part of the current through the inductor is little, the equivalent reactance of the TCR is high, and at  $180^\circ$  it becomes infinite.

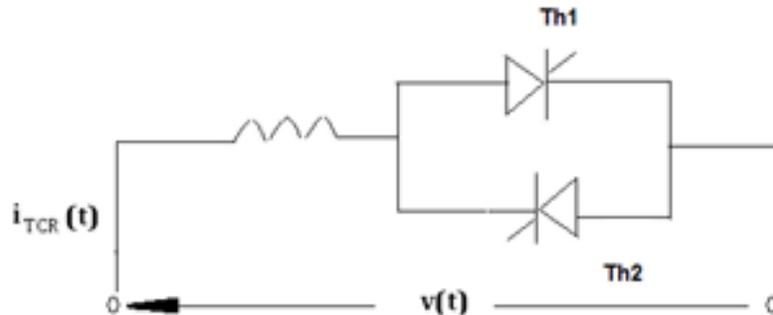


Figure 4-1 Thyristor Controlled Reactor

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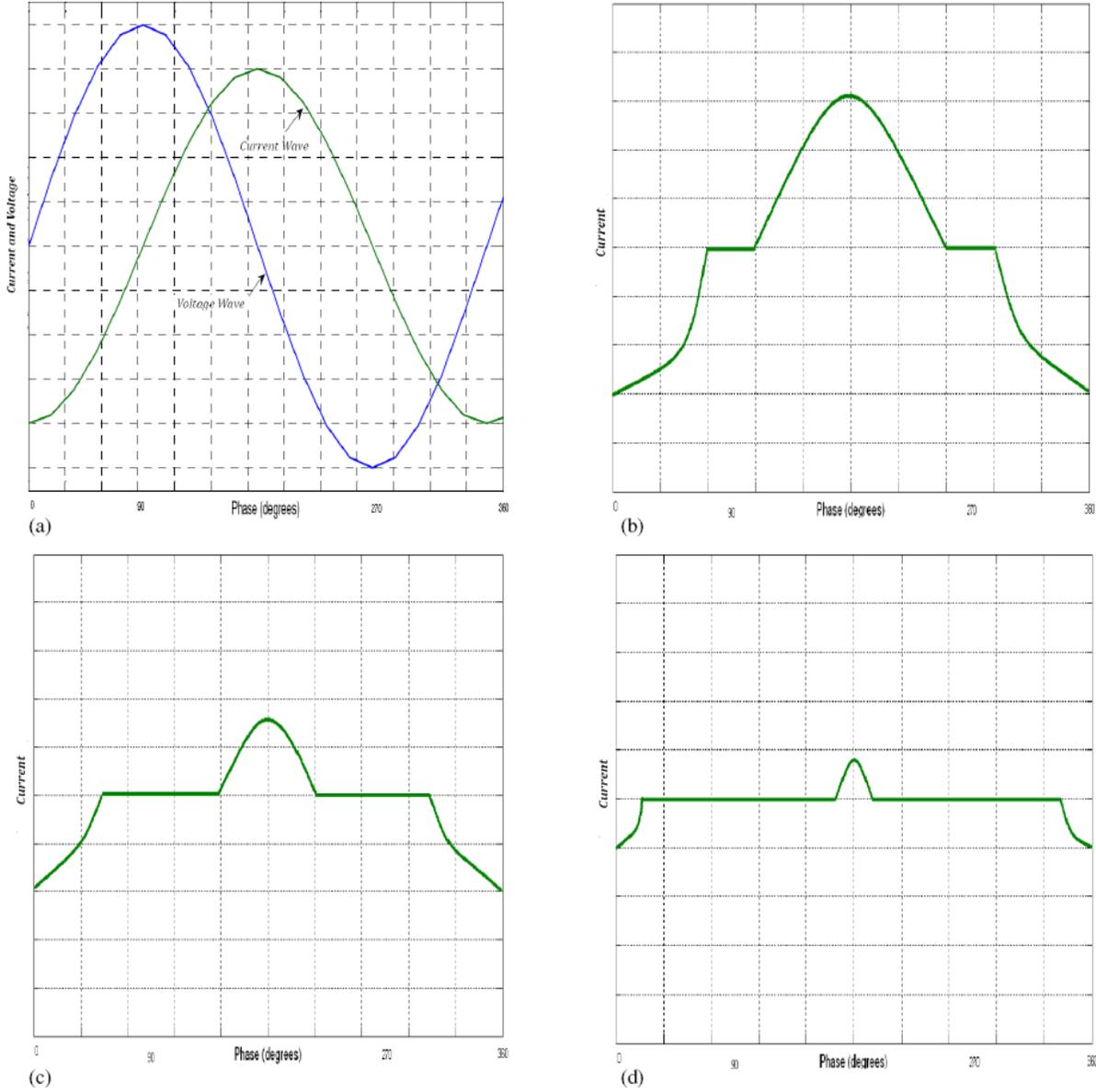


Figure 4-2 Current waveforms in TCR (a) 90o (b) 100o (c) 130o (d) 150o [16]

## 4.4 Thyristor Based FACTS Devices

TCR based FACTS devices are Static Var Compensators (SVC) and Thyristor Controlled Series Capacitor (TCSC).

### 4.4.1 Static Var Compensators (SVCs)

The development of the SVC comprises of a TCR in parallel with a capacitors bank. From a specialized point of view, the SVC works as a shunt-associated variable reactance that can delivers or attracts reactive power to direct the voltage level at the point of connection in system. It is utilized productively to supply quick reactive power and voltage regulation. The firing angle control of the thyristor gives the SVC a fast speed of response [5].

A graphical representation of the SVC is appeared in Figure 4-3, where a three-phase, three winding transformer is used to associate the SVC to the system. The transformer has two indistinguishable auxiliary windings: the first is for the delta association, six-pulse TCR and the

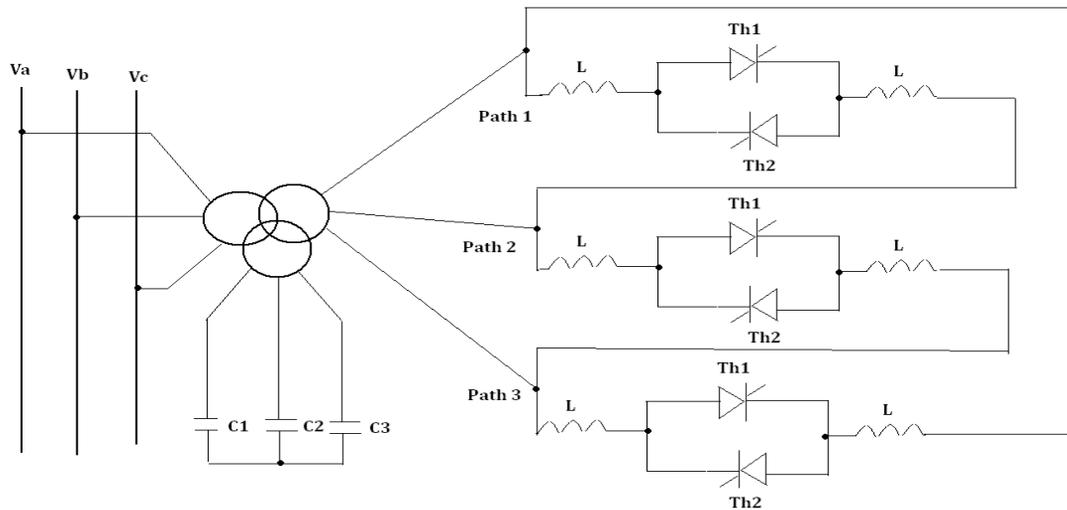


Figure 4-3 Static VAR compensator (SVC). [33]

second for the star connection, is a three-phase bank of capacitors, with its star point floating. The three transformer windings are likewise taken to be star-connected, with complex star connections. The compensator is typically worked to control the transmission's voltage at a chosen terminal.

The V-I characteristics for the SVC, appeared in Figure 4-4, shows that regulation with a given incline around the nominal voltage can be accomplished in the ordinary operating range that are characterized by the maximum capacitive and inductive currents of the SVC. While the most capacitive current lessens linearly and the delivered reactive power is in quadrature with the system voltage since the SVC goes about as an altered capacitor when the greatest capacitive output is accomplished. Results in, the voltage regulation ability of the traditional thyristor-controlled static Var compensator expediently impairs with reducing system voltage [33].

SVCs are likewise utilized for transient first swing, steady state stability and damping changes. SVC acts like a perfect mid-point compensator until the maximum capacitive induction  $BC_{max}$  is accomplished. From this point power transmission curve becomes same while its admittance is  $BC_{max}$ . The steady state stability of power oscillation damping can be acquired by replacing the output of the SVC between appropriate capacitive and inductive values to change the angular acceleration and deceleration of the units involved. The purpose is to increase the outputted electrical power by changing the transmission line voltage (via capacitive vars) when the units accelerate and reducing the voltage (via inductive vars) when the units decelerate. The powerful of the SVC in power oscillation damping is a function of the allowed voltage variation.

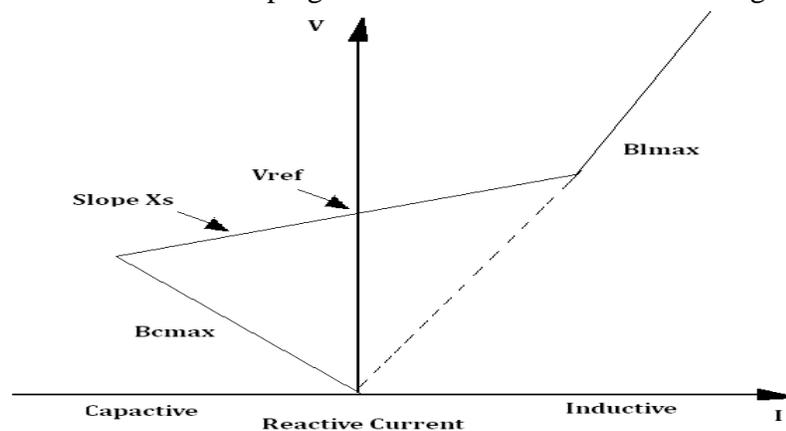


Figure 4-4 V-I characteristics. [33]

### *4.4.2 Thyristor Controlled Series Capacitor (TCSC)*

A basic TCSC module consists of a TCR in parallel with a capacitor. An actual TCSC comprises one or more modules. Figure 4-5 shows the layout of one phase of the TCSC installed in the Slatt substation on USA. The TCSC comprises a capacitor bank inserted in series with the transmission line, a parallel metal oxide varistor (MOV) to protect the capacitor against over-voltage and a TCR branch, with a thyristor valve in series with a reactor, in parallel with the capacitor. Mechanically bypass breakers are provided in parallel with the capacitor bank and in parallel with the thyristor valve. During normal operation, the bypass switch is open, the bank disconnect switches (1 and 2) are closed and the circuit breaker is open. When it is required to disconnect the TCSC, the bypass circuit breaker is switched on first, and then the bypass switch is switched on. The damping circuit is used to limit the current when the capacitor is switched on or when the bypass circuit breaker is switched on.

In the fixed-capacitor thyristor-controlled reactor scheme, the degree of series compensation in the capacitive operating region and the admittance of the TCR are kept below that of the parallel-connected capacitor is changed with the change in the thyristor conduction angle and also with TCR current. Minimum series compensation is achieved when the TCR is off. The TCR may be designed to reach the capability to limit the voltage across the capacitor during faults and other system contingencies of similar effect.

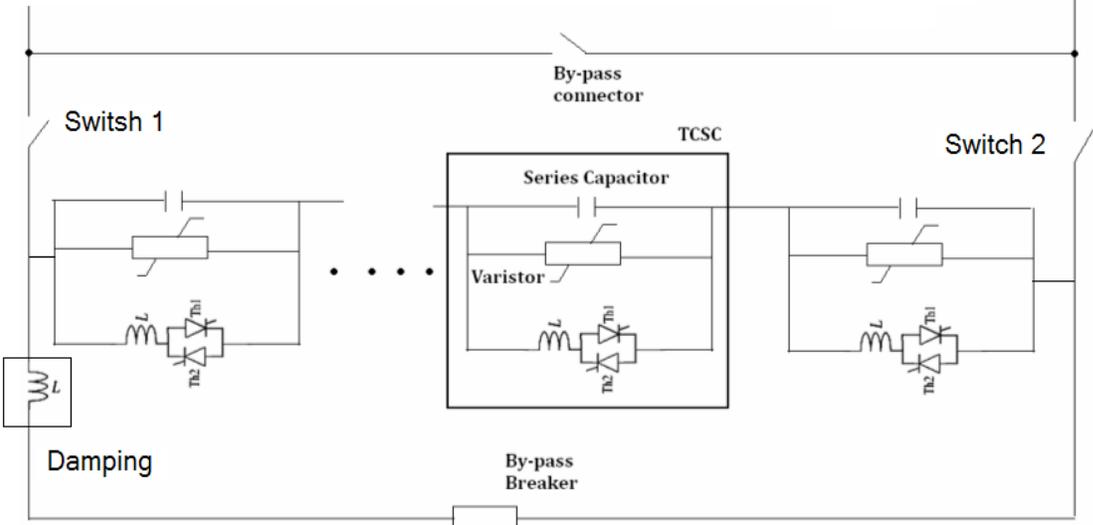


Figure 4-5 Thyristor controlled series capacitor (TCSC). [34]

The overall impedance of the TCSC is given as:

$$X_{TCSC} = \frac{\pi X_C X_L}{X_C [2(\pi - \alpha) + \sin 2\alpha] - \pi X_L} \tag{4.1}$$

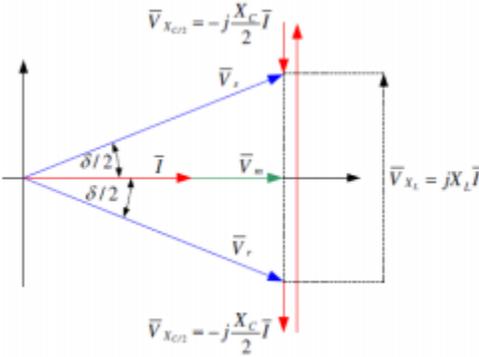


Figure 4-6 Series compensation vector diagram. [41]

The problem of the last equation is that the harmonic analysis has only been conducted for the TCR while the analysis of the capacitor charging has been neglected. The total impedance has

been obtained by paralleling the TCR equivalent impedance at the fundamental frequency and the fixed capacitor. This makes equation (4.1) only valid for the first cycle of the current. The reason is that after the first cycle has elapsed, the capacitor stores charge, leading to higher steady state voltages compared to cases when the capacitor charging effect is neglected.

The derivation of the TCSC impedance is started by examining the voltages and currents in the TCSC under the full range of operating conditions. The basic equation is:

$$Z_{TCSC(1)} = \frac{V_{TCSC(1)}}{I_{line}} \quad (4.2)$$

$V_{TCSC(1)}$  is the fundamental frequency voltage across the TCSC model,  $I_{line}$  is the fundamental frequency line current. The voltage  $V_{TCSC(1)}$  is equal to the voltage across the TCSC capacitor and (4.2) can be written as:

$$Z_{TCSC(1)} = \frac{-jX_C I_{cap(1)}}{I_{line}} \quad (4.3)$$

If the external power network is represented by an idealized current source, as seen from the TCSC terminals, this current source is equal to the sum of the currents following through the TCSC capacitor and inductor. The TCSC can then be expressed as:

$$Z_{TCSC(1)} = \frac{-jX_C (I_{line} - I_{TCR(1)})}{I_{line}} \quad (4.4)$$

$I_{TCR(1)}$ : The fundamental component of the TCR current, can be found by the following:

The line current is,  $i_{line} = \cos(\omega t - \sigma) = \cos \omega t \cos \sigma + \sin \omega t \sin \sigma$  (4.5)

The voltage across the TCSC,  $L \frac{di_{TCR}}{dt} = \frac{1}{C} \int i_{cap} dt + V_C^o$  (4.6)

Where  $V_{cal}^o$  is the voltage across the capacitor when the thermistor turns on. In Laplace form equation (4.5) and (4.6) are

$$I_{line} = \cos \sigma \frac{s}{s^2 + \omega^2} + \sin \sigma \frac{\omega}{s^2 + \omega^2} \quad (4.7)$$

$$I_{cap} = s^2 L C I_{TCR} - C V_C^o \quad (4.8)$$

Applying Kirchhoff current law,  $I_{TCR} = I_{line} - I_{cap}$  (4.9)

Substituting (4.7) and (4.8) into (4.9), and solving for  $I_{TCR}$ ,

$$I_{TCR} = \omega_o^2 \cos \sigma \frac{s}{(s^2 + \omega^2)(s^2 + \omega_o^2)} + \omega_o^2 \omega \sin \sigma \frac{1}{(s^2 + \omega^2)(s^2 + \omega_o^2)} + \frac{\omega_o^2 C V_C^o}{s^2 + \omega_o^2} \quad (4.10)$$

Where  $\omega_o^2 = \frac{1}{LC}$  (4.11)

Substituting the expression for  $I_{TCR(1)}$  (The fundamental component of the TCR current) into (4.4) and assuming  $I_{line} = I_m \cos \omega t$ , leads to the fundamental frequency TCSC equivalent reactance, as a function of the TCSC firing angle  $\alpha$  as:

$$X_{TCSC} = -X_C + C_1(2(\pi - \alpha) + \sin(2(\pi - \alpha))) - C_2 \cos^2(\pi - \alpha) (\overline{\omega} \tan(\overline{\omega}(\pi - \alpha)) - \tan(\pi - \alpha)) \quad (4.12)$$

Where

$$\bar{\omega} = \frac{\omega_0}{\omega} \quad , \quad \omega_o^2 = \frac{1}{LC} \quad , \quad C_1 = \frac{X_C + X_{LC}}{\pi} \quad , \quad C_2 = \frac{4X_{LC}^2}{X_L\pi} \quad , \quad X_{LC} = \frac{X_C X_L}{X_C - X_L}$$

Comparing Equations 4.1 and 4.12, the resonant firing angle in the two equations are not the same. Depending on the ratio between  $X_C$  and  $X_L$ , there could be more than one resonant angle for the TCSC expressed by Equation 4.5.

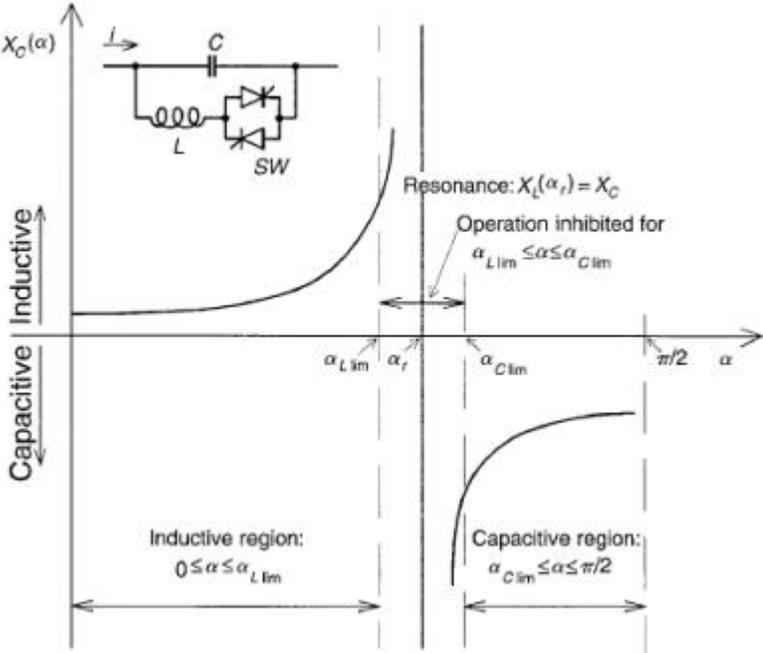


Figure 4-7 TCSC reactance vs. firing angle  $\alpha$ . [41]

4.4.2.2 *Resonance firing angle:*

Examining (4.5), the firing angle that cause resonance is obtained when

$$\cos(\pi - \alpha_{res}) \cos(\bar{\omega}(\pi - \alpha_{res})) = 0 \quad (4.13)$$

$$\text{So } \alpha_{res} = \pi - \frac{(n+1)\pi}{2} \sqrt{\frac{X_L}{X_C}} \quad \text{where } n = 0, 2, 4, \dots \quad (4.14)$$

Although of the effective enhancement on transmittable power, high levels of series compensation are not typically used. The feasible upper boundary to the limit of series compensation is about 70 % [53], as more steady state compensation may produce uncontrollable variations in the power for low alteration in terminal voltages or angles, and large transient currents and voltages during disturbances at series resonance conditions.

## 4.5 SVS Based-FACTS Device

Among the SVS based Facts devices are the STATCOM, the SSSC and the UPFC.

### 4.5.1 *Static Compensator (STATCOM)*

The STATCOM consists of one VSC and its associated shunt-connected transformer. It is the static form of the rotating synchronous condenser but it supplies or draws reactive power with a fast rate because there is no moving parts inside it. In principle, it performs the same voltage regulation function as the SVC but in a more robust manner because, unlike the SVC, its operation is not impaired by the presence of low voltages. A schematic representation of the STATCOM and its equivalent circuit are shown in Figure 4-8.

If the energy storage is of suitable rating, the SVS can exchange both active and reactive power with the network. The active and reactive power, supplied or drawn by the SVS, can be controlled independently of each other, and any combination of active power, generated or absorbed, with active power, generated or absorbed, is possible. The active power that the SVS exchanges at its network terminals with the grid must, of course, be supplied to, or absorbed from, its DC terminals by the energy storage device. In contrast, the reactive power exchanged is internally generated by the SVS, without the DC energy storage device playing any significant part in it.

The bi-directional real power exchange capability of the SVS, that is, the ability to absorb energy from the AC system and deliver it to the DC energy storage device (large storage capacitor, battery, superconducting magnet) and to reverse this process and deliver power for the AC system from the energy storage device, makes complete, temporary system support possible. Specifically, this capability may be used to improve system efficiency and prevent power outages. In addition,

in combination with fast reactive power control, dynamic active power exchange is considered as an extremely powerful method for transient and dynamic stability enhancement.

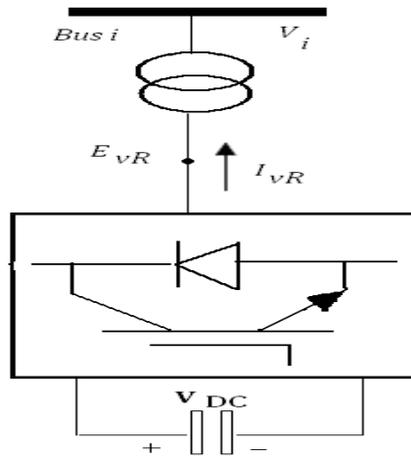


Figure 4-8 Static compensator (STATCOM)

If the SVS is used strictly for reactive shunt compensation, like a conventional static Var compensator, then the DC energy storage device can be replaced by a relatively small DC capacitor, as shown in Figure 4-8. In this case, the steady-state power exchange between the SVS and the AC system can only be reactive.

When the SVS is applied for reactive power supplying, the inverter itself can maintain the capacitor charged to the desired voltage level. This is achieved by making lagging in the output voltages of the inverter and the system voltages by a little angle. In this way, the inverter draws a small amount of active power from the grid to replenish its internal losses and keep the capacitor voltage at the required level. The same control procedure can be applied to raise or reduce the capacitor voltage, and thereby the magnitude of the output voltage of the inverter, for the purpose of controlling the reactive power generation or absorption. The DC capacitor also has a function of establishing an energy balance between the input and output during the dynamic changes of the Var output.

The V-I characteristic of the STATCOM is shown in Figure 4-9. As can be seen, the STATCOM can act as both capacitive and inductive compensators and it is able to control its output current independently over the maximum range of the capacitive or inductive of the network voltage. That is, the STATCOM can produce complete capacitive output current at any grid voltage level. On the other side, the SVC can supply only output current with reducing system voltage as calculated by its maximum equivalent capacitive admittance. The STATCOM is, therefore, superior to the SVC in providing voltage support.

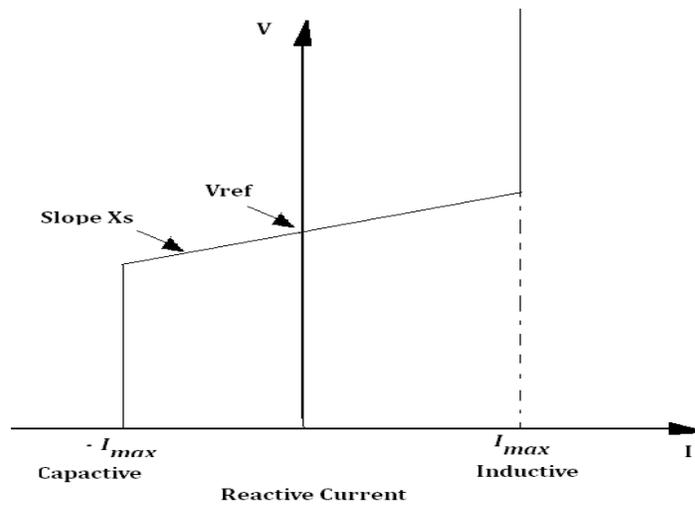


Figure 4-9 V-I characteristic of STATCOM. [55]

4.5.2 Static Series Synchronous Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller based on VSC and can be viewed as an advanced type of controlled series compensation, just as a STATCOM is an advanced SVC.

A SSSC has several advantages over a TCSC such as (a) elimination of bulky passive components (capacitors and reactors), (b) improved technical characteristics (c) symmetric capability in both inductive and capacitive operating modes (d) the possibility of connecting an energy source on the DC side to exchange real power with the AC network.

A solid-state synchronous voltage source, consisting of a multi-pulse, voltage-sourced inverter and a DC capacitor, is shown in series with the transmission line in Figure 4-10.

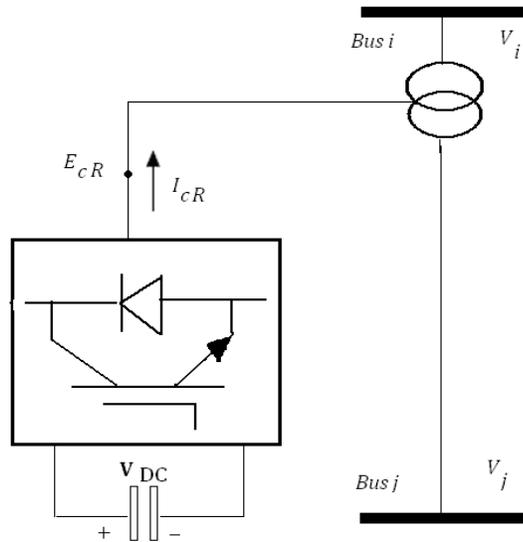


Figure 4-10 SSSC Schematic Diagram

In general, the active and reactive power exchange is controlled by the phase displacement of the injected voltage with respect to the line current. For example, if the injected voltage is in phase with the line current, then only active power is exchanged, and if it is in quadrature with the line current then only reactive power is exchanged.

The series-connected synchronous voltage source is an extremely powerful tool for power flow control and, it is able to control both the transmission line impedance and angle. Its capability to exchange active power with the grid makes it very effective in enhancing dynamic stability by means of alternately inserting a virtual positive and negative damping resistor in series with the line in sympathy with the angular acceleration and deceleration of the disturbed generators.

The idea of the solid-state synchronous voltage source for series reactive compensation is based on the rule that the characteristic between the impedance and the frequency of the practically employed series capacitor, which is different than the filter techniques, has no role in achieving the required line compensation. The function of the series capacitor is simply to produce an appropriate voltage at the fundamental AC system frequency in series with the line to partially cancel the voltage drop developed across the inductive line impedance by the fundamental component of the line current. So that the resulting total voltage drop of the compensated line becomes electrically equivalent to that of a shorter line. Therefore, if an AC voltage supply with fundamental frequency, which has a quadrature lagging relationship to the line current and whose magnitude is proportional to the line current is injected in series with the line, a series compensation equivalent to that supplied by a series capacitor at the fundamental frequency is provided.

Mathematically, this voltage source can be defined as follows:

$$V_n = -jkXI \quad (4.15)$$

Where  $V_n$  is the injected compensating voltage phasor,  $I$  is the line current phasor,  $X$  is the series reactive line impedance, and  $k$  is the degree of series compensation. For conventional series compensation,  $k$  is defined as  $X_C/X$ , where  $X_C$  is the impedance of the series capacitor.

For regular capacitive compensation, the output voltage must lag the line current by 90 degrees, in order to directly oppose the inductive voltage drop of the line impedance. However, the inverter output voltage can be reversed by a proper control method to direct it to be leading the line current by 90 degrees. At this moment, the injected voltage is in phase with the voltage produced across the inductive line impedance and thus the series compensation has the same effect as if the reactive line impedance was raised. This capability can be invested to increase the effectiveness of power oscillation damping and, with sufficient inverter rating; it can be used for fault current limitation.

In practice, however, the semiconductor switches of the inverter are not loss-less, and therefore the energy stored in the DC capacitor would be used up by the internal losses of the inverter. These losses can be supplied from the AC system itself by making the inverter voltage lag the line current by somewhat less than 90 degrees. The typical deviation from 90 degrees is a fraction of a degree. In this way, the inverter absorbs a small amount of real power from the AC system to replenish its internal losses and keep the DC capacitor voltage at the desired level. This control procedure can also be applied to raise or reduce the DC capacitor voltage by making the inverter voltage lag the line current by an angle smaller or greater than 90 degrees. Thereby, control the magnitude of the AC output voltage of the inverter and the degree of series compensation.

#### 4.6. Unified Power Flow Controller (UPFC)

The UPFC may be considered to be constructed of two VSCs sharing a common capacitor on their DC side and a unified control system. A simplified schematic representation of the UPFC is given in Figure 4-11.

The UPFC gives simultaneous control of real and reactive power flow and voltage amplitude at the UPFC terminals. Additionally, the controller may be adjusted to govern one or more of these criteria in any combination or to control none of them. This technique allows not only the combined application of phase angle control with controllable series reactive compensations and voltage regulation, but also the real-time transition from one selected compensation mode into another one to deal with particular system contingencies more effectively. For example, series reactive compensation could be replaced by phase-angle control or vice versa. This may become essentially important when relatively large numbers of FACTS devices will be applied in interconnected power grids, and control compatibility and coordination may have to be kept in the face of devices failures and system changes. The technique would also give considerable operating flexibility by its inherent adaptability to power system expansions and changes without any hardware alterations.

The implementation problem of the unrestricted series compensation is simply that of supplying or absorbing the real power that it exchanges with the AC system at its AC terminals, to or from the DC input sides of the inverter applied in the solid-state synchronous voltage source. The implementation in the proposed configuration called unified power flow controller (UPFC) [55] employs two voltage-sourced inverters operated from a common DC link capacitor; it is

shown schematically in Figure 4.11. This arrangement is actually a practical realization of an AC to DC power converter with independently controllable input and output parameters.

Inverter 2 in the arrangement shown is used to generate voltage  $V_B(t) = V_B \sin(\omega t - \delta_B)$  at the fundamental frequency with variable amplitude ( $0 \leq V_B \leq V_{Bmax}$ ) and phase angle ( $0 \leq \delta_B \leq 2\pi$ ), which is added to the AC system terminal voltage by the series connected coupling (or insertion) transformer. With these stipulations, the inverter output voltage injected in series with the line can be used for direct voltage control, series compensation, and phase-shift.

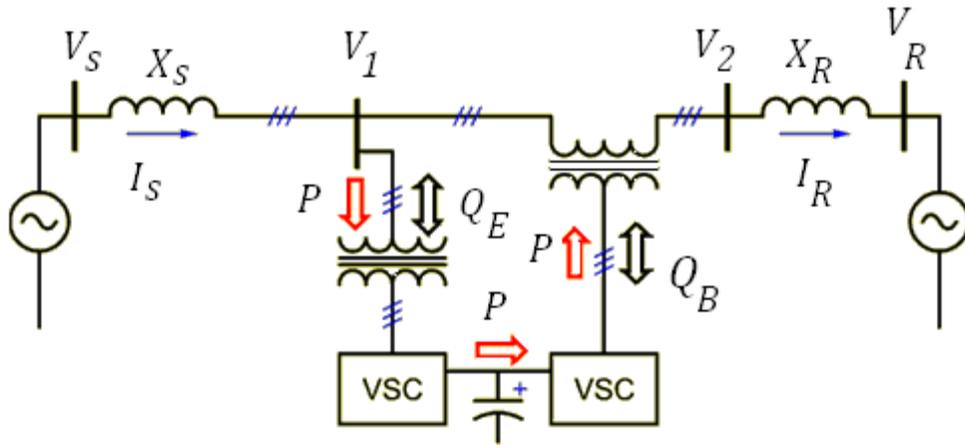


Figure 4-11 UPFC Schematic diagram

The inverter output voltage inserted in series with the line is considered mainly as an AC voltage source. The current flowing through the injected voltage source is the transmission line current; it depends on the transmitted electric power and the impedance of the transmission line. The product of the maximum injected voltage determines the VA rating of the injected voltage source of Inverter 2 and the maximum line current at which power flow control is still provided.

This total VA consists of two components: the first is the maximum active power, which is calculated by the maximum line current, and the maximum injected voltage component that is in phase with this current. The second is the maximum reactive power, which is calculated by the

maximum line current and the maximum injected voltage component that is in quadrature with this current.

It is evident that if the unified power flow controller is operated only with the phase angle reference input, it automatically acts as a perfect phase-shifter. It internally supplies the reactive power involved in the phase-shifting process and negotiates the necessary real power from the AC system. Since the active power component is generally smaller than the total VA demand resulting from phase-shifting, the rating of Inverter 1 would be normally less than that of Inverter 2, unless the “surplus” rating of Inverter 1 is, again, intentionally utilized for controllable reactive shunt compensation.

## 4.7 Comparisons of FACTS devices

### 4.7.1 SVC and STATCOM

<b>SVC</b>	<b>STATCOM</b>
An SVC operates as a shunt connected, controlled reactive admittance.	STATCOM functions as a shunt connected synchronous voltage source. This difference accounts for the STATCOM's superior functional characteristics, better performance, and greater application flexibility than those attainable with an SVC.
In the linear operating range the V-I characteristics and functional compensation capability are similar to an SVC	In the linear operating range the V-I characteristics and functional compensation capability are similar to an SVC
The maximum attainable compensating current of the SVC decreases linearly with the AC voltage.	In the non-linear operating range, the STATCOM is able to control its output current over the rated maximum capacitive or inductive range independently of the AC system voltage.

<p>An SVC does not have the capability to provide the active power compensation.</p>	<p>STATCOM can provide active power compensation in addition to the reactive power compensation.</p>
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4.7.2 SSSC and TSSC

<b>TSSC</b>	<b>TCSC</b>	<b>SSSC</b>
<p>TSSC is a impedance type series compensator</p>	<p>TCSC is a impedance type series compensator</p>	<p>SSSC is a voltage source inverter type series compensator</p>
<p>The compensating voltage of the TSSC over a given control range is proportional to the line current.</p>	<p>The TCSC can maintain compensating voltage with decreasing line current over a control range determined by the current boosting capability of the thyristor controlled reactor.</p>	<p>The SSSC is capable of internally generating a controllable compensating voltage over identical Inductive and Capacitive range independently of the magnitude of the line current.</p>

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<p>TSSC cannot exchange real power with the transmission line and can only exchange reactive power</p>	<p>TCSC cannot exchange real power with the transmission line and can only exchange reactive power</p>	<p>The SSSC has the inherent ability to interface with an external DC power supply to provide compensation for the line resistance by the injection of real power, as well as for the line reactance by the injection of reactive power for the purpose of keeping the effective X/R ratio high, independently of the degree of series compensation.</p>
<p>The TSSC uses conventional thyristors (with no internal turn-off capability). These thyristors are rugged power semiconductors, available with the highest voltage and current</p>	<p>The TCSC uses conventional thyristors (with no internal turn-off capability). These thyristors are rugged power semiconductors, available with the highest voltage and current</p>	<p>The SSSC uses the GTO thyristors. These devices presently have lower voltage and current ratings and considerably lower short-term surge current ratings. They are suitable for short term bypass</p>

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<p>ratings, and they also have the highest surge current capability. For short-term use they also provide bypass operation to protect the associated capacitors during line faults.</p>	<p>ratings, and they also have the highest surge current capability. For short-term use they also provide bypass operation to protect the associated capacitors during the line faults.</p>	<p>operation only if the anticipated line fault current is relatively low. Therefore they need external fast protection during severe line faults by an auxiliary conventional thyristor by pass switch.</p>
<p>TSSC are coupled directly to the transmission line and therefore are installed on the high voltage platform. The cooling system and control are located on the ground with high voltage insulation requirements and control interface.</p>	<p>TCSC are coupled directly to the transmission line and therefore are installed on the high voltage platform. The cooling system and control are located on the ground with high voltage insulation requirements and control interface.</p>	<p>The SSSC requires a coupling transformer rated at 0.5 p.u. of the total series compensating range, and a DC storage capacitor. However, it is installed in a building at ground potential and operated at a relatively low voltage. Thus the installation needs low voltage insulation for the cooling system and a control interface.</p>

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<p>At rated line current the loss exhibited by the TCSC would be 0.5% of the rated VAr output.</p>	<p>At rated line current the loss exhibited by the TCSC would be 0.5% of the rated VAr output.</p>	<p>At rated line current the loss exhibited by the SSSC would be 0.7 to 0.9% of the rated VAr output</p>
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## 5 Microgrid Design & Control

This chapter gives an overview on microgrid configuration, modeling,controlling parameters and control modes in a microgrid.

### 5.1 Introduction

Figure 5-1 shows a microgrid architecture which consist of several busses. There is single connection to the main utility grid called Point of Coupling (PCC). CB1 in figure 1 means separation device works as an instant switch, which can disconnect grid from the microgrid whenever any fault occur in the microgrid. AC & DC loads are connected to their respective busses, these loads are subsidized by local generation. FACTS devices are connected to both load busses, marked as GP-EE. Corresponding FACTS for AC is MPFC and for DC is GPFC.

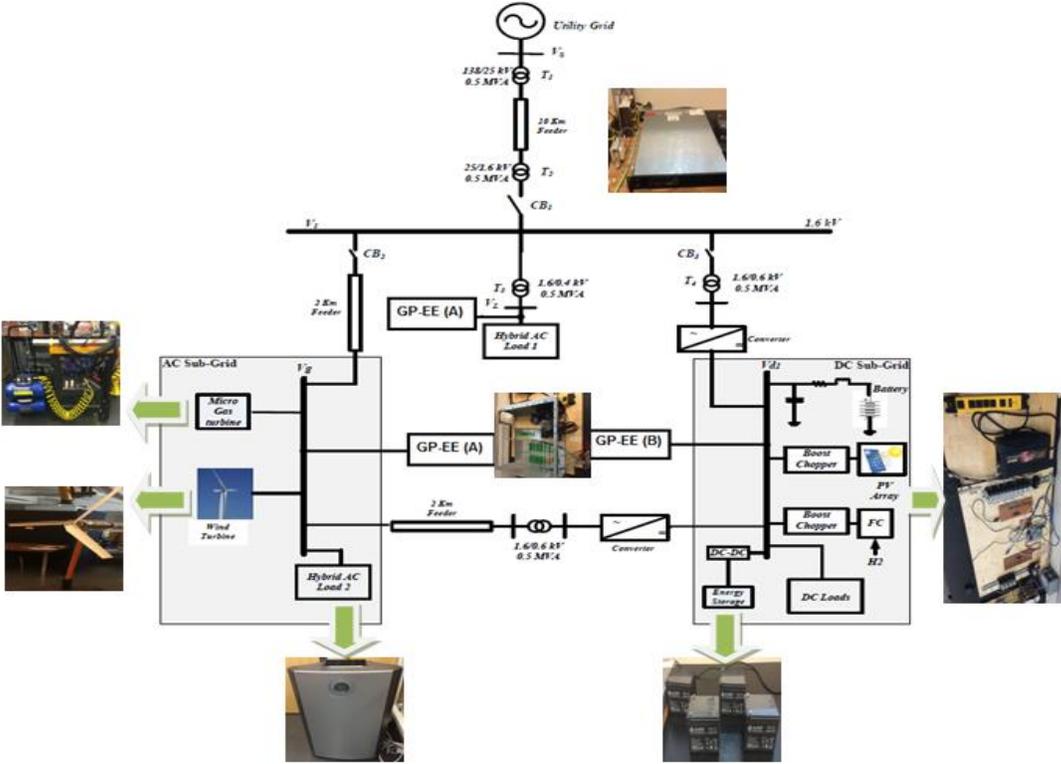


Figure 5-1 Mirogrid Architecture

The microgrid central controller works as a central control in power systems that controls distributed generator operations added to the microgrid [54].

### 5.2 Controlling in Microgrid

Main objective for microgrid is to inject or absorbed energy from the grid, control the power flows, and balance the voltage profile in grid. Generators, small storage devices, and loads are to be controlled to achieve these objectives. To connect distributed sources such as Wind turbines, PV, fuel cells or storage devices power electronic devices interfaces is used within the micro-grid [54]. According to [56] micro-grids are divided into different type of classes based on their controlling topology. Depending on their topology, microgrid control can be divided into three classes [55].

#### ***5.2.1 Simple Class or Virtual ‘Prime Mover’***

In this class, a central controller records the microgrid’s state variables and provides information to all local distributed generators. This topology makes one central virtual power supply which control all system generation and distribution behavior. Central control is based on telecommunication system that provides sub system access. Whole microgrid system shutdown if communication to the central control breaks. Also there are limited numbers of distributed generators channels are available. If all channels are full the central controller has to be replaced.

### ***5.2.2 Master Class or Physical ‘Prime Mover’***

In this class a separate and bigger central controller is installed within the microgrid. Mainly a generator or an energy storage device. Central controller works as a “master” to control all transient flows and balance the voltage profile in microgrid with utility grid (islanded connection). The other sources work as a “slave” that injects current to the microgrid buses. As one large central control all sources, it has some disadvantages too, as all control depends on one master controller, system reliability also depends on master unit. In future if any loads needed to increase in the microgrid results in resizing of central controller to adopt load changes.

### **5.2.3 Peer to Peer or Distributed Control**

In this class each unit provides automatic variations for local variables such as power flow or voltage magnitude. This local control accommodates transient or local behavior. Each controller in microgrid has to ensure enough computational frequency to be able to secure stable operation in the microgrid. For ensuring frequency and voltage stability an ‘intelligent’ local controller is provided at each generation source location. On islanded connection mode, power flow in microgrid has to balance loads and sources without voltage variations. In the Table 5.1, the different methods of controlling microgrid and their characteristics are described.

## Design and Control of FACTS-based high performance Microgrid

*Table 5-1* Microgrid control method classifications [56]

	<b>Simple or “Virtual Prime Mover”</b>	<b>Master Control or Physical “Primer Mover”</b>	<b>Peer to Peer Control or Distributed Control</b>
<b>Specific Characteristics</b>	All sources acts as one central power plant	One “Master” generator control the voltage level and the “Slave” generators works as a current sources.	Each sources have their own local controller that controls frequency, voltage stability.
<b>Common Characteristics</b>	Several sources are injecting power on several loads in multiple locations. All the sources are connected to the microgrid bus. Every event are detected and response are controlled		

5.3 DER control

There are two main functions of DER control are

- (i) real- and reactive power control in the grid-connected mode
- (ii) Frequency and voltage regulation of microgrid in islanded mode

5.4. Grid-Connected-Mode DER Control

Grid connected mode DER control works with the frequency and magnitude of system voltages, which are provided by the grid controlled by utility. The main task in grid connected mode is to control active and reactive power exchange within the local networks. For regulation of output powers it can use current or voltage mode control technique. In Figure 5-2 defines a simplified schematic diagram of a voltage-controlled DER system, DER system is connected with the grid through a three phase inductor  $L$  and Voltage-Sourced Converter (VSC). In voltage mode control strategy, the output active and reactive powers ( $P_o$ ,  $Q_o$ ) are controlled through phase-angle and magnitude of the VSC on AC terminal voltage  $v_{abc}$  [57].

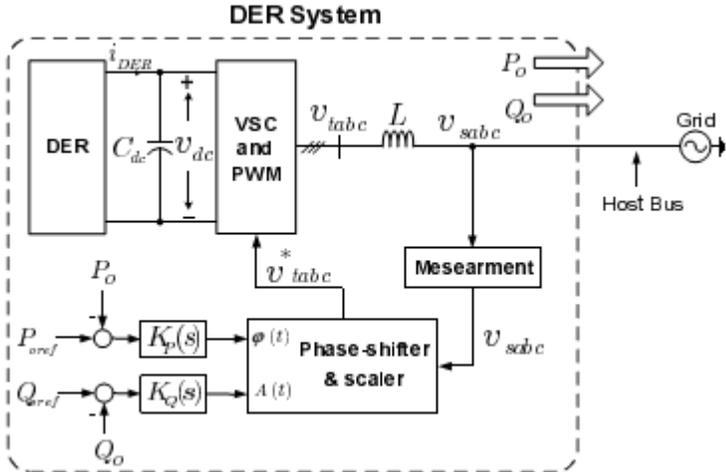


Figure 5-2 diagram of a grid-connected DER system with voltage mode [10]

Hence it conclude as every phase of voltage can added by VSC, ( $v^* abc$ ) is calculated from shifting the phase-angle and scaling the amplitude of the substitute phase of  $vsabc$  [57].

For the voltage-mode and current-mode control techniques of Figure 5-2 and 5-3 is used. The DER has been assumed to be ready to be dispatched, output real and reactive powers can be

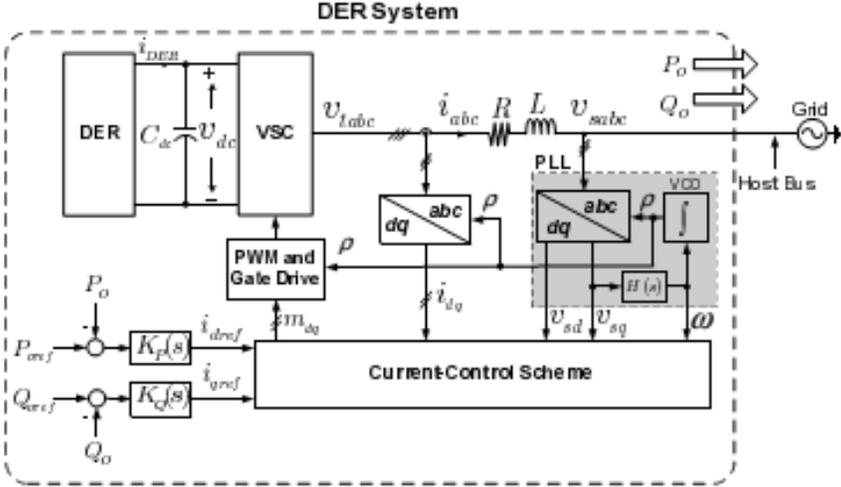


Figure 5-3 Schematic diagram of a grid-connected DER system with current mode [57]

controlled by the set points  $P_{oref}$  and  $Q_{oref}$  (which, in turn, are determined by the MCC). By contrast, the output powers of a non-dispatchable DER system are commonly the by-products of an optimal operating condition. For example, a PV system normally operates in the Maximum Power- Point Tracking (MPPT) mode [58], that is, it extracts the maximum possible power from its solar panels.

Figure 5-4 illustrates a simplified schematic diagram of a non-dispatchable DER system (e.g., a PV system [58]) in which the DER has been modeled by a dc voltage source whose voltage,  $v_{dc}$ , is related to its current,  $i_{DER}$ , through a  $v$ - $i$  characteristic. As Figure 5-4 illustrates, the kernel of the control system that is the real- and reactive-power control scheme (of Figure 5-3) by which  $P_o$  and  $Q_o$  can be controlled independently.

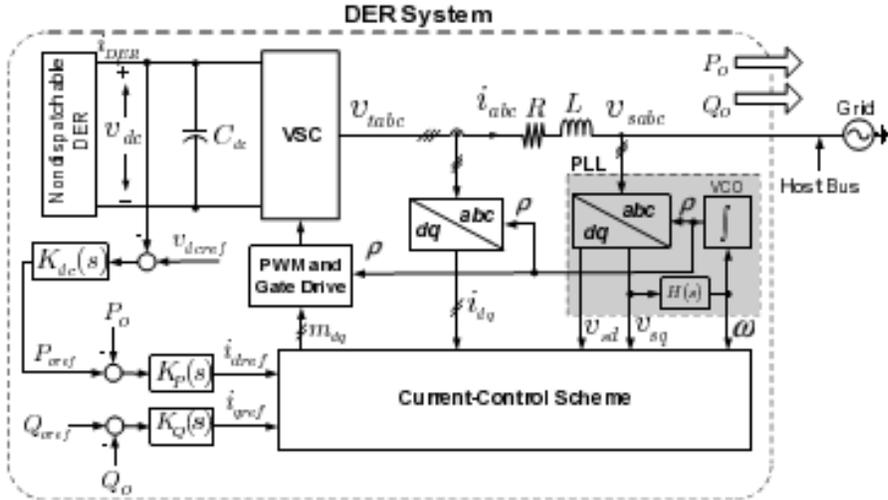


Figure 5-4 Schematic diagram of a grid-connected non-dispatchable DER system [57]

## 6 Control Design of FACTS-Based Microgrid

This chapter gives an overview on modeling and design of microgrid with FACTS devices. Also including the equations involved with different generation units which are PV, gas turbines, wind turbines, fuel cells and batteries.

The proposed microgrid design has modeled with FACTS devices on both AC and DC loads busses. Modulated power filter compensators (MPFC) are used at AC side to improve voltage stability, reduce harmonic current and power loss. Also green plug filter compensators (GPFC) are added at the DC-side FACTS device to stabilize DC voltage performance. Multi-loop error driven control strategies are configured for the converters to properly benefit the AC and DC buses with their FACTS. Intelligent algorithm using genetic algorithm is used for self-tune the converter and FACTS controllers gain.

### 6.1 Hybrid AC/DC Microgrid Design

The design of the hybrid AC/DC microgrid system is pictured in Figure 6-1, a connected meshed microgrid with different AC and DC sources and loads are connected to their alternating sub grids. Also these loads are connected to utility bus with hybrid local loads. The AC and DC grid is linked to utility sub grid with 10km and 5km feeder respectively. At AC sub grid a step up transformer is used to boost up AC and with DC sub grid a step down transformer is used. AC and DC both grid are also connected with AC/DC, DC/AC converter and inverter to exchange a hybrid connection in the grid. All parameters for microgrid loads, FACTS, DER and other sources specifications are mentioned in the Appendix section.

Design and Control of FACTS-based high performance Microgrid

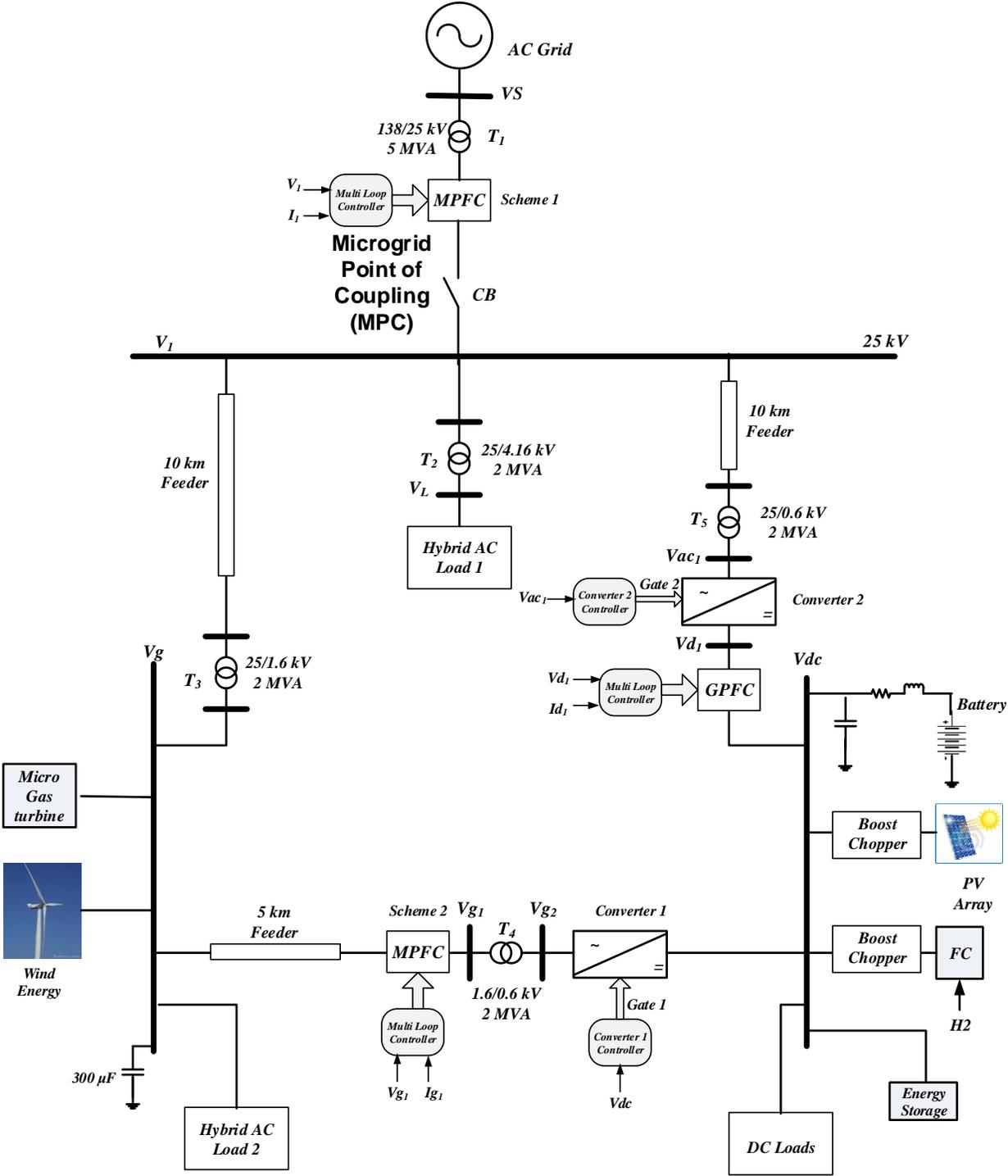


Figure 6-1 Hybrid AC/DC microgrid

# Design and Control of FACTS-based high performance Microgrid

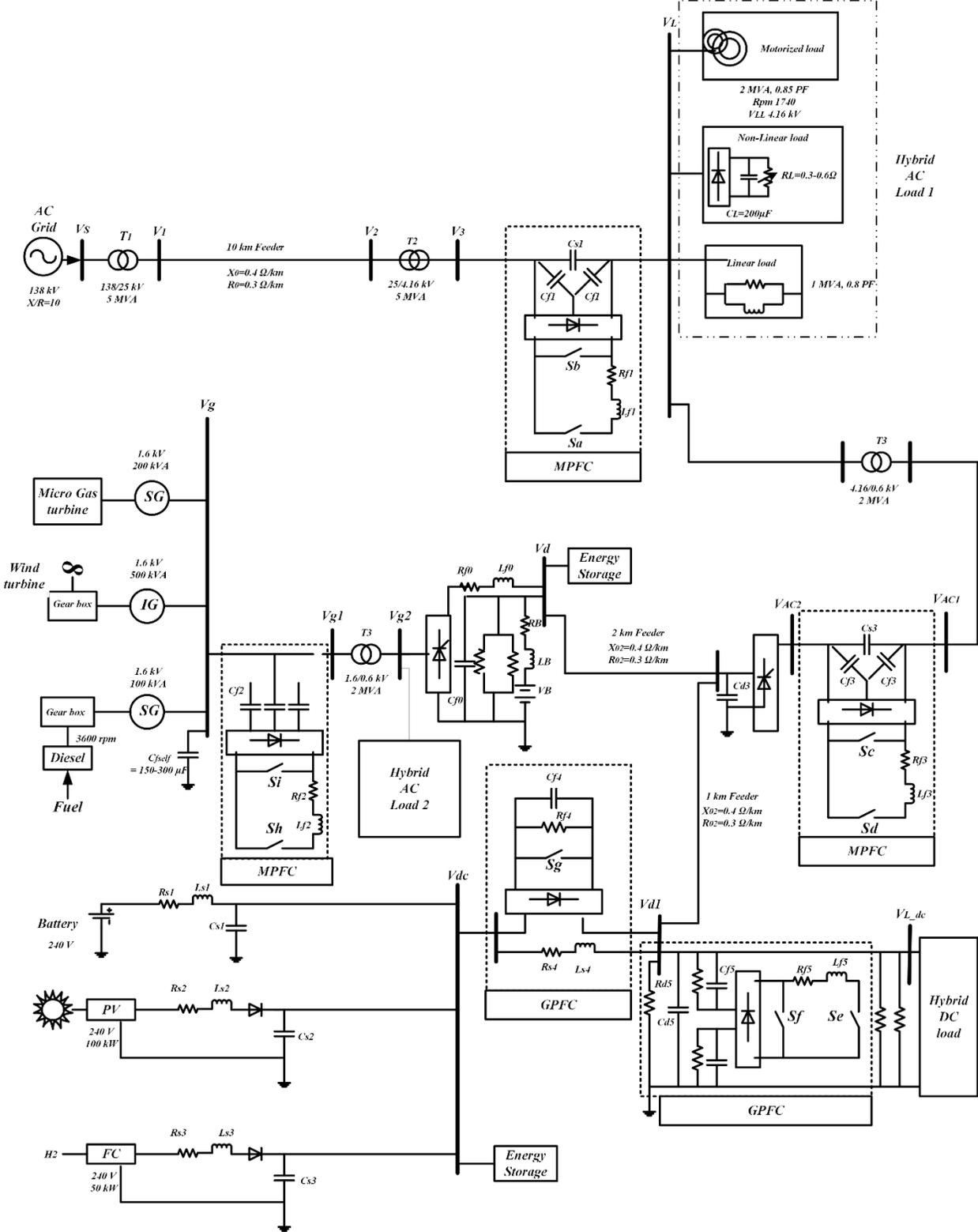


Figure 6-2 Full schematic of AC/DC microgrid

## 6.2 Modeling of the hybrid AC/DC Microgrid

This chapter discuss the modeling concepts of hybrid AC/DC micrgird. Also description about DER modeling and their configuration characteristics.

### 6.2.1 Wind turbine

Wind turbine is the world's very old and renewable energy source, it is world rapid growing renewable source. In figure 6-3 an wind growing capacity is shown from 1997-2014

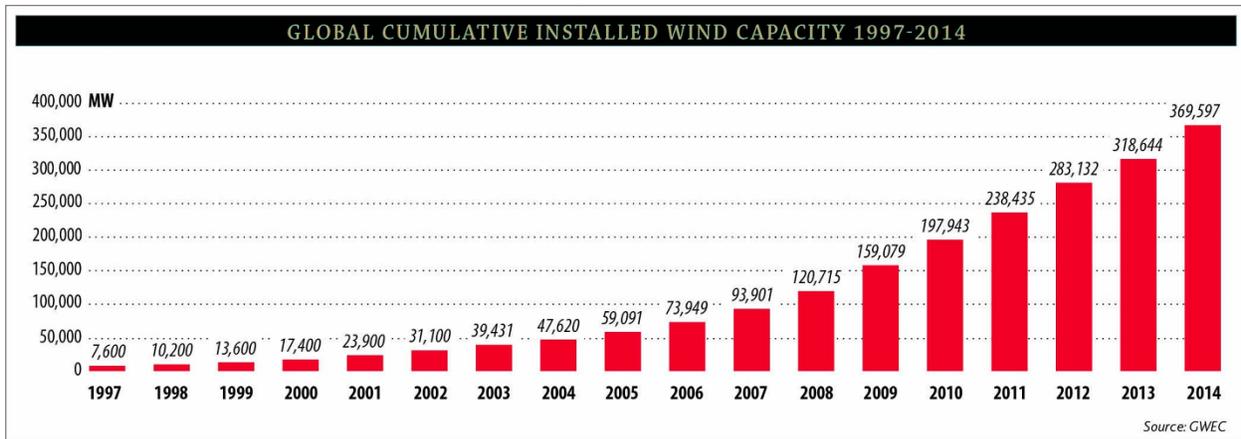


Figure 6-3 Installed global wind capacity (1997 - 2014) source: gwec.net

In wind systems several different generators systems are used, these generators are depends upon wind turbine speed variable or fixed. Fixed speed turbine are mainly used with induction topologies. Some other topologies that are used in wind turbine systems are [52]:

- Synchronous generator multi pole
- Permanent magnet synchronous generator multi-pole
- Wounded rotor induction generator
- Synchronous generator

## Design and Control of FACTS-based high performance Microgrid

Wind turbines also use power electronic device interface, which allow variable frequency of generator to be converted to grid frequency. In following Table 6.1, different wind turbines systems are defined with specific characteristics

*Table 6-1 Wind Turbine Systems [52]*

<b>Wind turbines</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>	<b>G</b>	<b>H</b>	<b>I</b>
<b>Speed</b>	Fixed	Fixed	Fixed	Limited range	Variable	Variable	Variable	Variable	Variable
<b>Generator</b>	Induction	Induction	Induction	Wound rotor Induction	Double-Fed Induction	Induction	Synchronous	Synchronous Multi-Pole	PM-Synchronous Multipole
<b>Power converter</b>	No	No	No	Partially rated	Partially rated	Full Scale	Full scale	Full scale	Full scale
<b>Aerodynamic control</b>	Pitch	Stall	Active Stall	Pitch	Pitch	Pitch	Pitch	Pitch	Pitch
<b>Gear Box</b>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No

A fixed speed wind turbine is considered in this proposed design, shown in figure 6-4

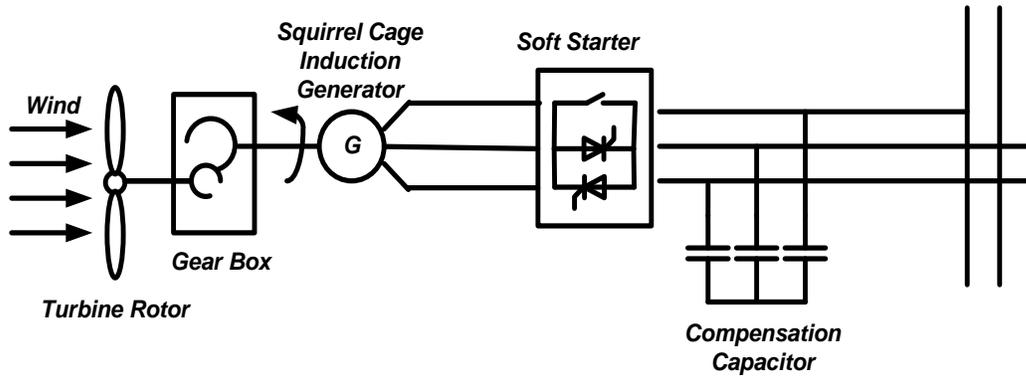


Figure 6-4 Wind turbine with fixed speed

From [23] an equation for output is derived as:

$$P_m = 0.5\rho AC_p(\lambda, \beta)V_w^3 \quad (6.1)$$

Where

$\rho$  = air density,

$A$  = rotor swept area,

$V_w$  = wind speed,

$C_p(\lambda, \beta)$  = the power coefficient with function of tip speed ratio  $\lambda$  and pitch angle  $\beta$ .

Wind turbine output power depends on  $C_p$  which is a power coefficient under constant wind speed. For maximum power from wind turbine,  $C_p$  have to control for optimum values of turbine rotating speed and pitch angle. Standard active controller is the controller of machine. Wind turbine is controlled with a soft starter and bank of capacitors in the grid.

6.2.2 Photovoltaic

Photovoltaic (PV) generation usage are increasing significantly, due to their noise less and small size, PVs becoming famous day by day. In figure 6-5, an overview of current installed and forecasted PV solar capacity are shown.

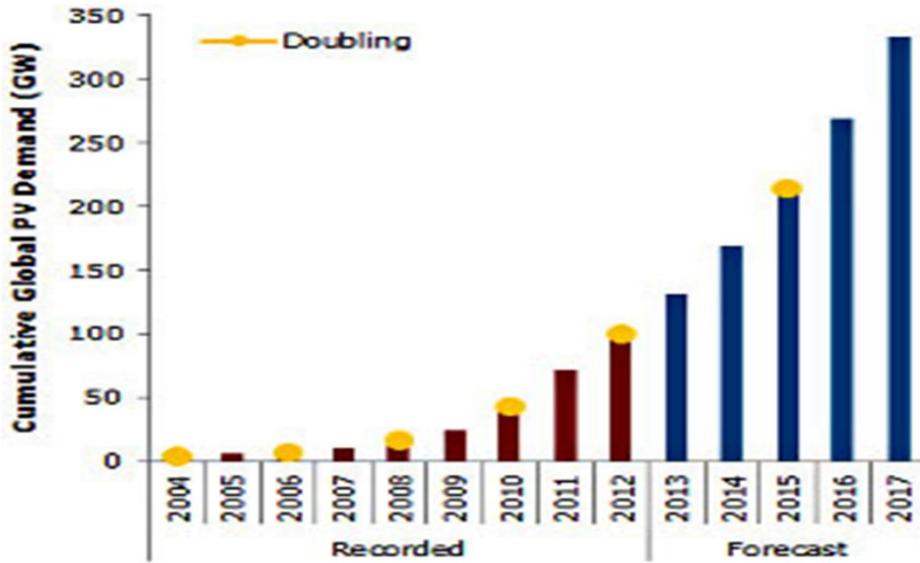


Figure 6-5 Recorded and Forecasted PV Capacity. Source: ewind.es

A series and parallel combination of PV cells constitute a PV array. The simplified equivalent circuit of the PV array is used where the output voltage is a function of the output current while the current is a function of load current, ambient temperature and radiation level [47]. The current and voltage equation of the PV is defined by [47]:

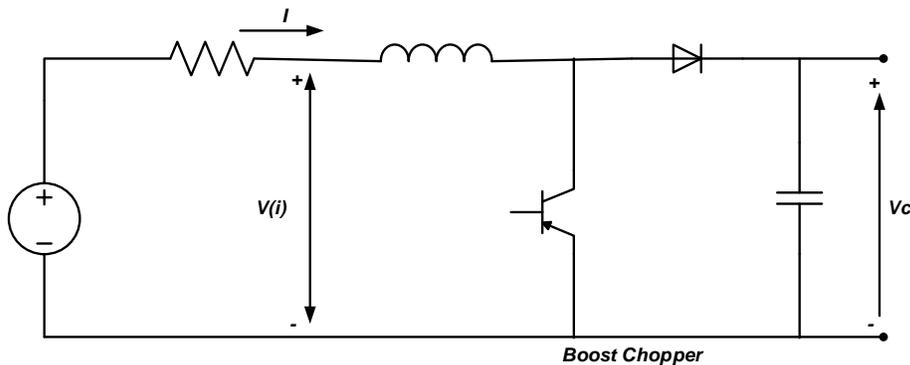
$$V_{PV} = \frac{AkT_c}{e} \ln \left( \frac{I_{ph} + I_o - I_c}{I_o} \right) - R_S I_c \quad (6.2)$$

where A is a constant value for curve fitting, e is the electron charge ( $1.602 \times 10^{-19}$  C), k is Boltzmann constant ( $1.38 \times 10^{-23}$  J/K),  $I_c$  is the output current of PV cell,  $I_{ph}$  is the photocurrent

(1 A),  $I_o$  is the diode reverse saturation current (0.2 mA),  $R_s$  is the series resistance of PV cell ( $1\text{m}\Omega$ ),  $V_{PV}$  is the output voltage of PV cell and  $T_c$  is the PV cell reference temperature ( $25^\circ\text{C}$ ). The output boost chopper controls the voltage  $V_{out}$  across the capacitor.

### 6.2.3 Fuel Cell

Fuel Cells are emerging as an attractive power supply source for applications such as distributed generation and small grids because of their high efficiency and high reliability [48]. A typical PEMFC (proton exchange membrane fuel cell) are connected in series/parallel for desired output rating. For regulating Fuel cell output DC voltage a boost chopper is used. An overall circuitry is detailed in following figure.



### 6.2.4 Energy Storage Batteries

Common energy storage lead acid batteries are used. These batteries are low cost, have fast response and have prolong half-life. These batteries power capacity are based on the size and geometry of electrodes. A standard 240 V battery is selected for current microgrid model.

### 6.2.5 AC and DC loads

As viewed in figure 6-1, there are following loads:

- Hybrid AC load 1, that are resistive load consist of an induction motor with a nonlinear load which is combination of harmonic and unbalance load.
- Hybrid AC load 2, consist of different ratings but same loads as AC load 1.
- DC loads, consist of resistive load connected with series DC motor.

### 6.2.6 FACTS Devices

Two types of FACTS devices used in current AC/DC microgrid

#### **Modulated Power Filter Compensator (MPFC):**

The circuitry diagram shown in Figure 6-7, which is consists of one series and two shunt capacitor banks including a tuned arm power filter. The output path for shunt capacitors is created by the diode rectifier having resistance ( $R_f$ ) and inductance ( $L_f$ ) for tuned arm filter at the rectifier's DC length [49, 50]. Two IGBT switches ( $S_a$  and  $S_b$ ) are controlled by two adjacent switching signals ( $P_1$  and  $P_2$ ), as viewed in figure 6-6. These signals are created by dynamic multi-loop error driven in PID controller. Then feed to the PWM switching circuit to control IGBT switches.

The MPFC can be substituted in following cases;

Case 1: If  $P_1$  is high and then  $P_2$  is low, the resistor and inductor will be connected into the circuit as a tuned arm filter.

Case 2: If P1 is low and P2 is high, the resistor and inductor of the arm filter will be fully shorted and the combined shunt and series capacitors will provide the required shunt and series capacitive compensation to the AC distribution system.

**Green Plug Filter Compensator (GPFC):**

The main reason to adding FACTS at the DC side of microgrid is to enhance DC performance and to stabilize buses voltages. GPFC compensation block diagram can be viewed in figure 6-8, introducing a switching signal through PID controller. GPFC will regulate DC bus voltage and decrease inrush current sampling transients and also for FC and PV nonlinear Volt-Ampere characteristics.

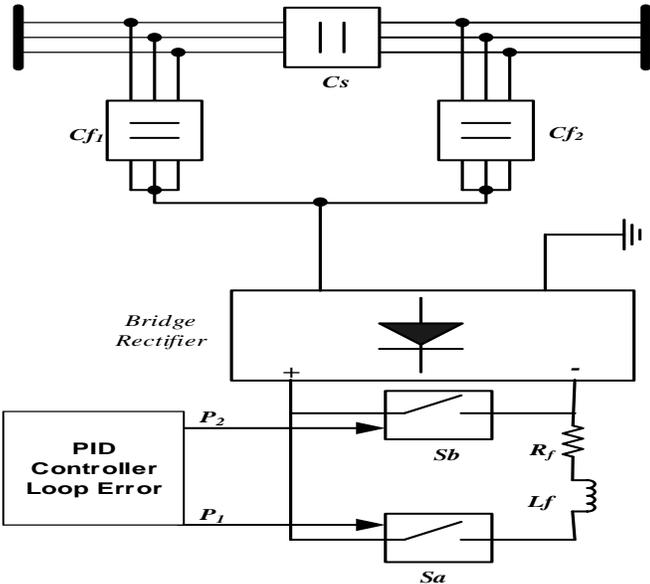


Figure 6-6 Modulated Power Filter Scheme

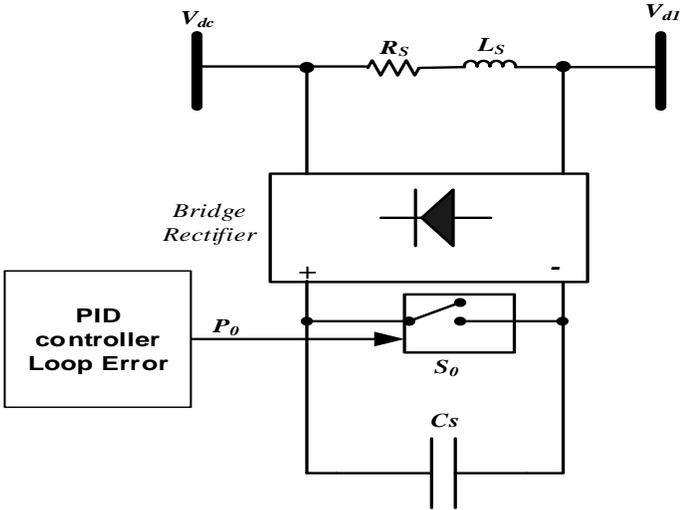


Figure 6-7 Green Plug Filter Compensator Scheme

### 6.3 Control Design

For controlling all FACTS device PID controller are used, that can control whole microgrid performance. PID controller is a set of three controllers by names are proportional, integral, derivative controller. An optimal method for tuning PID controller which includes time varying delays is considered in current microgrid scheme. PID controller's parameters are considered as function of the time constant.

#### 6.3.1 PID Controller

PID controller is mainly used in many industrial application because of its easy control strategy, cheap cost and simple design. But mainly the performance of PID controller is very bad for highly nonlinear and uncontrolled loads schemes. In PID, proportional controller uses 'portion' of system error to control whole system output, Integral controller's output is proportional to the length of time error present in the system, lastly derivative controller is proportional to the rate at which error changes in the system. By using proportional controller an offset of error is introduced in the system, by integral controller this offset error is removed from the system and by derivative controller overshoot in the system is reduced. PID control scheme for current control model using time varying dependent is described as:

$$\Delta u(t) = kcTs \frac{kcTs}{TI} e(t) - kc(\Delta + \frac{TD}{Ts} \Delta^2) y(t), t = 0.1, 2, \dots \dots \dots (6.3)$$

Where

$u(t)$  = The control variable,

$e(t)$  = The control error signal,

$e(t)=y_{ref}(t)-y(t)$

$y_{ref}(t)$  = The reference value,

$y(t)$  = The system output.

$k_c$ ,  $TI$  and  $TD$  are the proportional gain, integral and the derivative time, respectively.

For controlling FACTS devices and other converter following are controlled through PID are:

- MPFC
- GPFC
- AC/ DC converter

**6.3.2 MPFC controlling:**

For controlling modulated power filter compensator a multi-loop error driven dynamic controller is added in coordinate with PWM switching. The multi-loop global error ( $e_1$ ) is the sum of the multi-loop individual errors including synthesis dynamic power loops, voltage stability and current limiting. Error vector ( $e_V$ ,  $e_I$ ,  $e_P$ ) and global error ( $e_1$ ) are evaluated by the following equations:

$$e_{V_1} = \frac{V_{1ref} - V_1 \left( \frac{1}{1+ST_1} \right)}{V_{1base}} \quad (6.4)$$

$$e_{I_1} = \frac{I_{1ref} - I_1 \left( \frac{1}{1+ST_1} \right)}{I_{1base}} \quad (6.5)$$

$$e_{P_1} = \left( \frac{V_1}{V_{1base}} \times \frac{I_1}{I_{Lbase}} \right) - \left( \frac{V_1}{V_{1base}} \times \frac{I_1}{I_{Lbase}} \right) \left( \frac{1}{1+ST_2} \right) \quad (6.6)$$

$$e_1 = \gamma_{V_1} |e_{V_1}| + \gamma_{I_1} |e_{I_1}| + \gamma_{P_1} |e_{P_1}| \quad (6.7)$$

The output of the PWM generator is a series of pulses with varying duty cycles and constant frequency. MPFC scheme for voltage controlling in the system can be defined by:

$$V_{C1}(t) = K_{P1} e_1(t) + K_{I1} \int_0^t e_1(t) dt + K_{d1} \frac{d(e_1(t))}{dt} \quad (6.8)$$

The filter arm modulation is achieved through two complementary pulses (Sa and Sb) governed by PWM. These signal are controlled through gate pulse which is dependent of switching frequency ( $f_{sw}$ ).

$$T_{Sw} = \frac{1}{f_{sw}} = T_{on} + T_{off} \quad (6.8)$$

Where

$f_{sw}$  = The switching frequency and  $0 < T_{on} < T_{sw}$

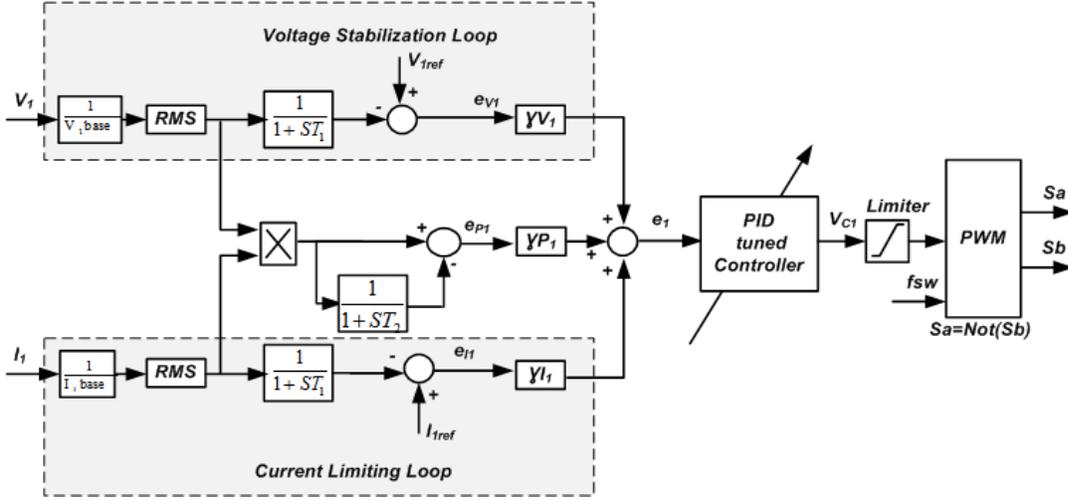


Figure 6-8 MPFC multi-loop error driven scheme

### 6.3.3 GPFC controlling

The GPFC control scheme is handled through voltage and decoupled current part of DC bus, shown in figure 6-9. Following are multi-loop error equations:

$$e_3 = \gamma_{V_{d1}} |e_{V_{d1}}| + \gamma_{I_{d1}} |e_{I_{d1}}| + \gamma_{P_{d1}} |e_{P_{d1}}| \quad (6.9)$$

$$e_{V_{d1}} = \frac{V_{d1ref} - V_{d1} \left( \frac{1}{1+ST_5} \right)}{V_{d1base}} \quad (6.10)$$

$$e_{I_{d1}} = \frac{I_{d1}}{I_{d1base}} \left( \frac{1}{1+ST_5} \right) \left( 1 - \frac{1}{1+ST_6} \right) \quad (6.11)$$

$$e_{P_{d1}} = \left( \frac{V_{d1}}{V_{d1base}} \times \frac{I_{d1}}{I_{d1base}} \right) \left( 1 - \frac{1}{1+ST_6} \right) \quad (6.12)$$

GPFC scheme in the time domain for the controlling PID controller through PWM has following equations:

$$V_{C3}(t) = K_{P3}e_3(t) + K_{I3} \int_0^t e_3(t)dt + K_{d3} \frac{d(e_3(t))}{dt} \quad (6.13)$$

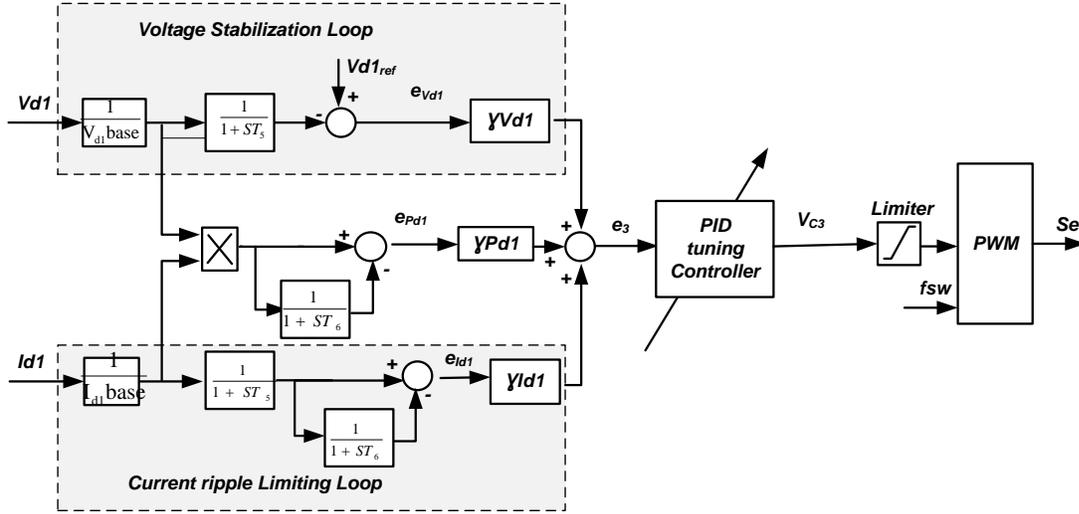


Figure 6-9 GPFC multi-loop error regulating scheme

**6.3.4 AC/DC Converter controlling:**

AC/DC control through by changing the pulses of duty cycle that used to change on/off state. By controlling that pulse DC output voltage of controller is stabilize.

For tuning and optimizing all controller that effect overall microgrid performance all controllers' gains are objected in optimization problem.

MPFC PID controller gains ( $K_{p1}$ ,  $K_{i1}$  and  $K_{d1}$ ),

GPFC PID controller gains ( $K_{p2}$ ,  $K_{i2}$  and  $K_{d2}$ ),

AC/DC converter 1 controller gains ( $K_{p3}$ ,  $K_{i3}$  and  $K_{d3}$ )

In current microgrid model shown in figure 6-1, two MPFC, two AC/DC converter and one GPFC are used. To minimize the sum of all controllers' errors:

$$J = e_1 + e_2 + e_3 + e_4 + e_5 \quad (6.14)$$

Current system has following Key Performance Indicators (KPI), by optimizing these KPI whole microgrid performance are optimized:

1) *The voltage stabilizations at the AC and DC buses:*

$$V_{min} \leq V_{bus} \leq V_{max} \quad (6.15)$$

2) *The feeder current capacity limit:*

$$0 \leq I_{Feeder} \leq I_{max} \quad (6.16)$$

3) *The power factor at the AC buses:*

$$PF_{AC} \geq PF_{ACref} \quad (6.17)$$

4) *The total harmonic distortion of the voltage (THD<sub>v</sub>) at the AC buses:*

$$THD_v < THD_{v,max} \quad (6.18)$$

The THD can be calculated by:  $THD_v = \frac{\sqrt{\sum_{h=2}^n V_h^2}}{V_1}$  (6.19)

5) *the total harmonic distortion of the current (THD<sub>i</sub>) at the AC buses:*

$$THD_i < THD_{i,max} \quad (6.20)$$

$$THD_i = \frac{\sqrt{\sum_{h=2}^n I_h^2}}{I_1} \quad (6.21)$$

The power balance equation of overall hybrid AC/DC microgrid is as follows:

$$P_{gAC} + P_{gDC} \pm P_S = P_{LAC} + P_{LDC} + P_{Losses}$$

Where

$P_{gAC}$ : Generated real power of the AC sources (Micro gas turbine and wind turbine)

$P_{gDC}$ : Generated power of the DC sources (PV, fuel cells, battery)

$P_S$ : Injected power from/to the utility grid.

**6.3.5 Genetic Algorithms**

The genetic algorithms (GAs); is used for optimizing above KPI. GA is inspired by Darwin’s reproduction and survival of fittest individual. GA searches for the fittest individual from a group of solutions known by population. These solution is corresponds to mutation, crossover and selection operators to find the best solution. The fitness function estimate the possibility of every individual. The selection operator selects the fittest individual. For variety and different scenarios crossover and mutation operators are used. Starting values or chromosomes are randomly generated and selected for the initial population. The crossover and mutation probability are constant from start till end of the function. The size of population is remain fixed throughout the process, with fittest chromosome in each generation is saved. Then saved chromosome is directly moved to the next step to be evaluate again until expected population is converged. The whole algorithm ends when the population consist of the fit or the optimal solution [61] – [63]. The optimal solution are presented a set of parameters, these parameters are known as ‘gene’. These genes are formed together to form a string called a chromosome.

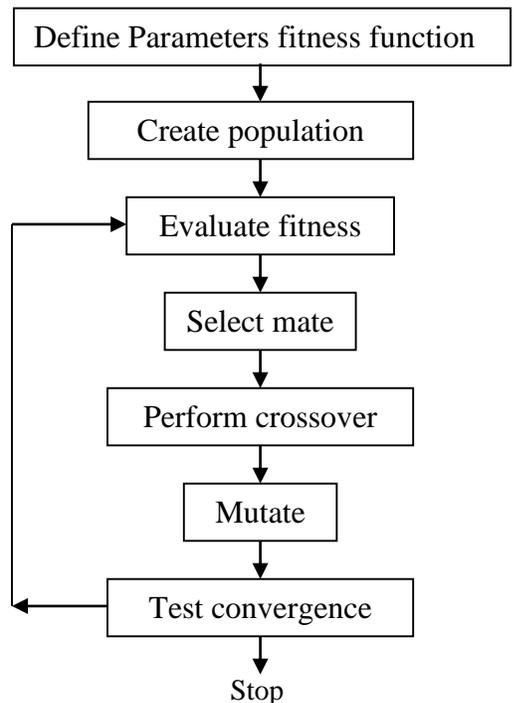


Figure 6-10 Overview of Genetic Algorithm

**6.3.6 Continuous-Parameter GA**

In the fitness function parameters are continuous, these function are represented as floating numbers. The fittest possible individual is selected by random generation considering the highest probability is selected. If  $P_1$  and  $P_2$  are chosen to perform crossover, the resulting crossover equation are to be:

$$P'_1 = r.P_1 + (1-r).P_2 \quad (6.22)$$

$$P'_2 = (1-r).P_1 + r.P_2 \quad (6.23)$$

Where

$r$  = random number between 0 and 1.

Non-uniform mutation is defined as follows, if an element  $P_k$  of a parent  $P$  is selected for mutation, the result would be:

$$P'_k = \begin{cases} P_k + (UB - P_k) f(gen) & \text{if a random digit is 0} \\ P_k - (LB + P_k) f(gen) & \text{if a random digit is 1} \end{cases} \quad (6.24)$$

Where

$UB$  and  $LB$  are the upper and lower bounds of the  $P_k$ ,

$gen$  is the current generation.

$$f(gen) = (r.(1 - \frac{gen}{gen\ max}))^b \quad (6.25)$$

$r$  = random number in the range [0, 1],

$genmax$  = The maximum number of generation,

$b$  = The shape parameter to calculate the non-uniformity.

**6.3.7 Self Tunning of PID Controller Using Genetic Algorithm**

Continuous genetic algorithm is used for current optimization problem. Self tuning of PID controller is done through genetic algorithms that simulated in MATLAB/ Simulink using GA toolbox [28]. It uses a low probability scheme usually in range of 0.001% to 0.01%. The function of mutation is to ensure that the probability for searching never becomes to zero and to works as safety wall to safe best genetic solution that lost in corresponding process. There are three option for mutation operator as it has multi non-uniformity distribution.

- The total number of mutations, with a probability of around 0.1%.
- The maximum number of generations.
- The shape of the distribution.

The genetic algorithm was initialized with a population of 30 and iterated for 50 generations. The bounds of the genetic algorithm reduced to a smaller range of numbers. The genetic algorithm code simulated the Simulink file, which includes the plant, and the RLS estimator. GA takes parameter estimates and start performing search through current values. GA optimization parameter are shown in Table 6-2. After possible solution GA updates all specified PID controller gains to get a stable system output. Through discrete poles values (real and imaginary) system stability is examined.

Table 6-2 GA optimization parameters

<b>Genetic Algorithm Parameter</b>	<b>Value</b>
<i>Population size</i>	30
<i>Maximum generation</i>	50
<i>Probability of crossover</i>	70 %
<i>Probability of mutation</i>	0.5 %
<i>Convergence tolerance</i>	1X 10 <sup>-6</sup>

### 6.3.8 Intelligent Controlling

Intelligent controlling means to make controller self-reliable, self-adjustable and self-tuned. Making a controller an intelligent controllers is to impose the controller with humanlike behavior. In current controlling strategy fuzzy logic algorithm is used. Fuzzy logic is a set of fuzzy values that clearly defined within boundary. These sets form a degree of membership. This membership Function (MF) shows every point as an input criterion to a membership values (0 and 1). In fuzzy logic controller the dynamic behavior of system is configured through defined set of rules. These rules in the form of

IF (a set of condition are matched, that added with fuzzy terms) THEN (a set of results can occur in the system)

6.3.9 Integration of GA with Fuzzy

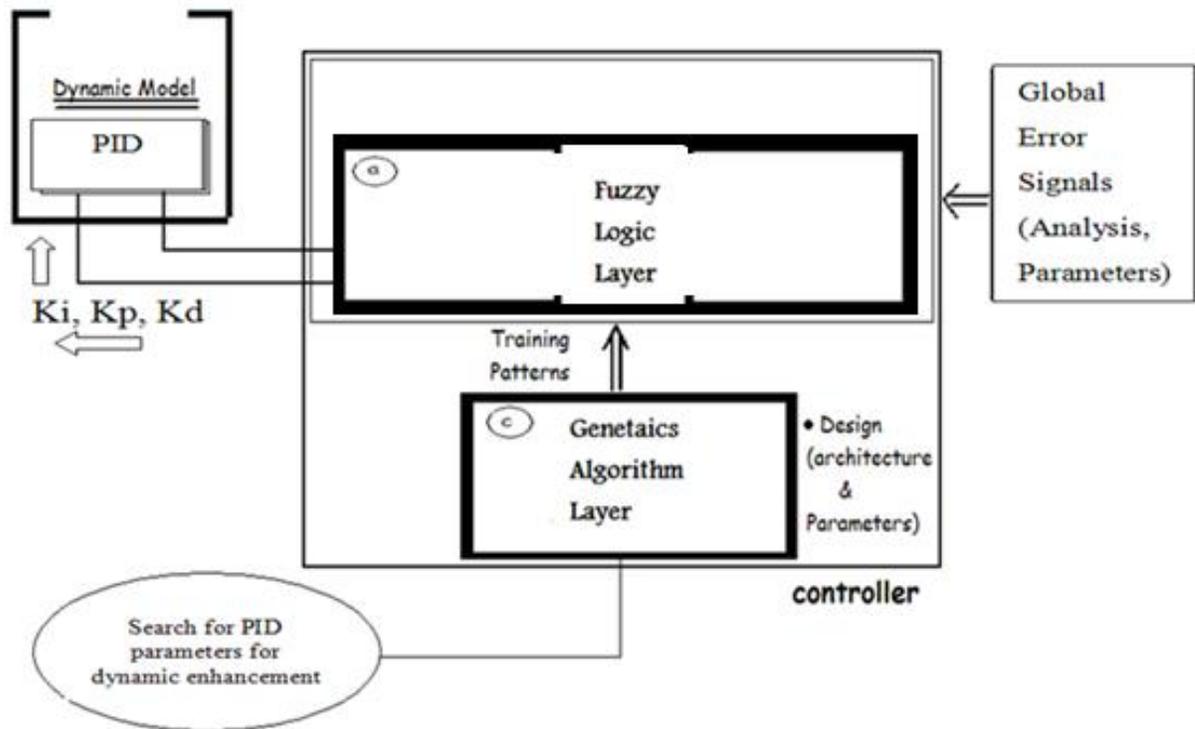


Figure 6-11 GA with Fuzzy

Integration of GA with Fuzzy logic Algorithm will enhance the dynamic response of the microgrid, that are done through controlling the PID gains. Firstly all possible best KPI values of microgrid are inputted in the GA to calculate an initial generation. By inspecting overall microgrid performance using random controllers' gains, best response of controller gains and KPI values are obtained. These values are used to self-tuned fuzzy system. These values are integrating in fuzzy system, figure 6-11 gives an overview of whole controlling of fuzzy integrating with PID and GA.

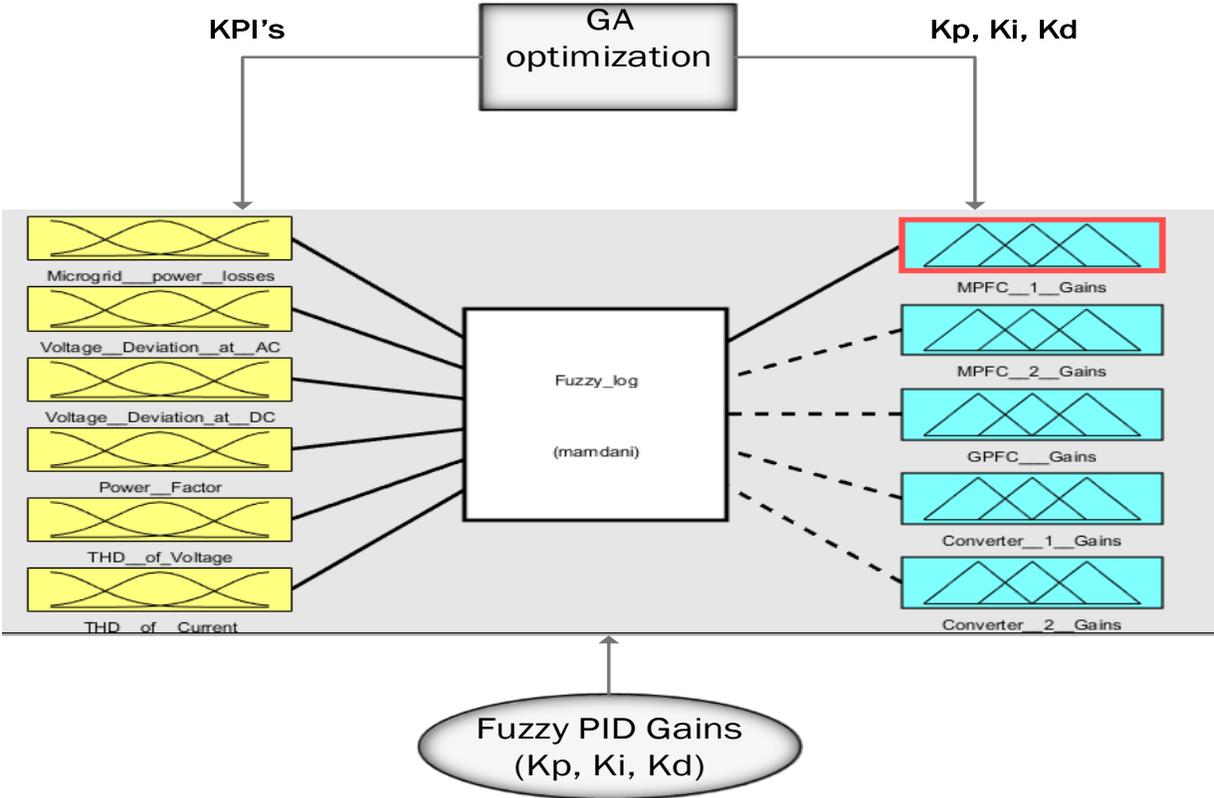


Figure 6-12 Fuzzy system tuning

In Figure 6-12, gives an overview of fuzzy system. It has KPI's of microgrid as input to the system and PID controllers gains as its output. After tuning and updating whole fuzzy system, best tuned controller gains are selected for the PID controller. This microgrid performance is more intelligent and reliable by using fuzzy gains for PID controller.

6.4 Matlab Simulation Block View

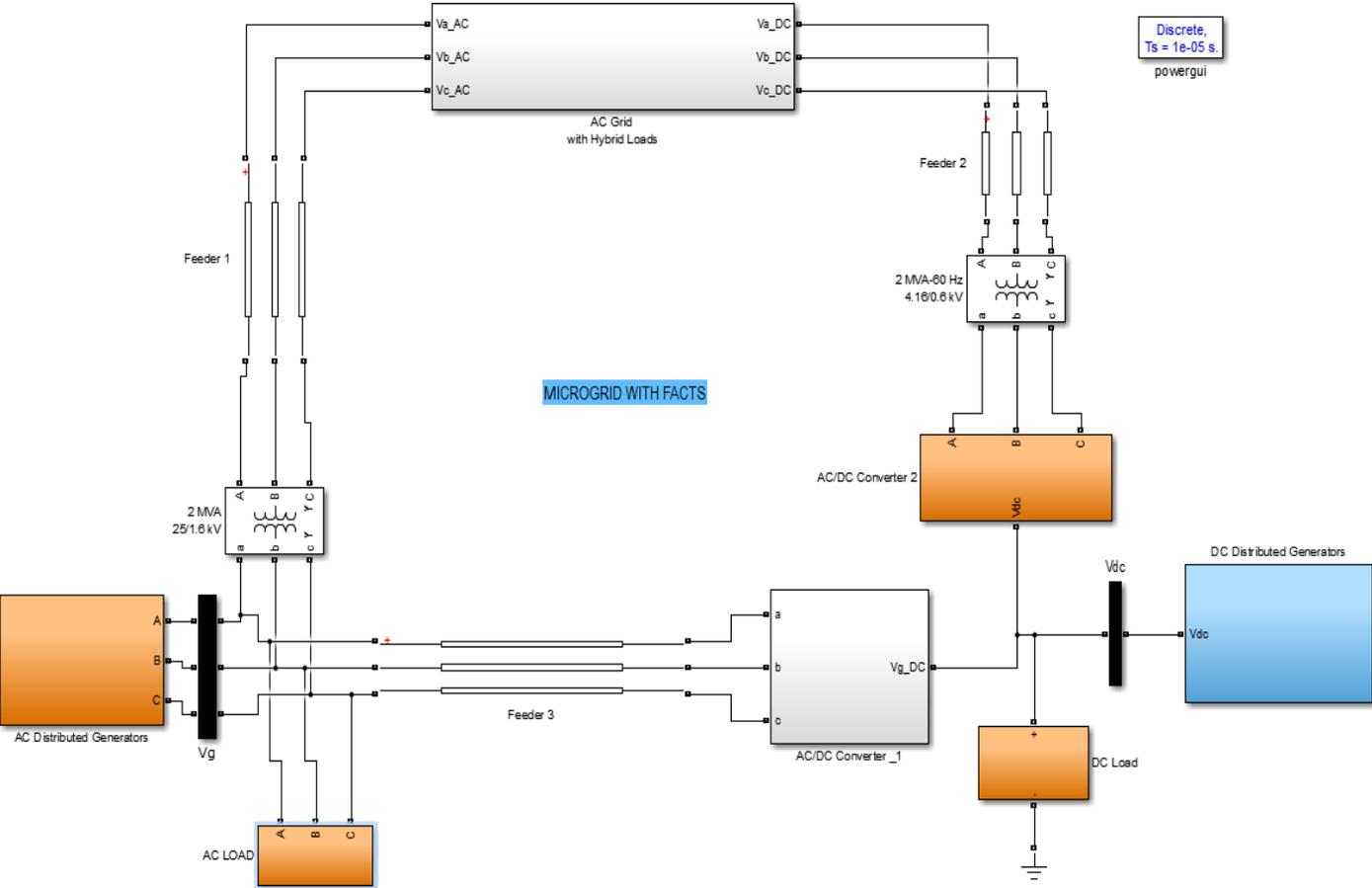


Figure 6-13 Simulink Block view Of Hybrid AC/DC microgrid

## 7 Simulation Results and Discussions

In this chapter simulation results is defined. Different scenarios are discussed with several parameters and configurations. These scenarios are consisted of

- Grid connected mode with FACTS using PID/Conventional Controller
- Islanded mode with FACTS using PID/Conventional Controller
- Grid connected mode with FACTS using Fuzzy Controller
- Islanded mode with FACTS using Fuzzy Controller

Each scenarios are compared with FACTS/ Without FACTS comparison.

### 7.1 Grid Mode With/Without FACTS using PID controller

In this mode Utility grid is still connected to the microgrid. Voltage, Line current, Reactive and power and power factor through all busses ( $V_s$ ,  $V_L$ ,  $V_g$ , and  $V_1$ ) are monitored. Conventional PID controller is connected to control all FACTS devices and converters.

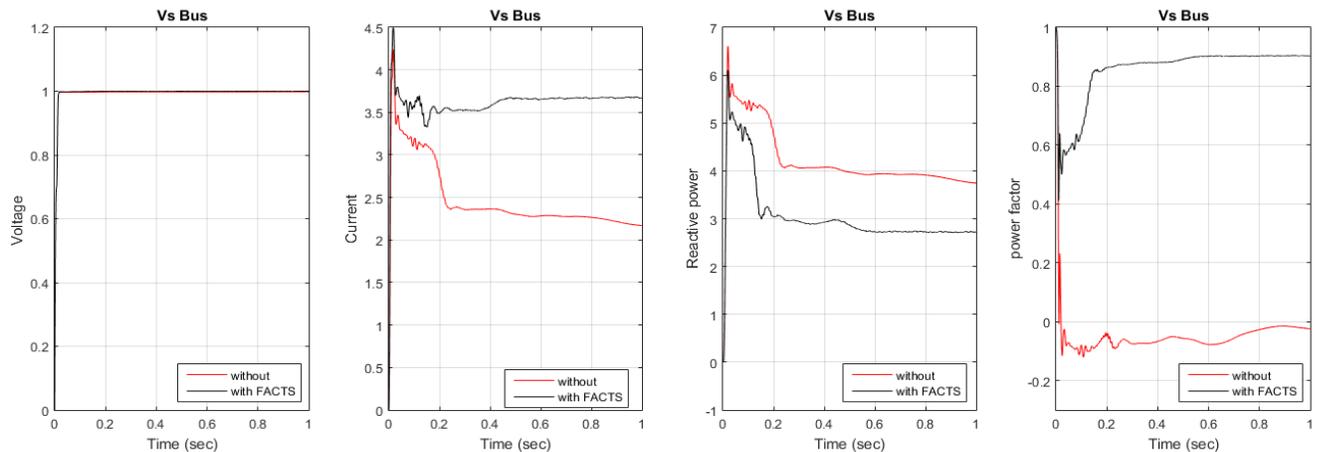


Figure 7-1 Voltage, Current, Reactive power and Power Factor at AC bus ( $V_s$ )

# Design and Control of FACTS-based high performance Microgrid

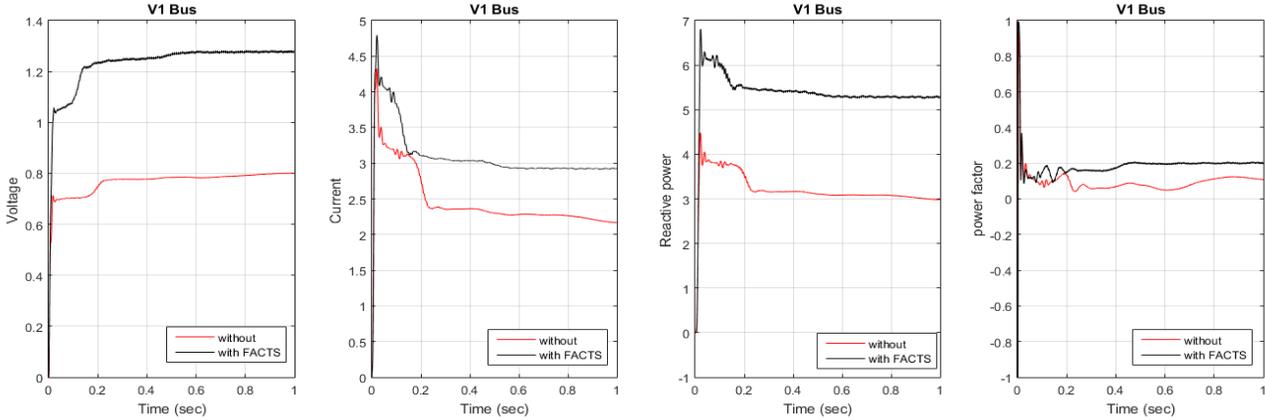


Figure 7-2 Voltage, Current, Reactive power and Power Factor at AC bus (V1)

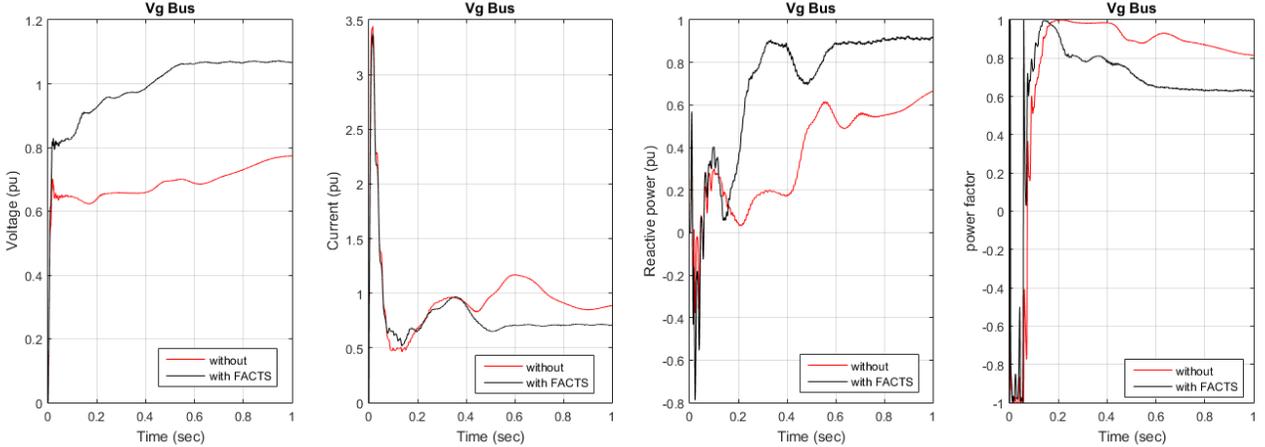


Figure 7-3 Voltage, Current, Reactive power and Power Factor at AC bus (Vg)

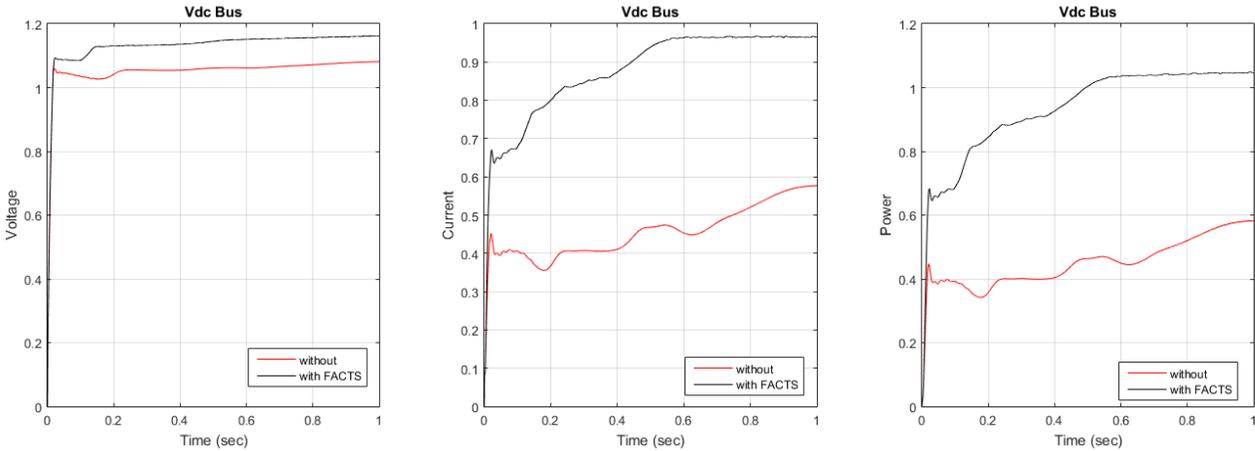


Figure 7-4 Voltage, Current and power at DC bus (Vdc)

## Design and Control of FACTS-based high performance Microgrid

*Table 7-1 Optimal values of PID controller*

	Optimal Values of PID Controllers Gains		
	<i>Kp</i>	<i>Ki</i>	<i>Kd</i>
<b>MPFC 1</b>	12	2.4	0.5
<b>MPFC 2</b>	15	5	0.2
<b>GPFC</b>	11	1.7	0.2
<b>Converter 1</b>	14	1.2	0.8
<b>Converter 2</b>	19	7	0.3

*Table 7-2 the %THD of voltage and current at all AC buses*

	<b>V<sub>s</sub></b>		<b>V<sub>1</sub></b>		<b>V<sub>L</sub></b>		<b>V<sub>g</sub></b>	
	<i>THD<sub>v</sub></i>	<i>THD<sub>i</sub></i>	<i>THD<sub>v</sub></i>	<i>THD<sub>i</sub></i>	<i>THD<sub>v</sub></i>	<i>THD<sub>i</sub></i>	<i>THD<sub>v</sub></i>	<i>THD<sub>i</sub></i>
<b>Without FACTS</b>	0.59	6.25	30.5	26	24.3	38	25	20
<b>With-FACTS</b>	0.2	4.65	4.72	4.57	4.6	4.72	3.51	4.3

In this scenario a good response is monitored, as shown in Figure 7-1 to 7-4. Comparison of FACTS devices is easily and widely recognize, as current microgrid design have high efficiency by using FACTS reactive power is decrease, line current is increased and power factor is improved, is shown in figure 7-1 at the utility bus  $V_s$ . After using FACTS increasing of power factor from 0.03 lead to 0.88 lag resulted as the reactive power from the micrgrid is transferred to the utility grid.

At the AC bus  $V_1$  voltage is stabilize and power factor is improved too, as shown in figure 7-2. From figure 7-3, Voltage profile at the  $V_g$  bus is also stabilized and improved (1 per unit) that

## Design and Control of FACTS-based high performance Microgrid

shows reactive power is fully compensated by FACTS. At the DC bus, voltage, current and power is stabilize and definite comparison of FACTS can be seen. In Table 7-2, THD for all busses are evaluated, this table shows the reduction in harmonic orders of microgrid voltage and current. Using FACTS all THD values for voltage and currents are improved and controlled to ensure them in within limits.

7.2 Islanded Mode With/Without FACTS using PID controller

In this scenario, utility grid is disconnected from the microgrid and connected DER uses to compensate loads needs. Control scheme is modeled with conventional PID controller.

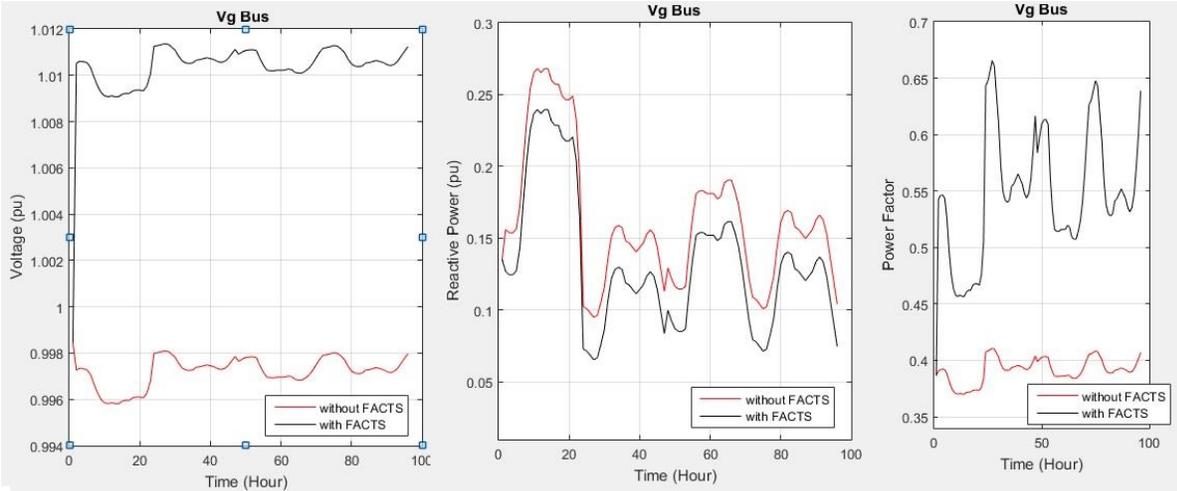


Figure 7-5 reactive power and Power factors at Vg buses

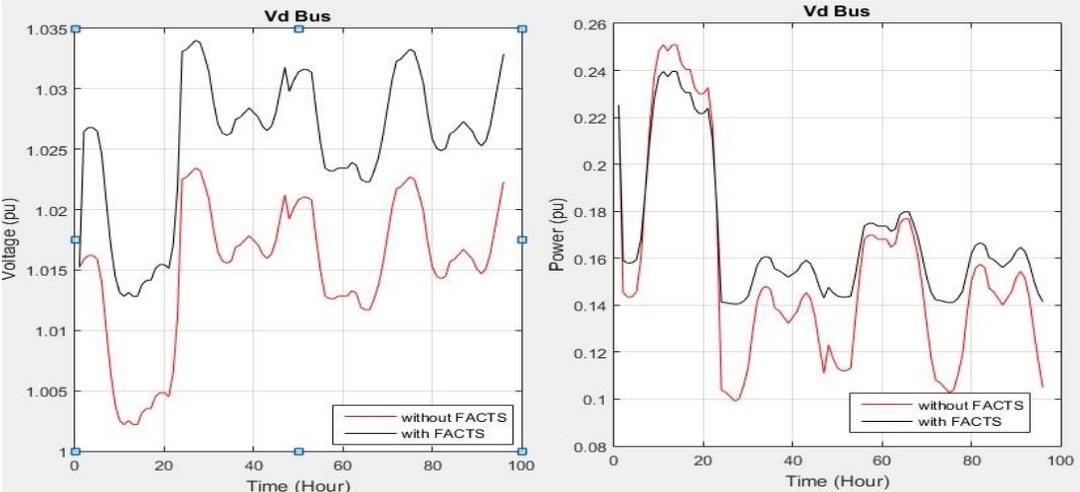
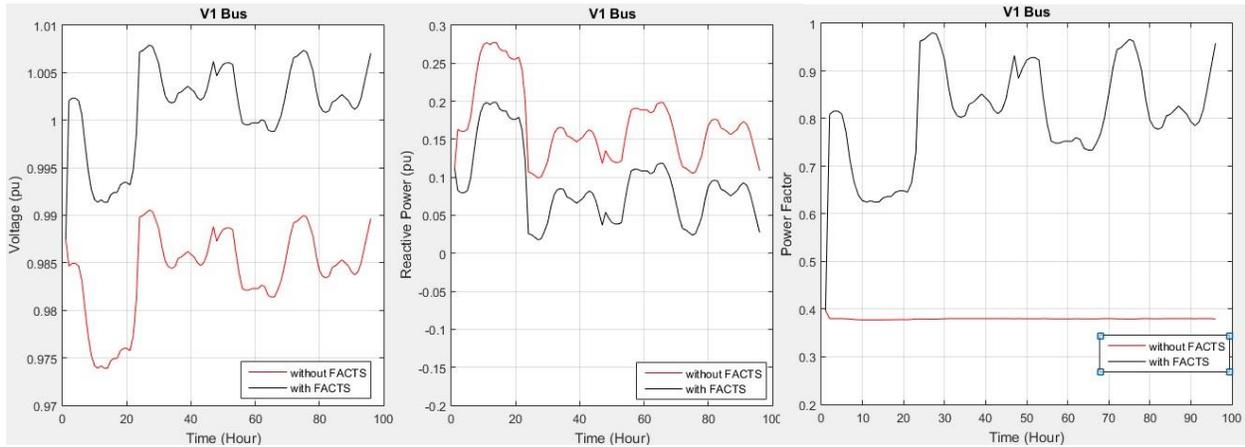


Figure 7-6 Voltage and power at Vd bus

## Design and Control of FACTS-based high performance Microgrid



*Figure 7-7 Voltage, Reactive power and Power factors at V1 buses*

*Table 7-3 Optimal values of PID controller*

	<b>Optimal Values of PID Controllers Gains</b>		
	<b><math>K_p</math></b>	<b><math>K_i</math></b>	<b><math>K_d</math></b>
<b>MPFC 1</b>	12	2.4	0.5
<b>MPFC 2</b>	15	5	0.2
<b>GPFC</b>	11	1.7	0.2
<b>Converter 1</b>	14	1.2	0.8
<b>Converter 2</b>	19	7	0.3

*Table 7-4 the %THD of voltage and current at all AC buses*

	<b>V<sub>1</sub></b>		<b>V<sub>L</sub></b>		<b>V<sub>g</sub></b>	
	<b>THD<sub>v</sub></b>	<b>THD<sub>i</sub></b>	<b>THD<sub>v</sub></b>	<b>THD<sub>i</sub></b>	<b>THD<sub>v</sub></b>	<b>THD<sub>i</sub></b>
<b>Without FACTS</b>	30.5	26	24.3	38	25	20
<b>With-FACTS</b>	4.5	3.5	4.7	4.4	4.2	4.6

## Design and Control of FACTS-based high performance Microgrid

All KPI shown in figure 7-5 to 7-7, shows the voltage profile, power factor and current is improved using FACTS. In Table 7-4, THD values for AC is calculated for voltage and current, as current microgrid performance criterion is in  $\pm 5\%$ . Through using FACTS THD of all busses are limited and controlled within normal regions, with significant high regional drops from 30.4 to 4.5 % at voltage harmonic order of V1 bus.

7.3 Grid With/Without FACTS using intelligent controller

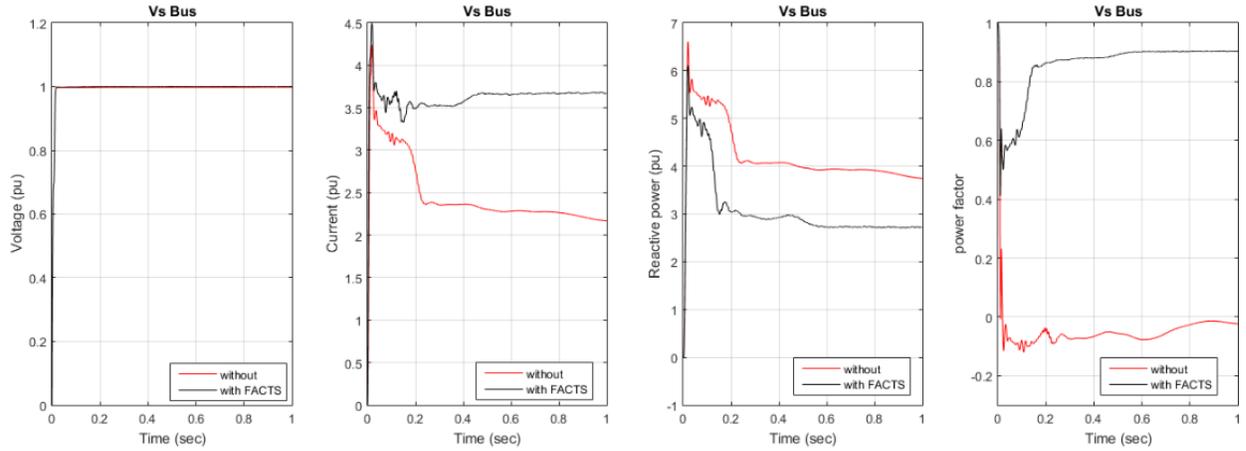


Figure 7-10 Voltage, Current, Reactive power and Power Factor at AC bus (Vs)

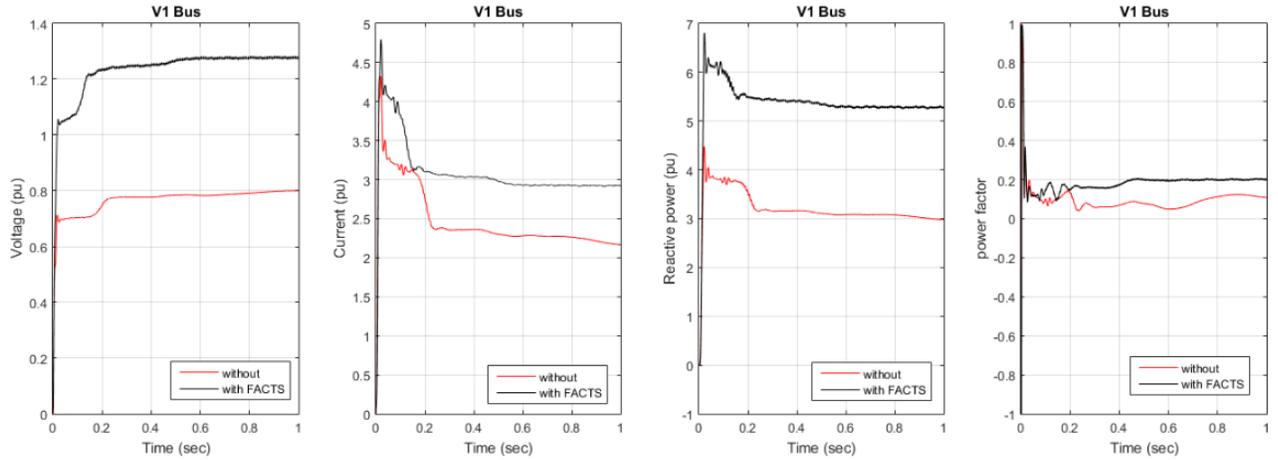


Figure 7-9 Voltage, Current, Reactive power and Power Factor at AC bus (V1)

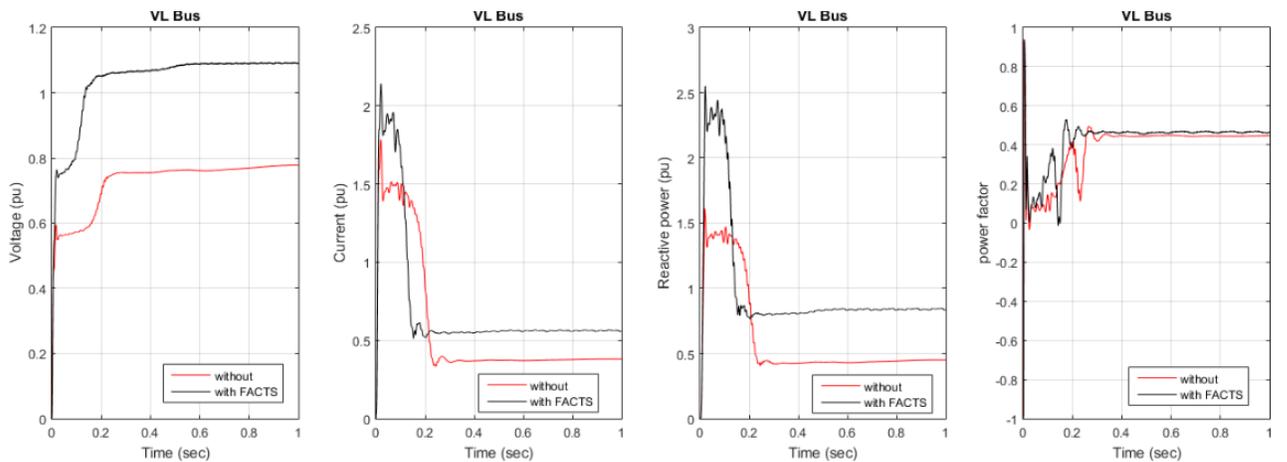


Figure 7-8 Voltage, Current, Reactive power and Power Factor at AC bus (VL)

# Design and Control of FACTS-based high performance Microgrid

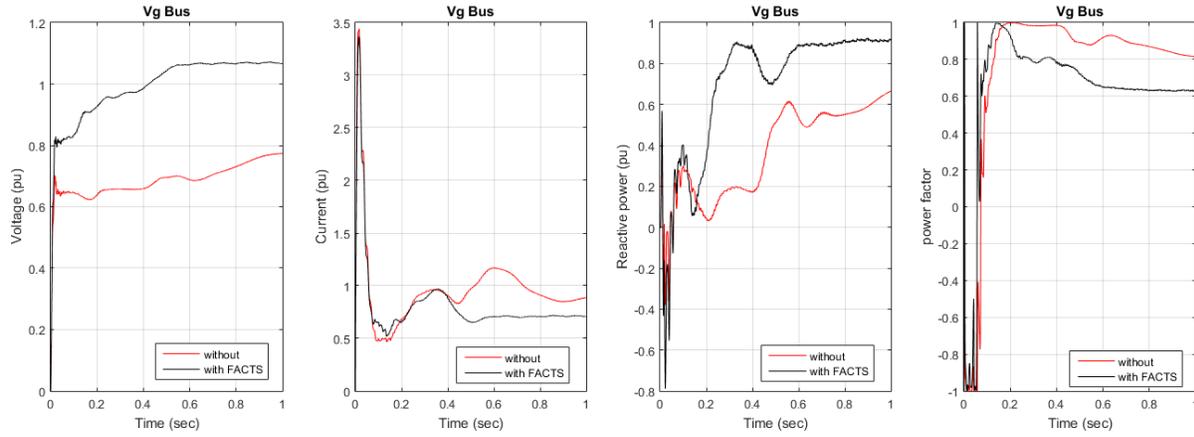


Figure 7-11 Voltage, Current, Reactive power and Power Factor at AC bus (Vg)

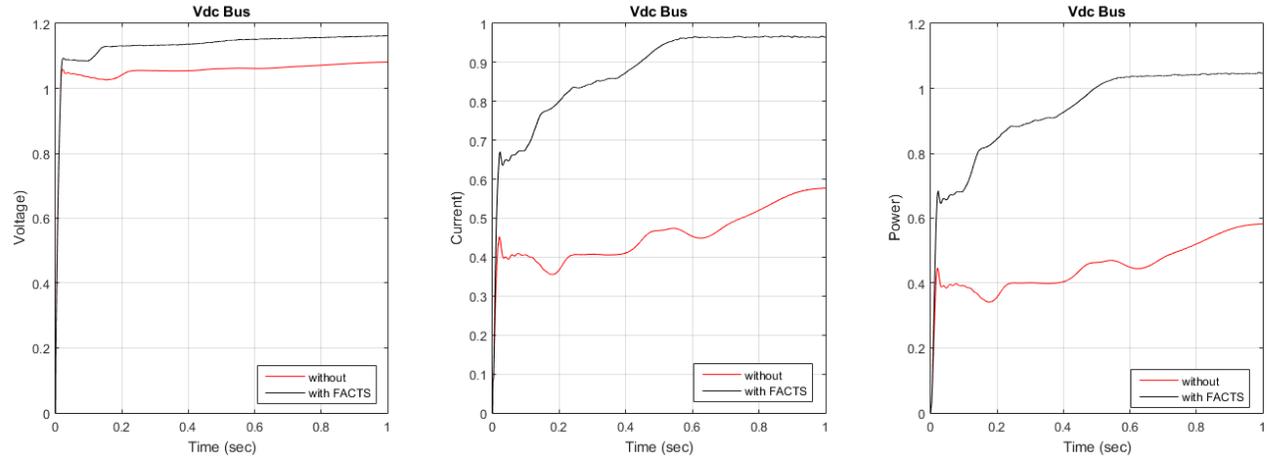


Figure 7-12 Voltage, Current and power at DC bus (Vdc)

Table 7-5 optimal values of PID controller

	Optimal Values of PID Controllers Gains		
	$K_p$	$K_i$	$K_d$
<b>MPFC A</b>	13	2.4	0.5
<b>MPFC B</b>	14	4.8	0.3
<b>GPFC</b>	11	1.7	0.2
<b>Converter 1</b>	12	1.4	0.8
<b>Converter 2</b>	18.5	6.5	0.25

Table 7-6 the %THD of voltage and current at all AC buses

	$V_s$		$V_1$		$V_L$		$V_g$	
	$THD_v$	$THD_i$	$THD_v$	$THD_i$	$THD_v$	$THD_i$	$THD_v$	$THD_i$
<b>Without FACTS</b>	0.59	6.25	30.5	26	24.3	38	25	20
<b>With-FACTS</b>	0.22	4.462	4.72	4.67	4.65	4.63	3.62	5.45

All KPI shown in figure 7-8 to 7-12, shows the voltage profile, power factor and current is improved using FACTS. In Table 7-6, THD values for AC is calculated for voltage and current, and by using FACTS THD for all busses are reduced and improved to  $\pm 5\%$  range. Wisely by comparing intelligent controller microgrid response with conventional controller, a significant change can be viewed. With power losses are decreased and current are increased as compared with conventional controller. Comparing PID with fuzzy controller KPI readings, a 6% improvement viewed through current KPI criterion.

7.4 Islanded With/Without FACTS using intelligent controller

In this scenario, utility grid is disconnected from the microgrid and on site DER uses to compensate loads supply needs. Control scheme is modeled with fuzzy controller.

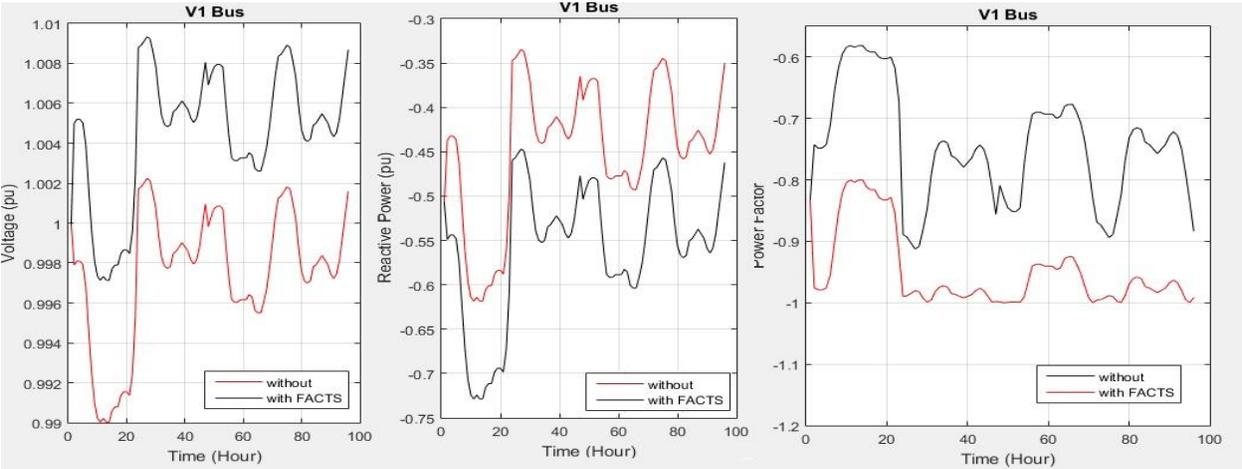


Figure 7-13 Voltage, Reactive power and Power Factor at AC bus (V1))

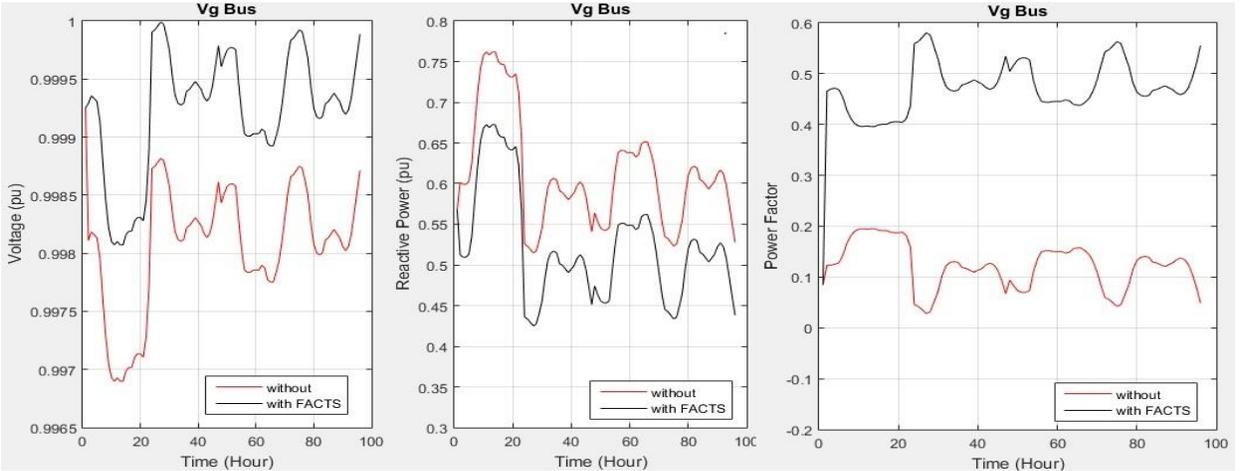


Figure 7-14 Voltage, Current, Reactive power and Power Factor at AC bus (Vg)

## Design and Control of FACTS-based high performance Microgrid

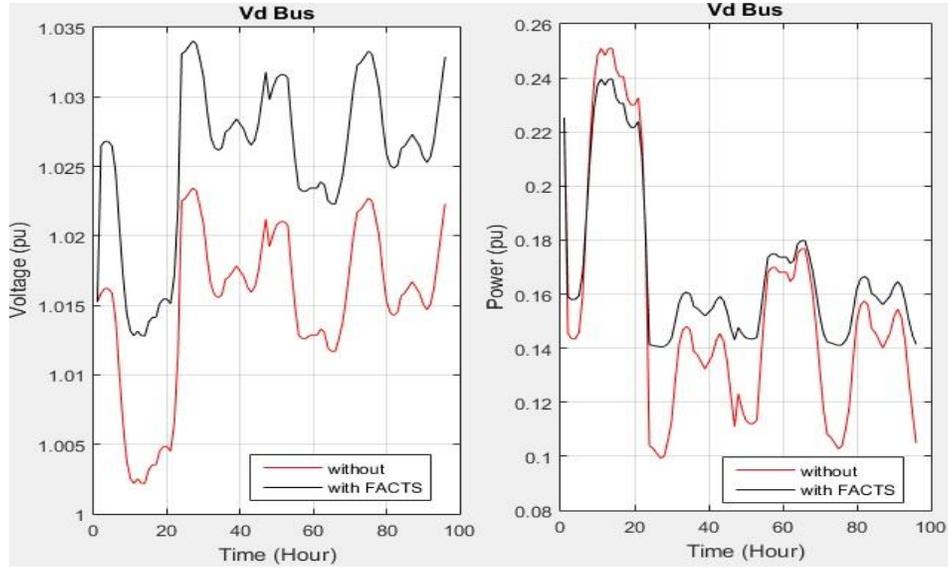


Figure 7-15 Voltage, Current, Reactive power and Power Factor at AC bus (Vdc)

Table 7-7 Optimal values of PID controller

	<b>Optimal Values of PID Controllers Gains</b>		
	<b><math>K_p</math></b>	<b><math>K_i</math></b>	<b><math>K_d</math></b>
<b>MPFC A</b>	13	2.4	0.5
<b>MPFC B</b>	14	4.8	0.3
<b>GPFC</b>	11	1.7	0.2
<b>Converter 1</b>	12	1.4	0.8
<b>Converter 2</b>	18.5	6.5	0.25

Table 7-8 the %THD of voltage and current at all AC buses

	<b>V<sub>1</sub></b>		<b>V<sub>L</sub></b>		<b>V<sub>g</sub></b>	
	<b>THD<sub>v</sub></b>	<b>THD<sub>i</sub></b>	<b>THD<sub>v</sub></b>	<b>THD<sub>i</sub></b>	<b>THD<sub>v</sub></b>	<b>THD<sub>i</sub></b>
<b>Without FACTS</b>	30.5	26	24.3	38	25	20
<b>With-FACTS</b>	6.72	5.67	5.65	6.63	5.62	6.45

## Design and Control of FACTS-based high performance Microgrid

All KPI shown in figure 7-13 to 7-15, shows the voltage profile, power factor and current is improved using FACTS. In Table 7-8, THD values for AC is calculated for voltage and current, and by using FACTS THD for all busses are reduced and improved to  $\pm 5\%$  range. As currently utility grid is not connected to the modeled microgrid, still by using onsite DER it gives improved performance. Significant performance of overall microgrid is improved, by using fuzzy controller, with power losses are decreased and current are increased as compared with conventional controller. Fuzzy controller good and better response with improvement of 3% as compared with conventional controller.

## 8 Conclusion

The modeling and control of FACTS-based microgrid has been successfully accomplished. Current model consisted of Distributed Energy Resources (DER) include Solar PV Cells, wind energy, fuel cell, battery, and batteries. Novel FACTS device, Green Plug-Filter Compensator (GPFC) and Modulated Plug-Filter Compensator (MPFC) with two DC/AC schemes installed in current microgrid design. Integrated Genetics algorithm (GA) with Fuzzy controller applied to control the parameter settings of FACT, to fine-tune the system dynamic response. Integrated GA and fuzzy adapted the dynamic gains of PID regulation error tri-loop. The proposed controller ensures the adaptation of the global control error to operate with online optimal profile. The proposed strategy leads to get full microgrid utilization by increasing the energy efficiency and reliability that ensure various technical impacts. Current model gives an effective and reliable design of microgrid that compensate reactive power, reduce THD and stabilize voltage and current profile, power factor improvement, bus voltage stabilizing, feeder loss minimization and power quality enhancement are achieved. Both Grid connected and islanded mode are simulated and compared, with adding fuzzy controller to the system, more improved and refined results are accomplished.

### 8.1 Future Work

- Economic analysis of designing FACTS-based microgrid
- Optimal location analysis of FACTS device effects on microgrid
- Different control strategies such as ANFIS, fuzzy –Neural can be used to tune gains of FACTS controllers.

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doi: 10.1109/61.634216

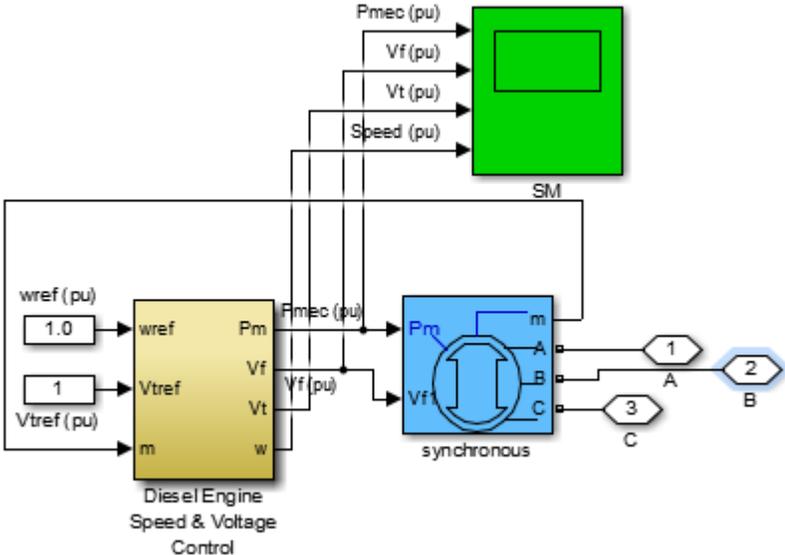
## 10 Appendix

The parameters of the hybrid AC/DC microgrid are as follow:

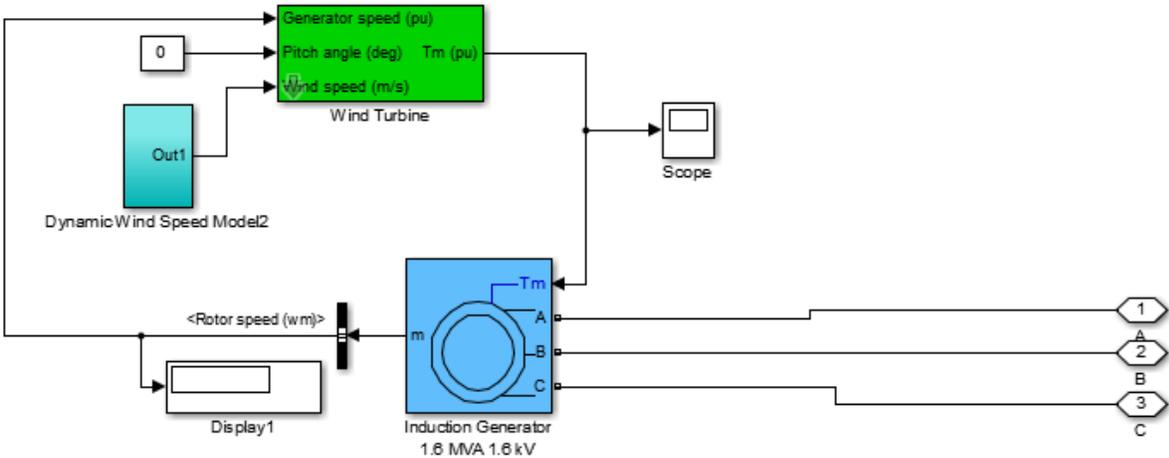
<i>AC Grid:</i>	138 KV <sub>LL</sub> , 5 GVA, X/R=10.
<i>Micro Gas Turbine:</i>	V=1.6 kV, P= 100 kW.
<i>Wind Turbine:</i>	V= 1.6 kV, P= 0.5 Mw.
<i>PV:</i>	240V, 100 KW, N <sub>s</sub> = 318, N <sub>p</sub> = 150, T <sub>x</sub> = 293, S <sub>x</sub> = 100, I <sub>ph</sub> = 5, T <sub>c</sub> = 20, S <sub>c</sub> = 205
<i>Fuel Cell:</i>	240 V, 100 KW, number of Cells = 220, nominal Efficiency, 55%,
<i>Battery:</i>	240 V, Rated capacity: 300 Ah, Initial State-Of-Charge: 100%, discharge current: 10, 5 A, R <sub>s1</sub> = 0.1 Ω, L <sub>s1</sub> = 10 mH, C <sub>s1</sub> =10 μF.
<i>Hybrid AC Load 1:</i>	linear load: 0.5 MVA, 0.8 lag pf, non-linear load: 0.5 MVA, Motorized load is an induction motor: 3phase, 0.8 MVA, 0.85 pf.
<i>Hybrid AC Load 2:</i>	linear load: 200 kVA, 0.8 lag pf., non-linear load: 200 kVA, Motorized load is an induction motor: 3phase, 100 kVA, 0.8 pf.
<i>DC Load:</i>	resistive load: 100 kw, motorized load dc series motor: 100 kw.
<i>Feeders:</i>	R/km = 0.4 Ω , X/km= 0.3 Ω.
<i>MPFC 1:</i>	C <sub>s1</sub> =1000 μF, C <sub>f1</sub> =C <sub>f2</sub> = 50 μF, R <sub>f1</sub> = 0.25 Ω, L <sub>f1</sub> = 3 mH
<i>MPFC 2:</i>	C <sub>s2</sub> =150 μF, C <sub>f3</sub> =C <sub>f4</sub> = 40 μF, R <sub>f2</sub> = 0.1 Ω, L <sub>f2</sub> = 1mH.
<i>GPFC:</i>	C <sub>s</sub> = 100 μF, R <sub>s</sub> = 0.1 Ω, L <sub>s</sub> = 5mH.

AC DER:

Diesel Engine:

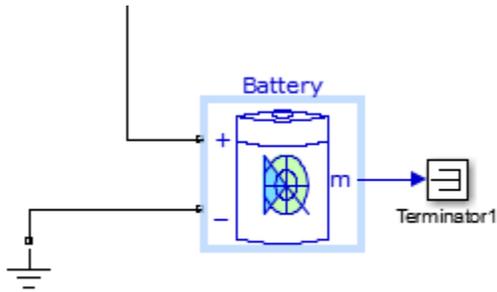


Wind Turbine:

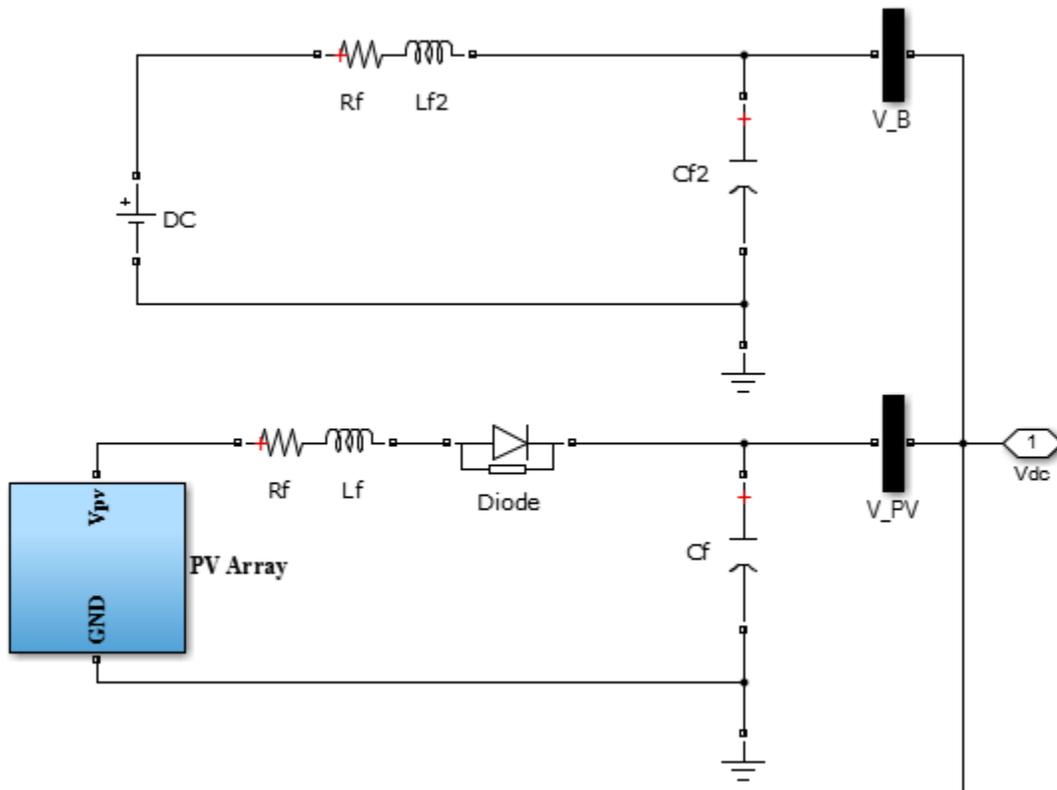


DC DER:

Batteries



PV Array:



Fuel Cell:

