SMART GRID Technologies

PE/PE/HT/324C

Professional Elective Course

Smart Grid Technologies

- **Automatic Generation Control (AGC)**
- Automatic Voltage Regulation (AVR)
- Energy Management System (EMS)
- Distribution Management System (DMS)
- Demand Side Management (DSM)
- Outage Management System (OMS)
- Wide Area Management System (WAMS)
- Advanced Metering Infrastructure (AMI)
- Meter Data Management (MDM)
- Geographical Information System (GIS)

Automatic Generation Control (AGC)

In conventional grid

Automatic Generation Control (AGC)

Frequency deviation is a direct result of the imbalance between the electrical load and the active power supplied by the connected generators

A permanent off-normal frequency deviation directly affects:

- power system operation
- Security
- Reliability
- efficiency

Effects of prolonged operation at deviated frequency

- damaging equipment
- degrading load performance
- overloading transmission lines
- triggering the protection devices

Automatic Generation Control (AGC)

Since the frequency generated in the electric network is proportional to the rotation speed of the generator

The problem of frequency control thus may be directly translated into a speed control problem of the turbine generator unit

This is initially overcome by adding a governing mechanism

- It senses the machine speed
- Then adjusts the input valve to change the mechanical power output of the prime mover to track the load change
- So as to restore speed (and hence frequency) to a nominal value

Automatic Generation Control (AGC)

The power system primarily ensures its stable and safe operation by maintaining a constant equilibrium between power production and load demands

Such an equilibrium is maintained to hold the frequency of the network within the appropriate limits as defined by the grid codes:

- The nominal frequency of operation in Indian grid is 50.0 Hz and the permissible frequency band specified by Indian Electricity Grid Code (IEGC) is 49.5 Hz to 50.2 Hz

Automatic Generation Control (AGC)

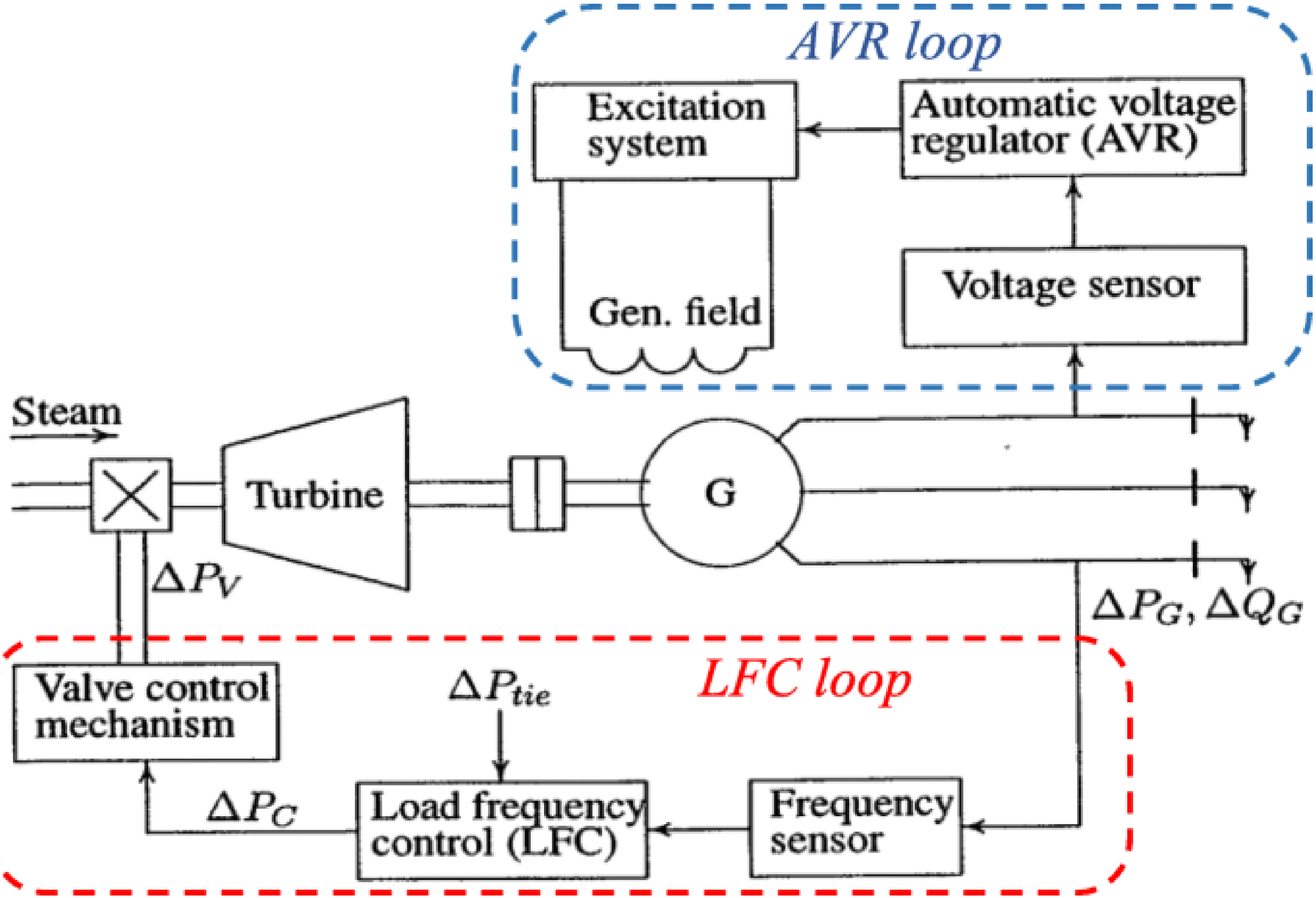
Main goal of AGC

- keep the operating frequency under prescribed limits
- maintain the interchange power between grids through tie-lines at the intended level

AGC system (also called the Load Frequency Control, LFC) must be supplemented with modern and intelligent control techniques to ensure desired performance

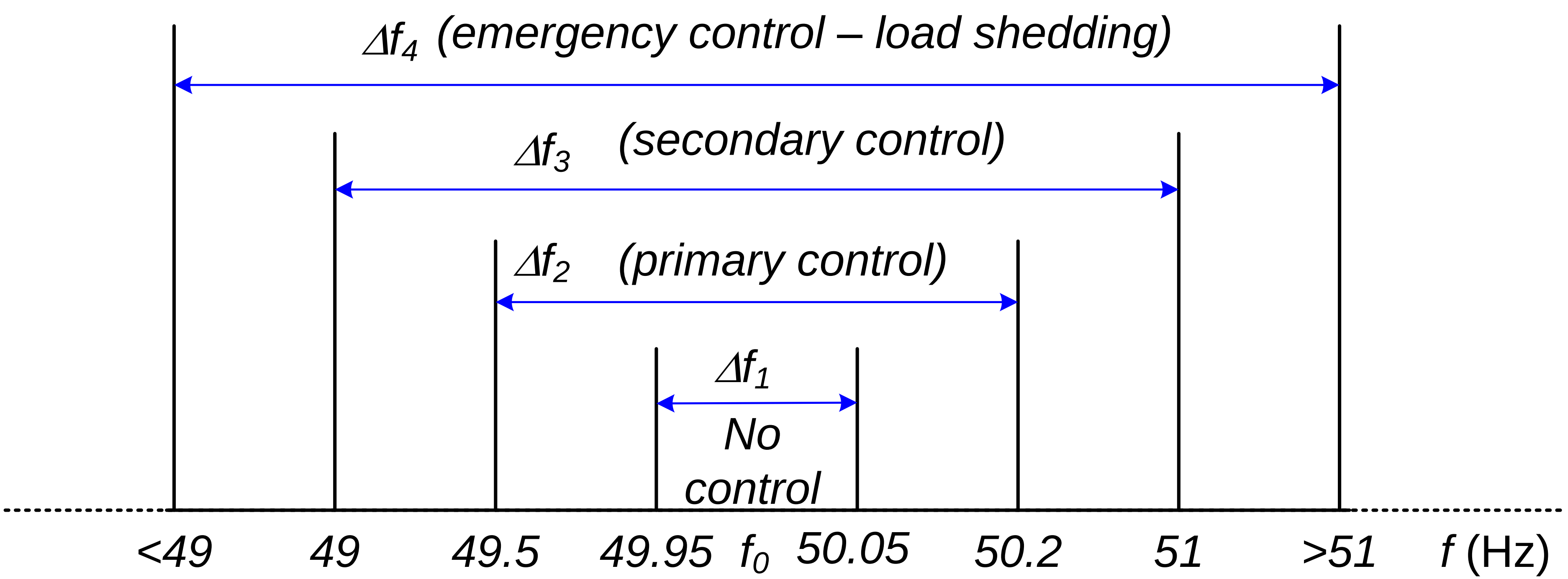
Automatic Generation Control (AGC)

- AGC / LFC



Automatic Generation Control (AGC)

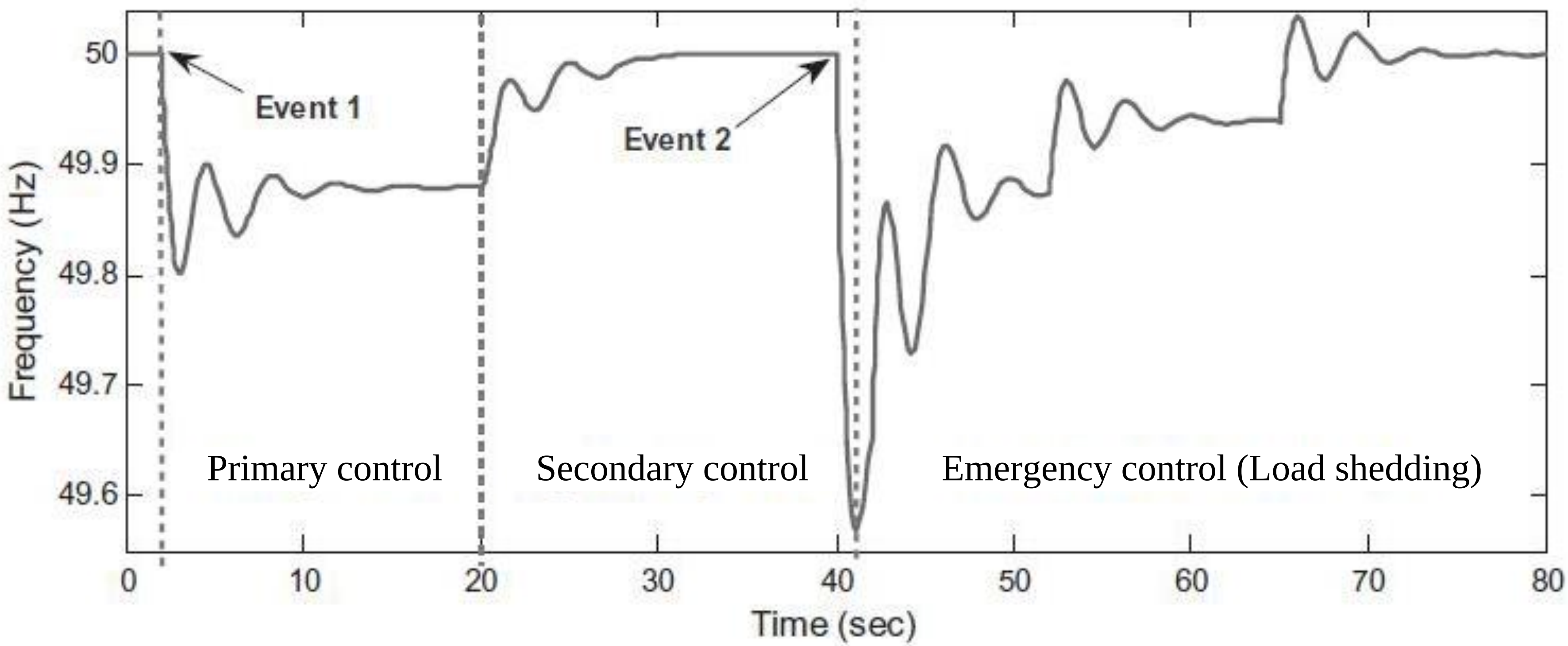
The frequency of the power system is mainly controlled using three control loops, namely primary, secondary and emergency



Automatic Generation Control (AGC)

Responses of the control loops

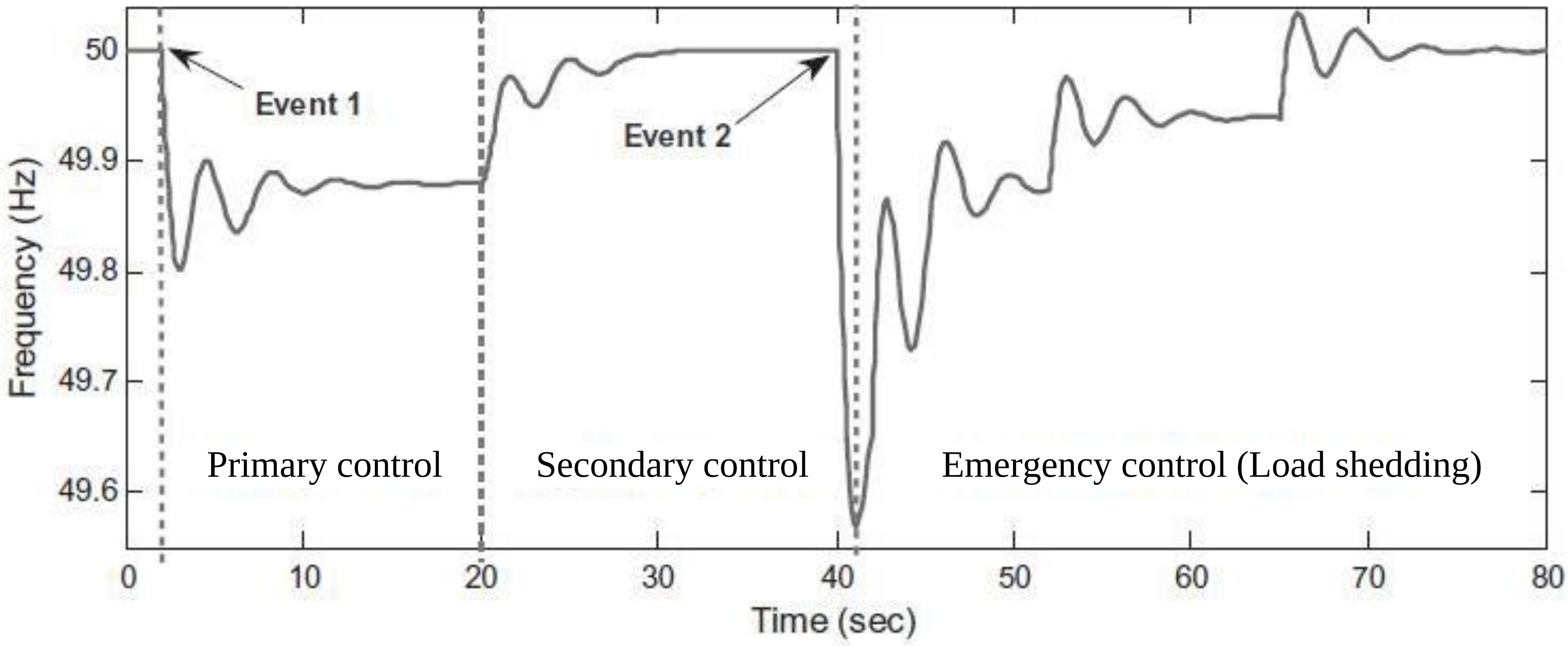
- Following event 1, the primary control loops of all generating units respond within a few seconds
- As soon as the balance is reestablished, the system frequency stabilizes and remains at a fixed value, but may differ from the nominal frequency



Automatic Generation Control (AGC)

Responses of the control loops

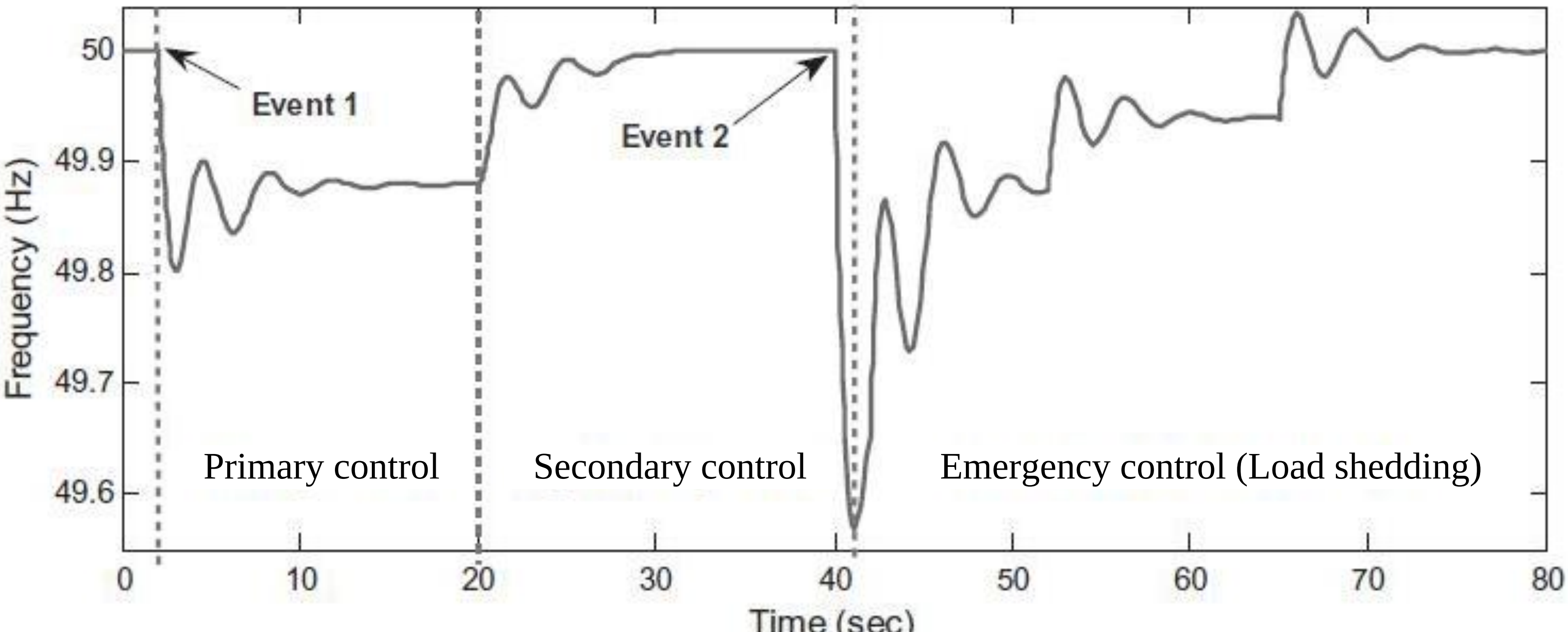
- Consequently, the tie-line power flows in a multi-area power system will differ from the scheduled values
- The secondary control will take over the remaining frequency and power deviation after a few seconds, and can reestablish the nominal frequency and specified power



Automatic Generation Control (AGC)

Responses of the control loops

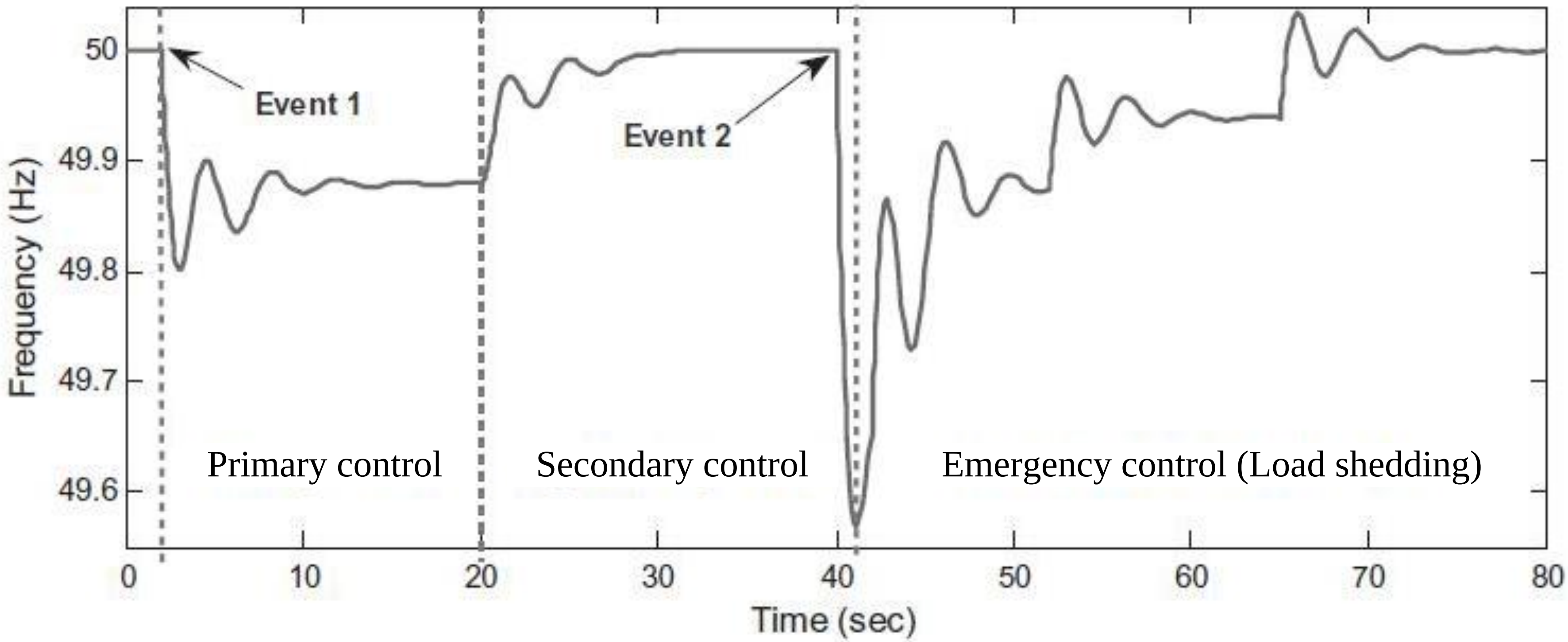
- Following event 1, if the frequency does not fall too quickly, so there is time for the AGC system to use the regulation power and thus recover the load-generation balance



Automatic Generation Control (AGC)

Responses of the control loops

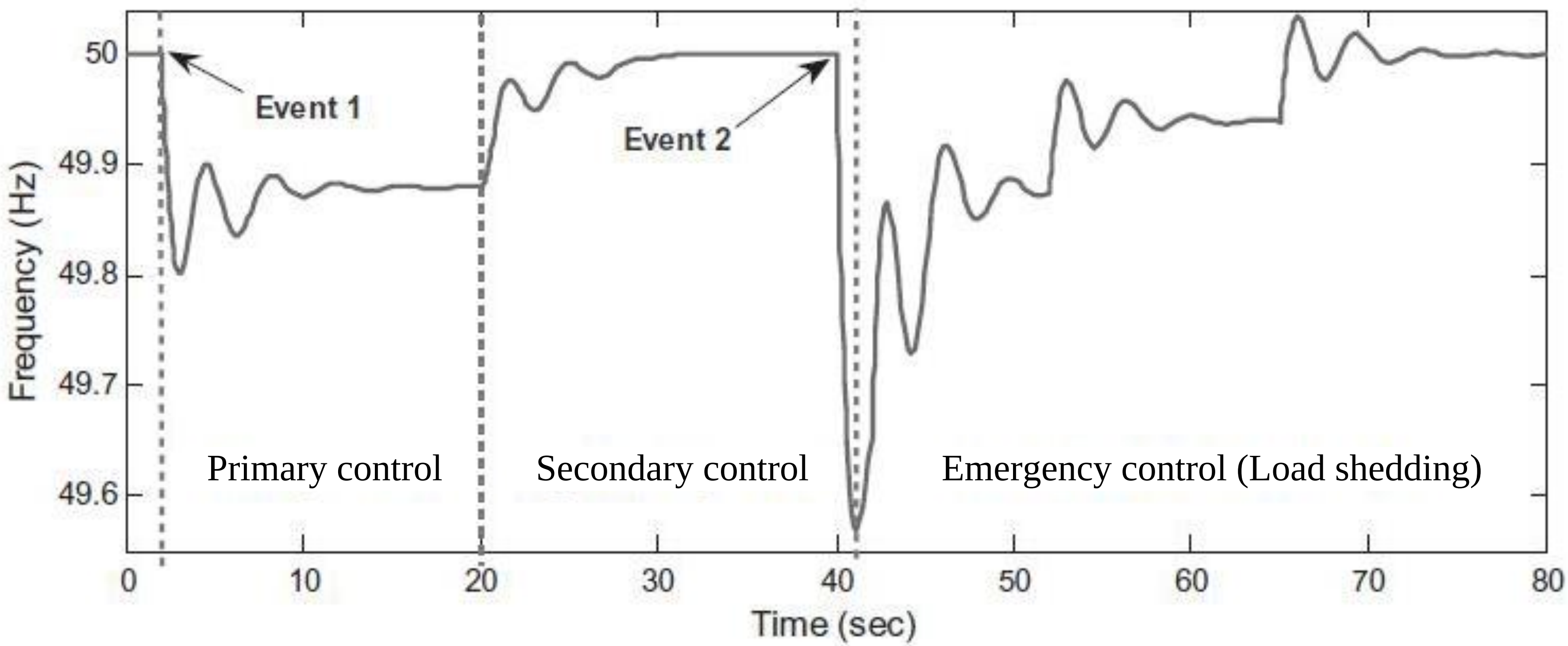
- However, it does not happen following event 2, where the frequency is quickly dropped to a critical value



Automatic Generation Control (AGC)

Responses of the control loops

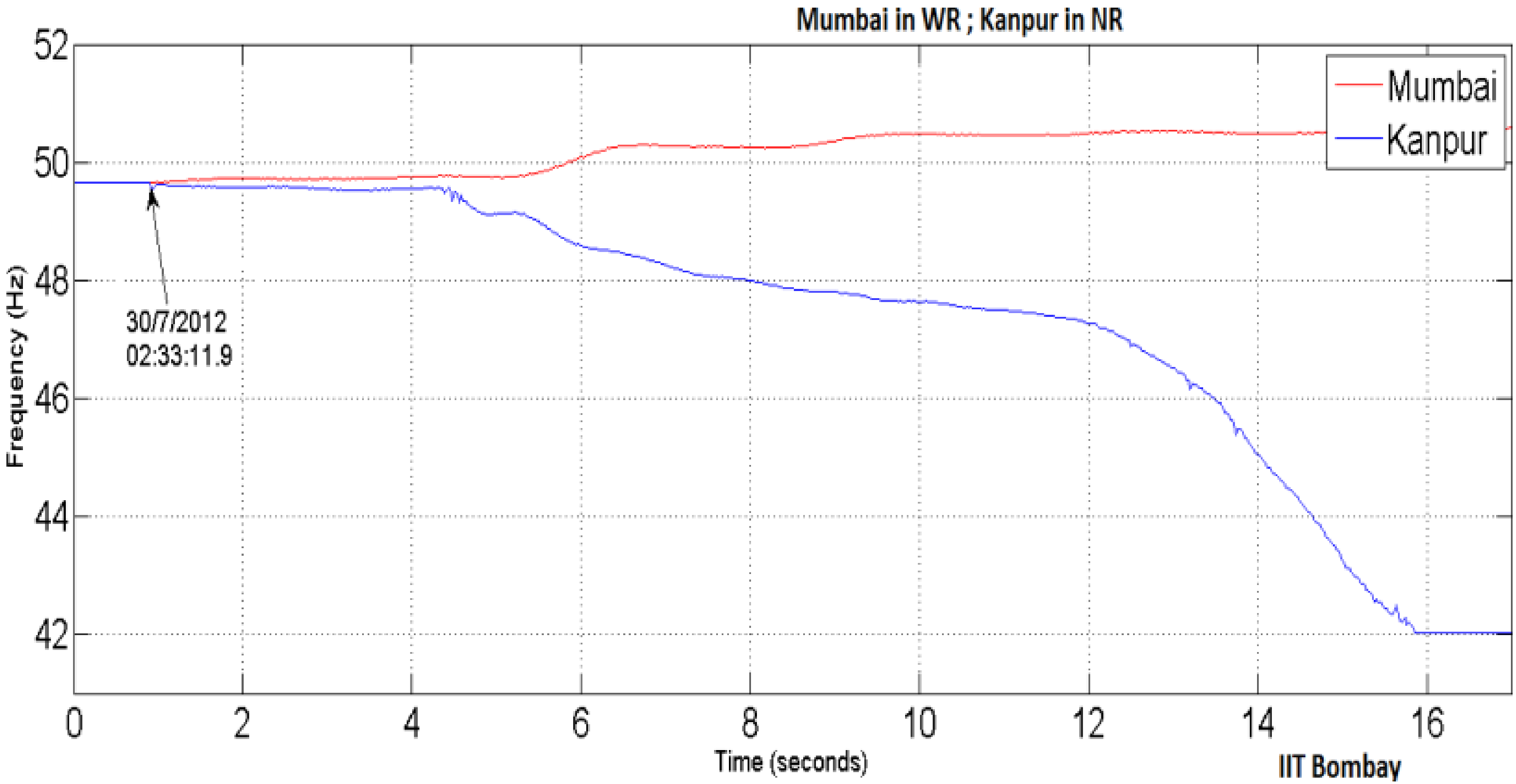
- In this case, where the frequency exceeds the permissible limits, an emergency control plan such as UFLS may need to restore frequency and maintain system stability
- Otherwise, due to critical under-speed, other generators may trip out, creating a cascade failure, which can cause widespread blackouts



Automatic Generation Control (AGC)

Indian Grid Blackout: July 30 & 31, 2012 - Affected 670 million people

Automatic Generation Control (AGC)

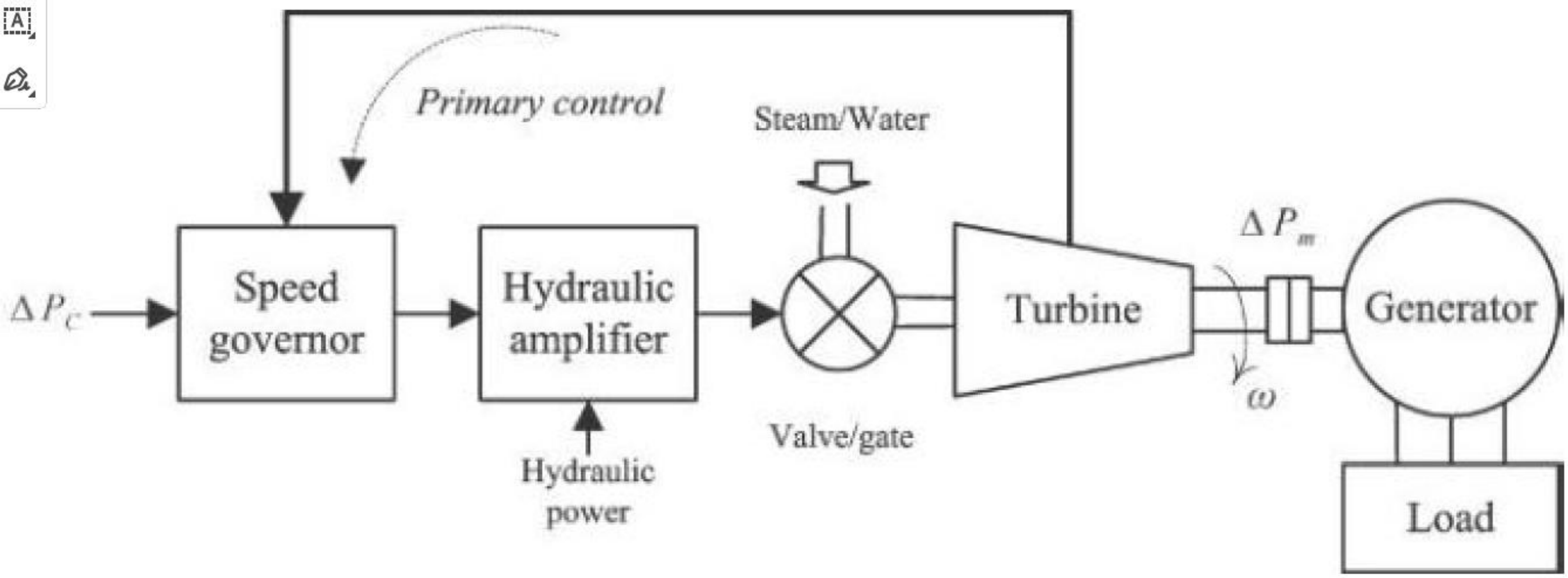


Indian Grid Blackout: July 30 & 31, 2012 - Affected 670 million people

Automatic Generation Control (AGC)

Primary control loop:

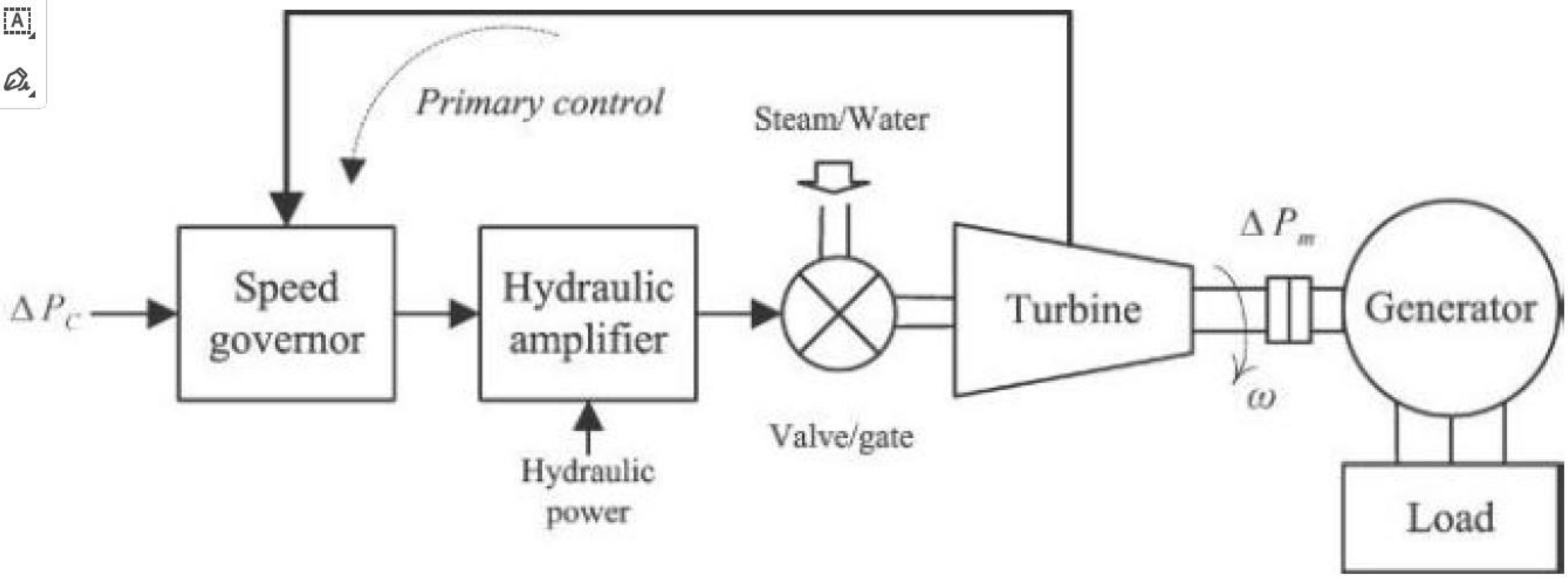
- It prevents instantaneous variations in the frequency before triggering the frequency protection switches



Automatic Generation Control (AGC)

Primary control loop:

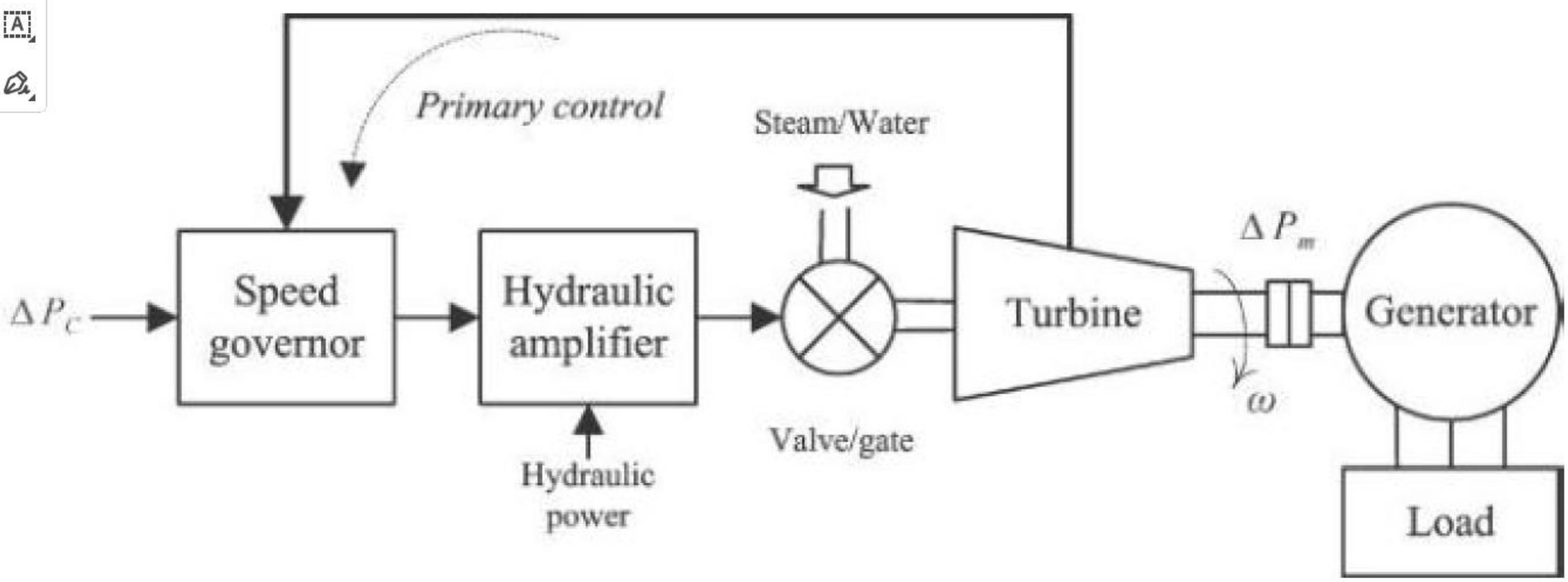
- The real power delivered by a generator is controlled by the mechanical power output of a prime mover such as a steam turbine, gas turbine, hydro turbine, or diesel engine



Automatic Generation Control (AGC)

Primary control loop:

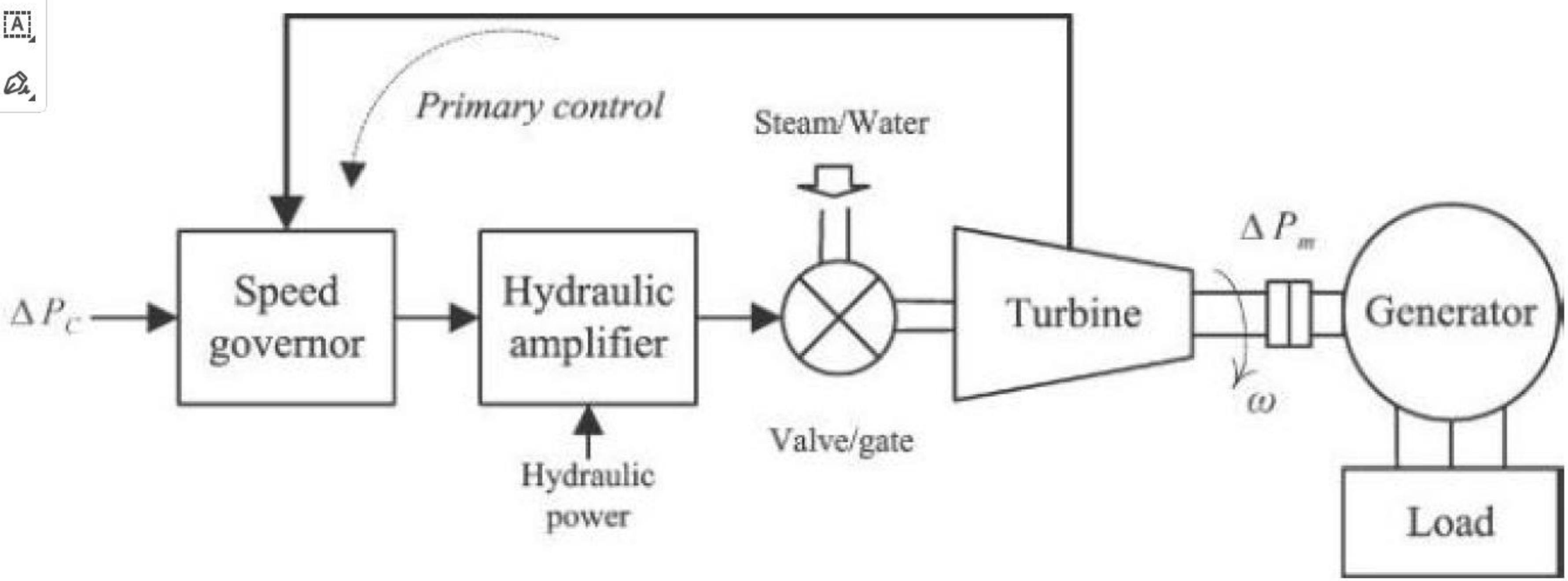
- In the case of a steam or hydro turbine, mechanical power is controlled by the opening or closing of valves regulating the input of steam or water flow into the turbine
- Steam (or water) input to generators must be continuously regulated to match real power demand



Automatic Generation Control (AGC)

Primary control loop:

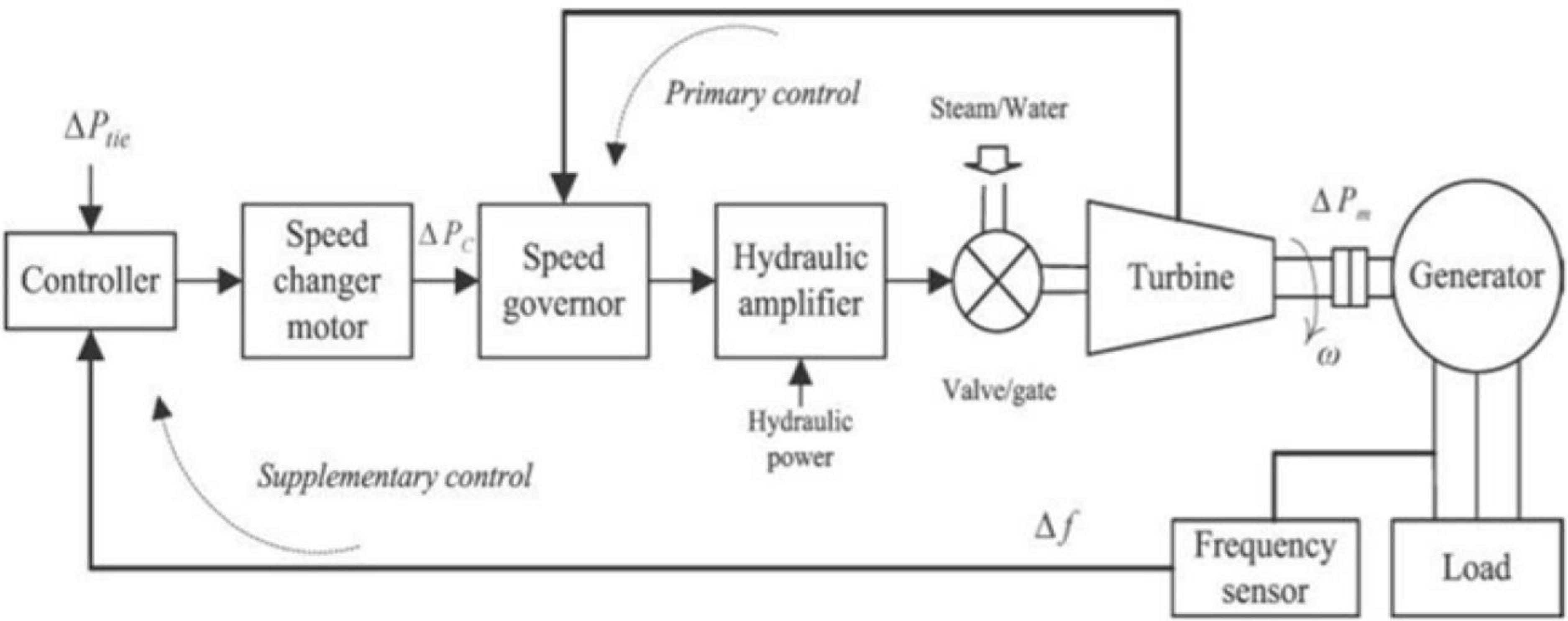
- Without this regulation, the machine speed will vary with consequent change in frequency
- The speed governor senses the change in speed via the primary control loop



Automatic Generation Control (AGC)

Secondary (Supplementary) control loop:

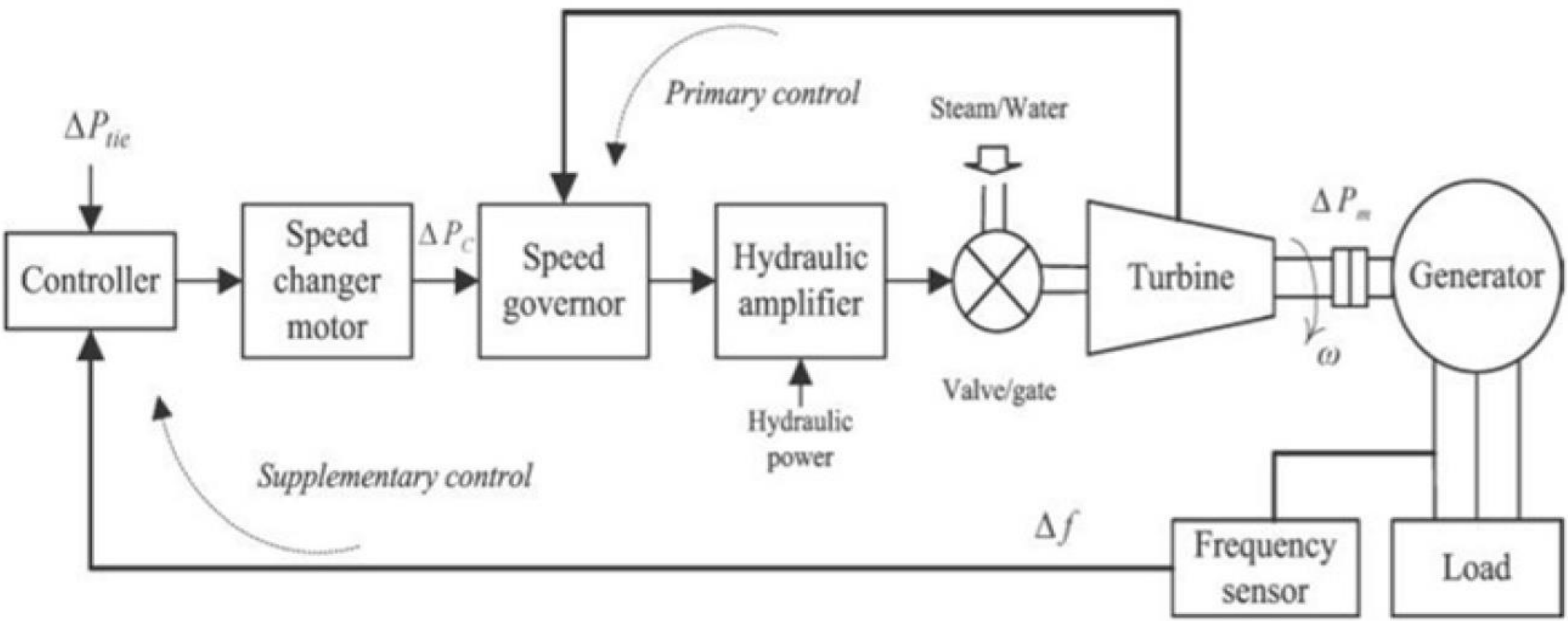
- Secondary control, also termed automatic generation control (AGC) or load frequency control (LFC), is implemented to regulate the system frequency to its nominal value in the power system network



Automatic Generation Control (AGC)

Secondary (Supplementary) control loop:

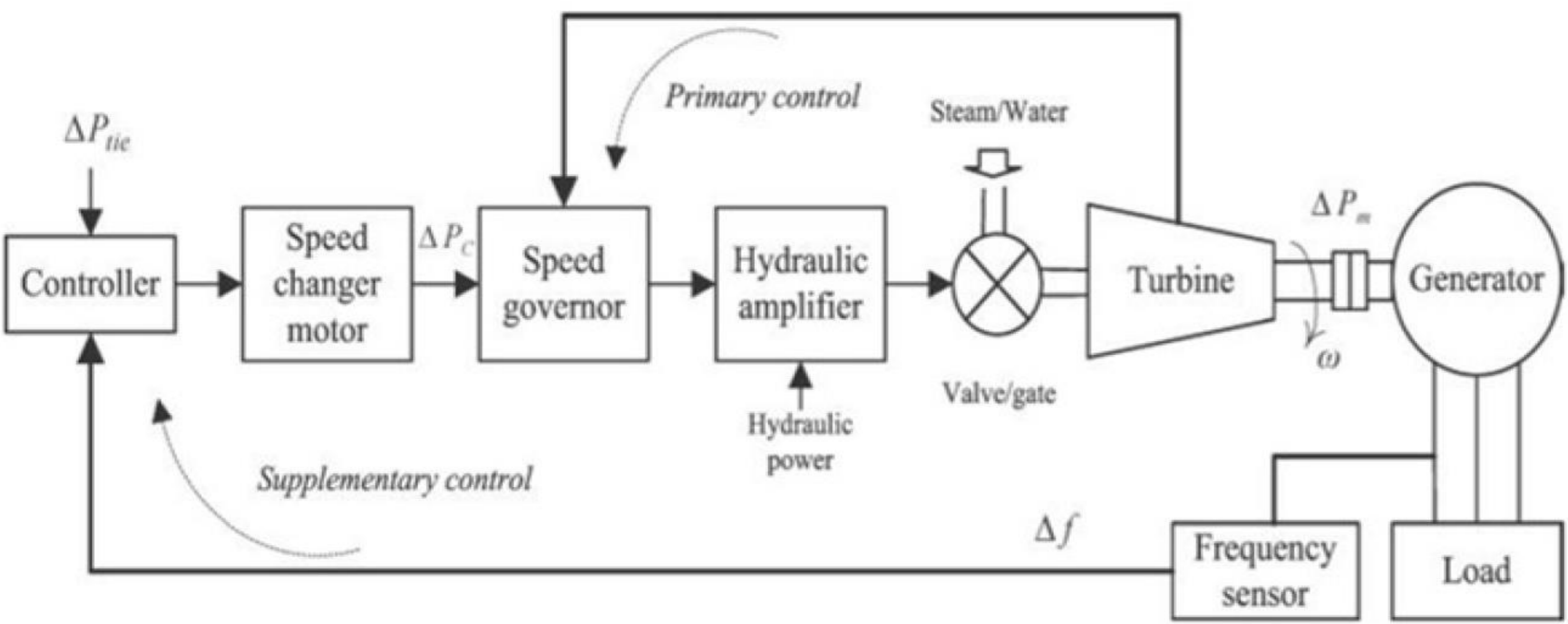
- The secondary control loop gives feedback via the frequency deviation and adds it to the primary control loop through a dynamic controller



Automatic Generation Control (AGC)

Secondary (Supplementary) control loop:

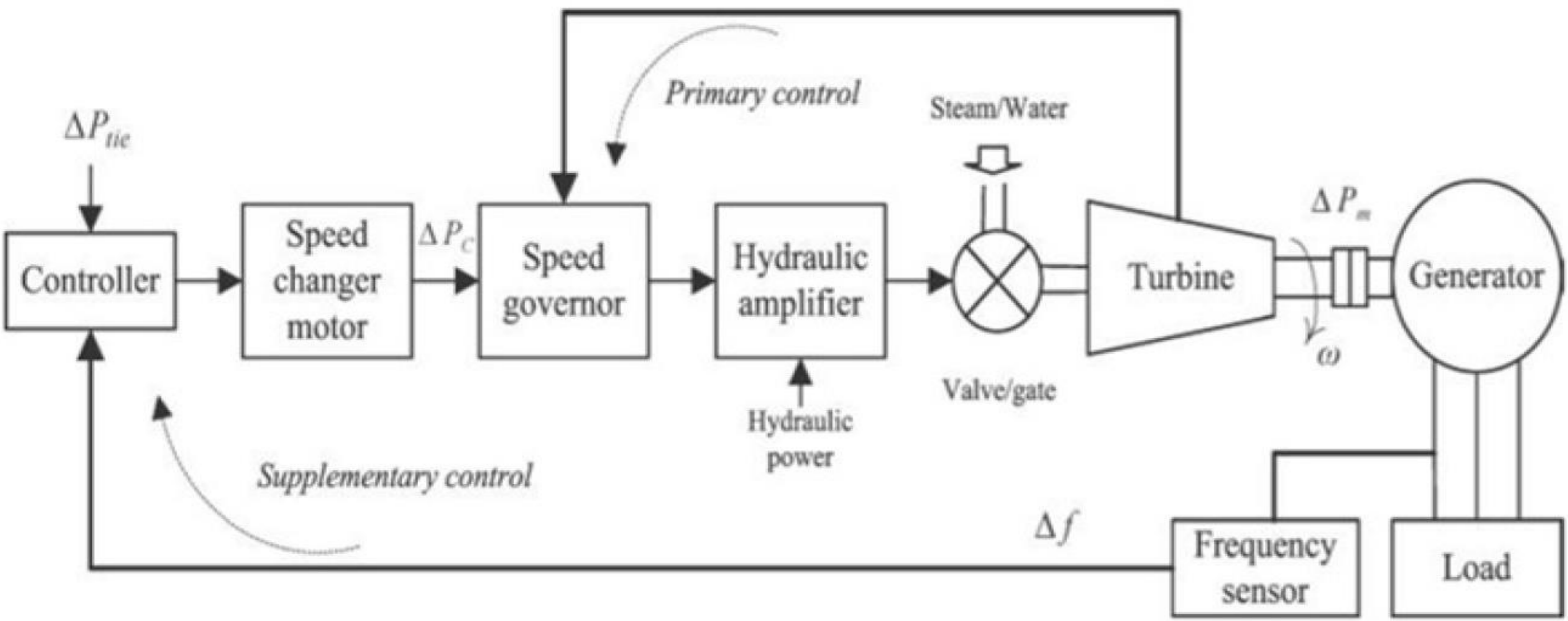
- The resulting signal is used to regulate the system frequency
- In real-world power systems, the dynamic controller is usually a simple integral (I) or proportional-integral (PI) controller



Automatic Generation Control (AGC)

Secondary (Supplementary) control loop:

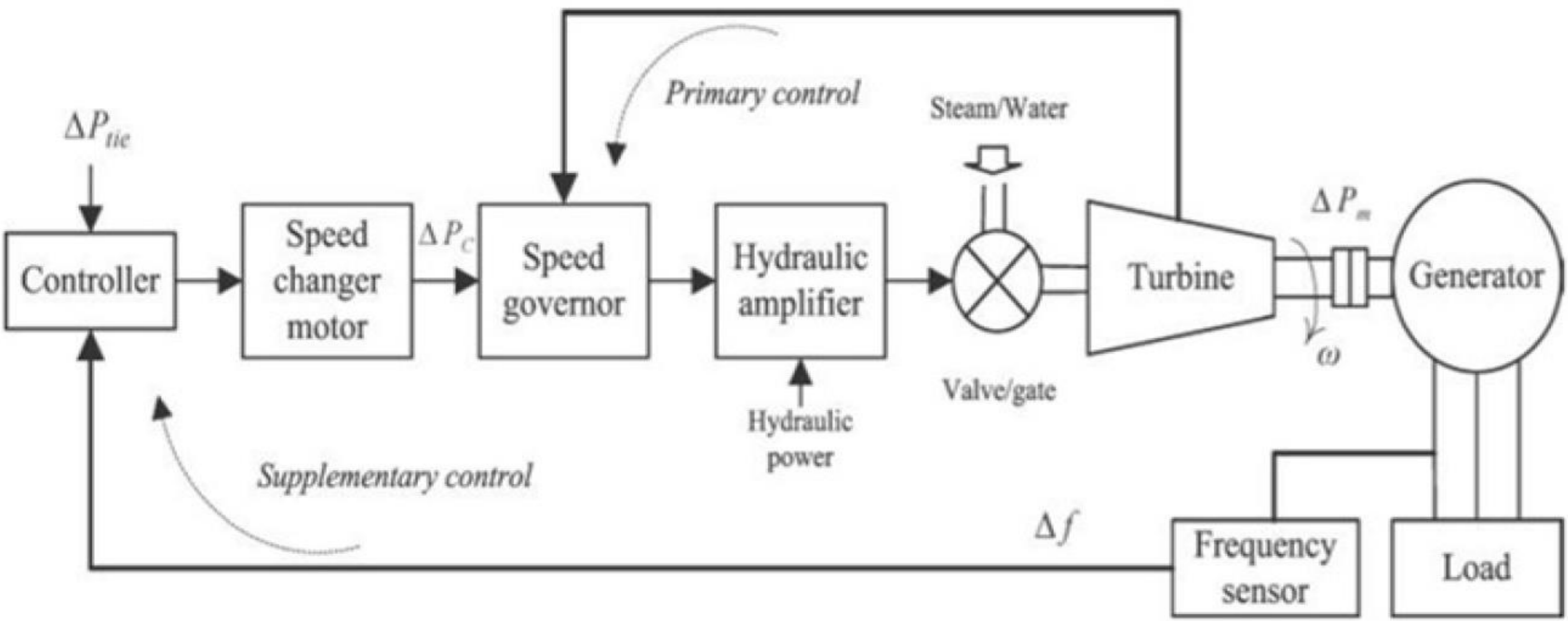
- Following a change in load, the feedback mechanism provides an appropriate signal for the turbine to make generation (ΔPm) track the load and restore system frequency



Automatic Generation Control (AGC)

The AGC thus operates with the objectives of:

- regulating the steady-state system frequency to its nominal value
- maintaining the tie-line power flow close to its scheduled value
- keep overshoot and settling time within the acceptable ranges



Automatic Generation Control (AGC)

Emergency control:

- Emergency control, such as load shedding, shall be established in emergency conditions to minimize the risk of further uncontrolled separation, loss of generation, or system shutdown
- Load shedding is an emergency control action to ensure system stability, by curtailing system load
- The load shedding will only be used if the frequency (or voltage) falls below a specified frequency (voltage) threshold
- Typically, the load shedding protects against excessive frequency (or voltage) decline by attempting to balance real (reactive) power supply and demand in the system
- The load shedding curtails the amount of load in the power system until the available generation can supply the remaining loads

Automatic Generation Control (AGC)

Emergency control:

- If the power system is unable to supply its active (reactive) load demands, the under-frequency (under-voltage) condition will be intense
- The number of load shedding steps, the amount of load that should be shed in each step, the delay between the stages, and the location of shed load are the important objects that should be determined in a load shedding algorithm
- A load shedding scheme is usually composed of several stages
- Each stage is characterized by frequency/ voltage threshold, amount of load, and delay before tripping
- The objective of an effective load shedding scheme is to curtail a minimum amount of load, and provide a quick, smooth, and safe transition of the system from an emergency situation to a normal equilibrium state

Automatic Generation Control (AGC)

AGC / LFC control algorithms

- **Classical controls**, which are mainly based on conventional proportional-integral-derivative (PID) controllers
- **Modern controls,** including model predictive controls, adaptive and sliding mode controls, optimal controls, and digital controls
- **Intelligent controls,** such as fuzzy logic and artificial neural networks
- **Soft computing control** approaches such as GA, Optimization, Expert system

Automatic Generation Control (AGC)

In Smart Grid

AGC / LFC in Smart Grid

Evolution of AGC/LFC strategies

- Last couple of decades have witnessed dramatic changes in the structure of power system network due to the dynamics of different load, incorporation of various equipment's, such as energy storage devices, HVDCs, and FACTS devices, and the integration of renewable energy sources
- This has further complicated the power system control problems, requiring intelligent methods
- Intelligent controllers and computing-based algorithms were introduced in this regard for the AGC to cope with such problems

AGC / LFC in Smart Grid

Evolution of AGC/LFC strategies

- Research on renewables integration proved that it has a substantial impact on the system frequency, which becomes more significant in large-scale penetrations, where the inverters do not have a enough spinning mass and eventually minimizes system inertia

- (Virtual Inertia Control) VICs were developed to enhance the system inertial response and reduce the stability issues in the renewable energy-based AGC systems

AGC / LFC in Smart Grid

AGC in renewable energy generation systems

AGC incorporating ESS

AGC in micro grid

AGC in smart grid

AGC with RES

AGC in Renewable Energy Generation Systems

- Integration of renewable generating resources affects the system frequency response
- Typically wind turbines and solar photovoltaic (PV) units do not provide inertia, and do not have primary controllers (governors)
- Therefore, increasing wind and solar penetrations requires some conventional generators to shut down, and therefore reduces the system inertia, reduce the system's response to frequency deviations, and make it more difficult to stabilize the system frequency
- Further, massive penetration requires network augmentation due to the risk of tie-line overloading
- The AGC system in this regard requires more intelligence and flexibility to balance the fluctuating power and regulate the frequency deviations due to the integration of renewable energy sources

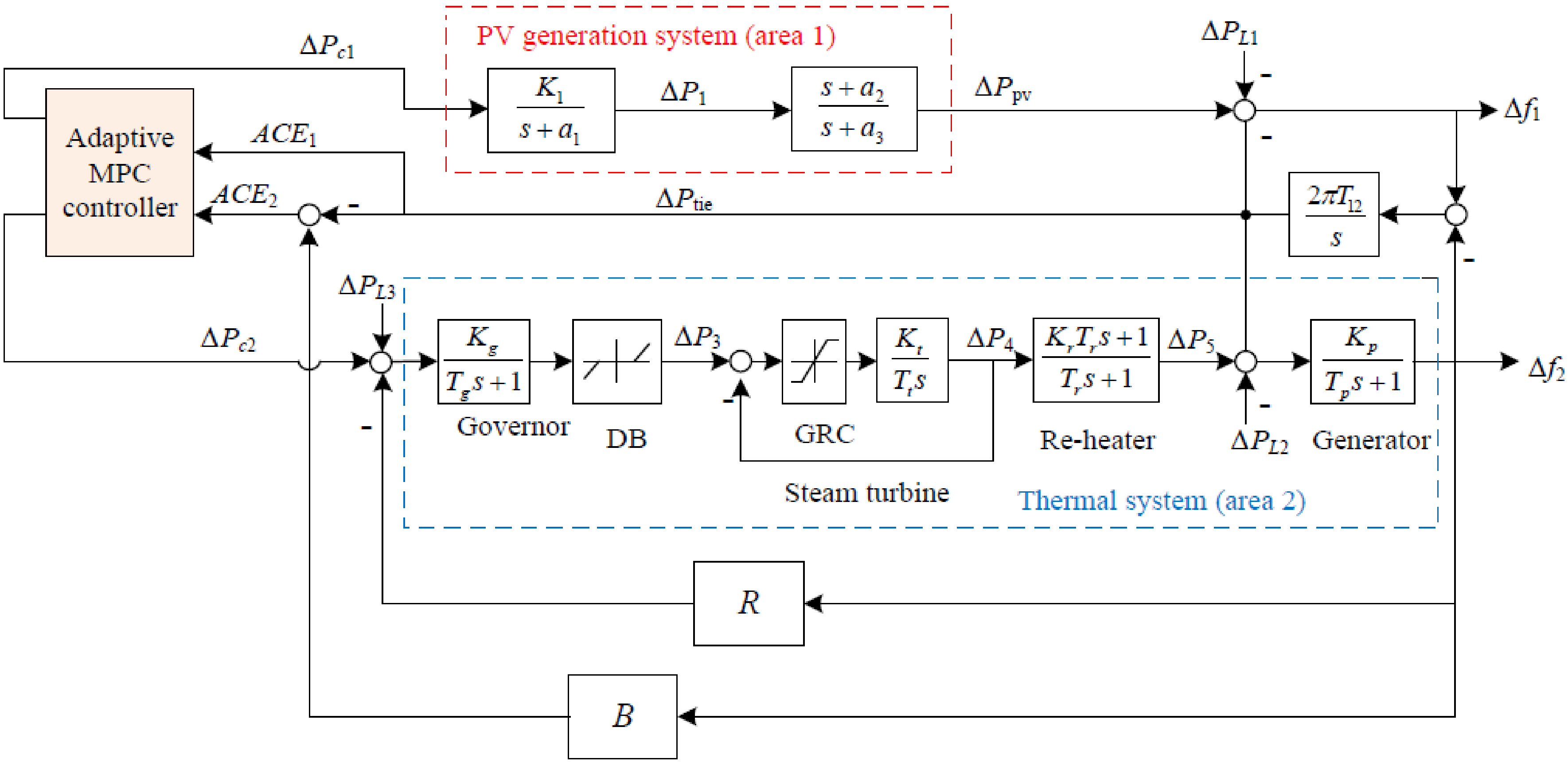
AGC with RES

AGC in Renewable Energy Generation Systems

- Integration of a **solar photovoltaic source** of 10% into the grid would approximately require a 2.5% increase in the capacity of AGC, compared to the conventional AGC regulators
- The AGC capacity depends on the intermittency speed of response of certain power plant to the PV fluctuation, and also on the level of solar insolation
- Control techniques include:
  - PID
  - Fuzzy
  - GA
  - PSO

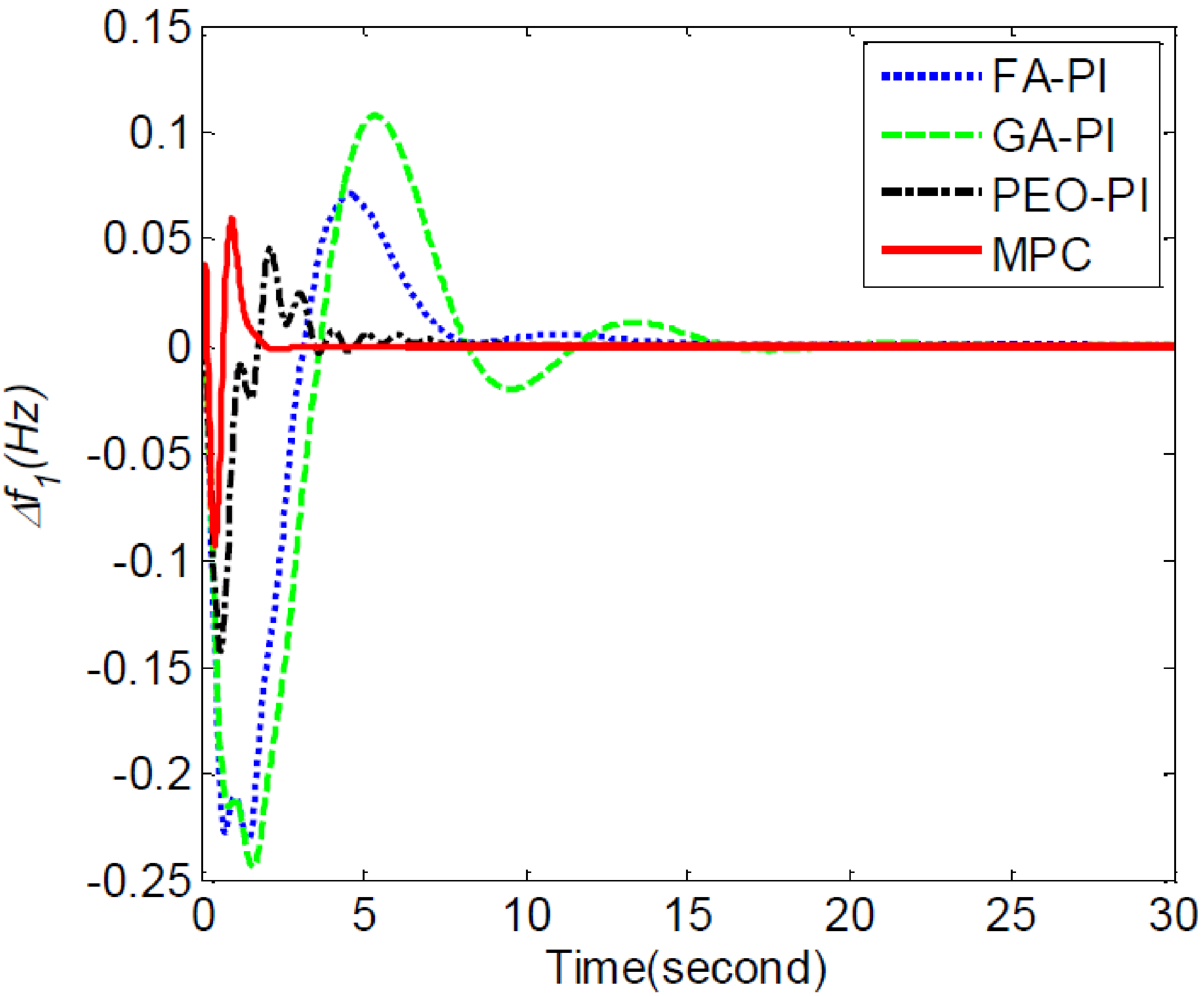
AGC with RES

AGC in Renewable Energy Generation Systems



AGC with RES

AGC in Renewable Energy Generation Systems



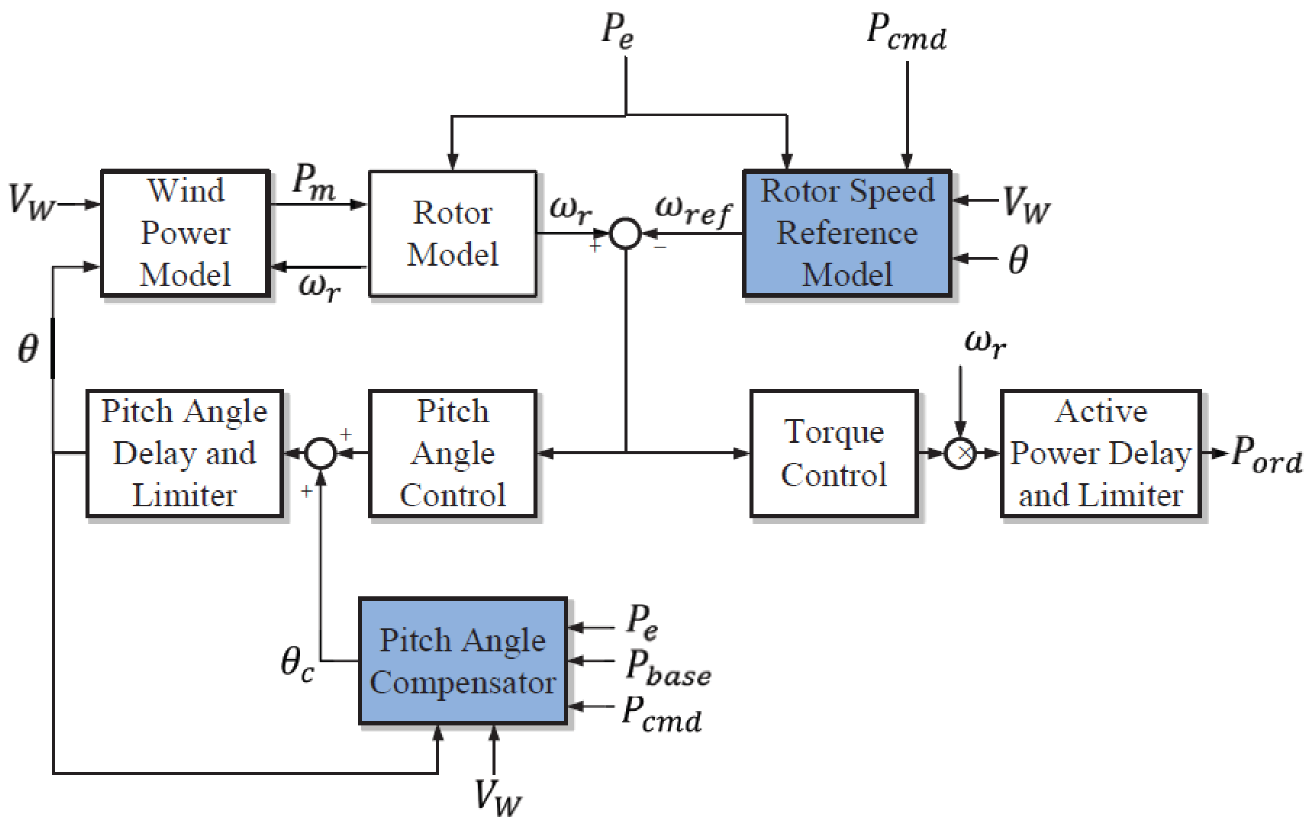
AGC with RES

AGC in Renewable Energy Generation Systems

- Integrating large-scale wind power into the system is a new challenge for AGC due to the unpredictable nature of wind energy.
- Generally, the active power control of WT is accomplished by pitch angle control (PAC) or rotor speed control (RSC), which give an exceptionally sluggish reaction and restricted controlling range
- To improve the regulating performance, an improved control technique can be to simultaneously enact both RSC and PAC and accomplish full use of the rotor kinetic energy to provide the required power
- The variable speed wind turbines are designed to be able to vary their rotational speed in some ranges during normal operations, making them capable to utilize their kinetic energy stored in the turbine-generator
- In this manner, it may provide active power support in a short term basis in the event of frequency deviations in the system

AGC with RES

AGC in Renewable Energy Generation Systems – Wind generator



Wind turbine model for combined PAC and RSC

AGC with RES

AGC in Renewable Energy Generation Systems – Wind generator

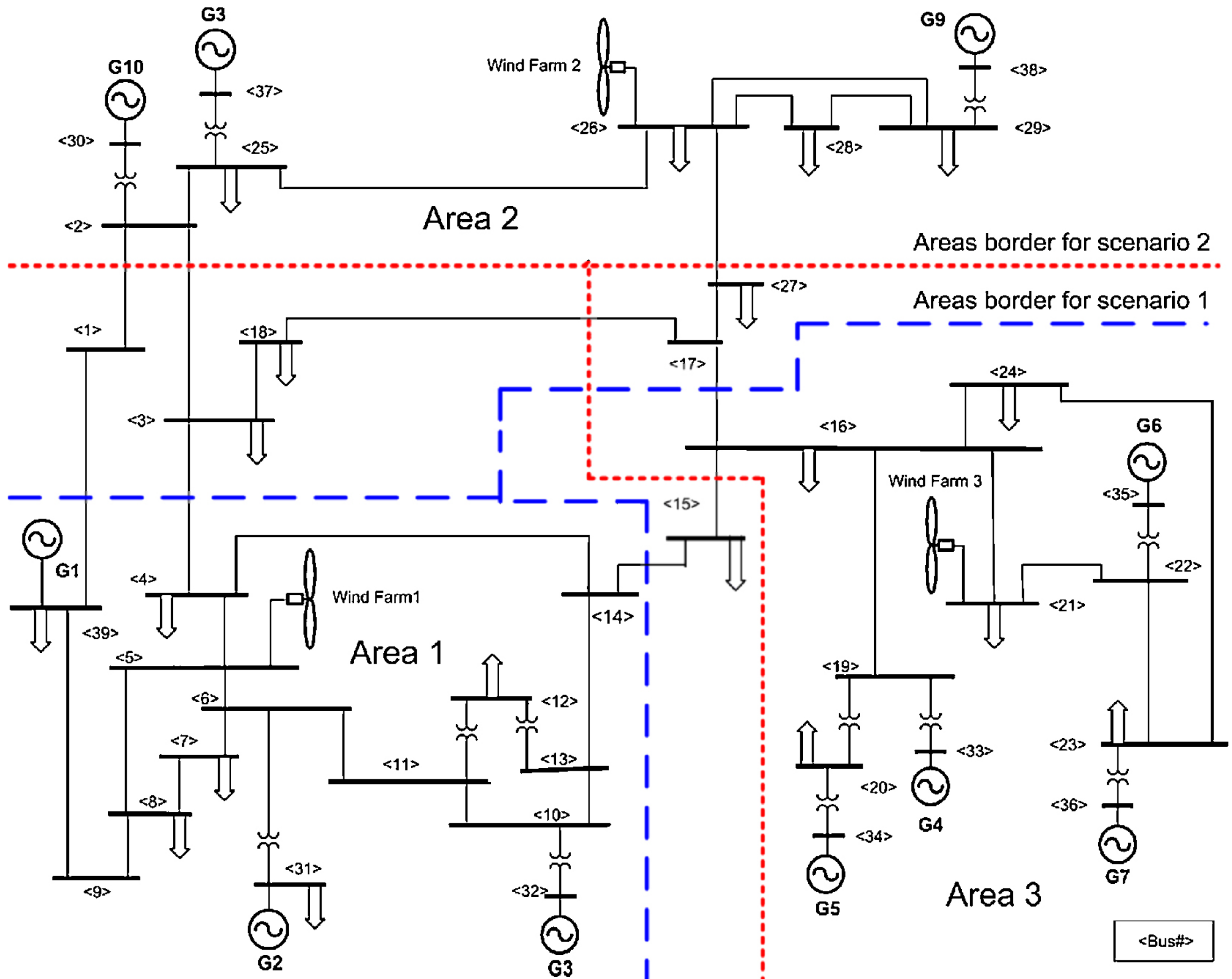
- Besides, the AGCs based on intelligent control schemes such as NN, FL, and GA are also proposed to make feasible the large wind power integrations into the conventional power system for frequency control capabilities

- Soft computing techniques can be utilized to concurrently optimize the parameters of the AGC and DFIG to additionally improve the frequency control ability of the system

AGC with RES

AGC in Renewable Energy Generation Systems – Wind generator

Single-line diagram of a typical test system for LFC with Wind Generators

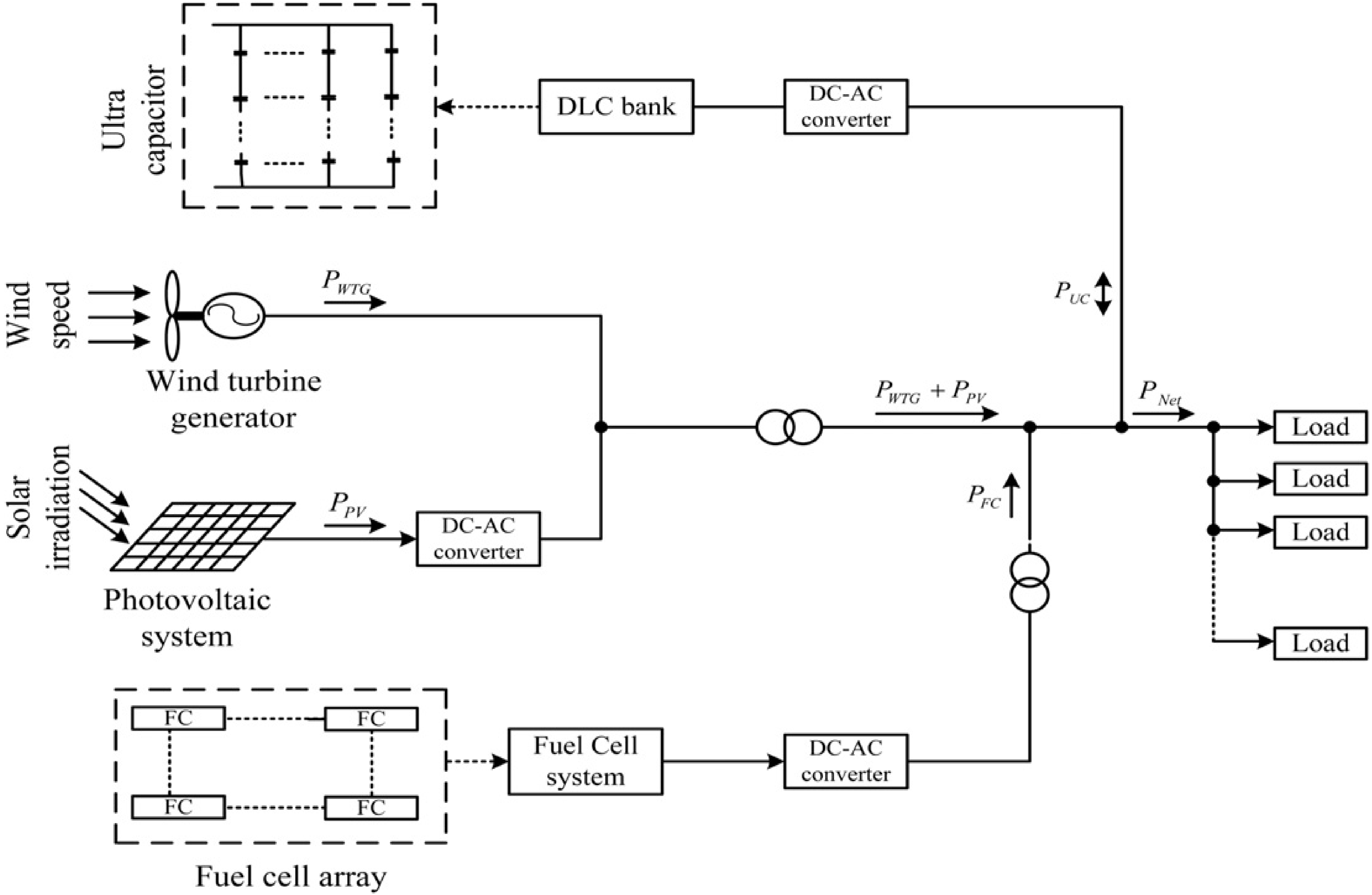


AGC with ESS

AGC Incorporating Energy Storage Systems (ESS)

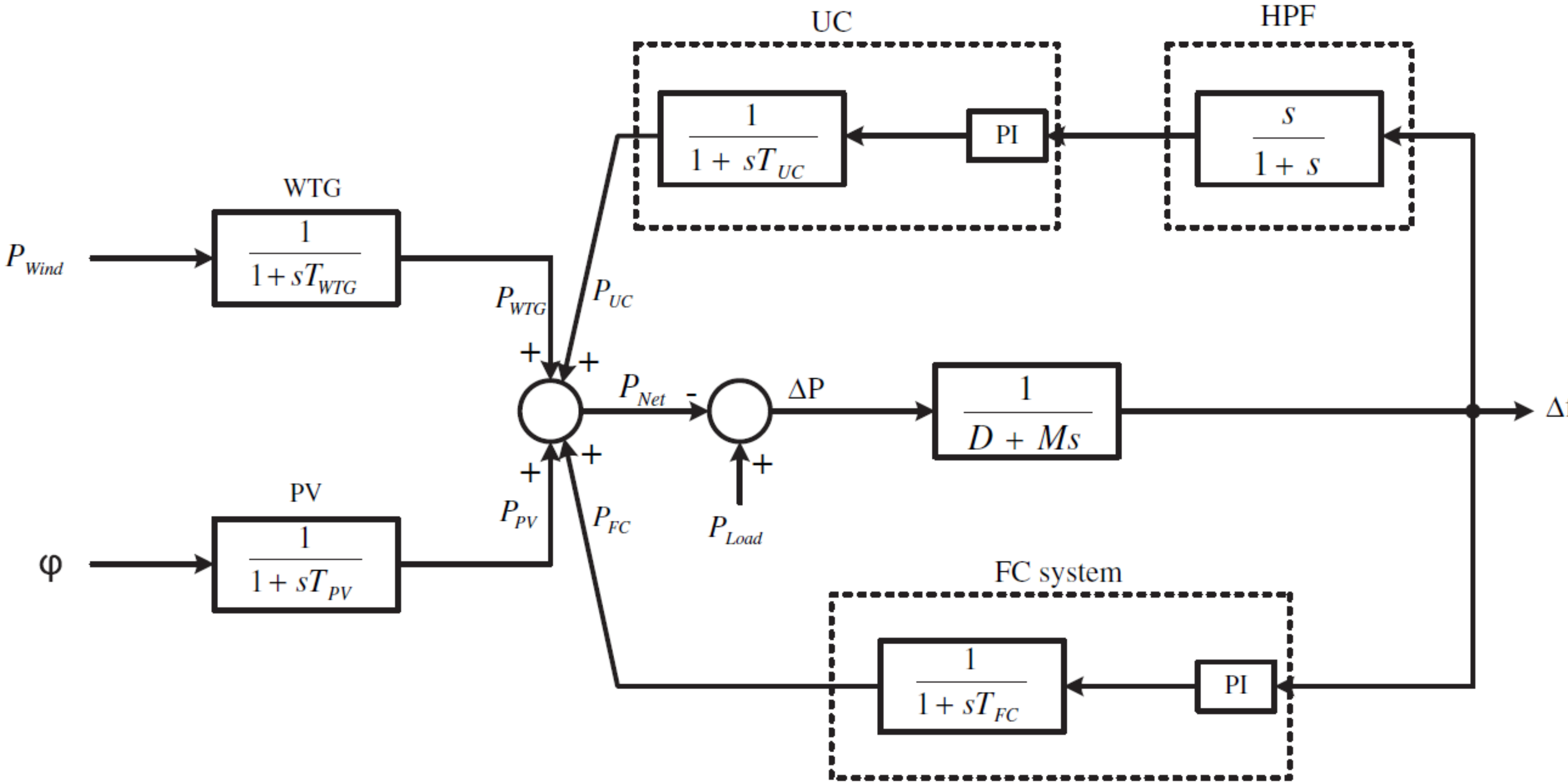
- The integration of capacitance storage units (CES) units with FACTS devices into the LFC provides better transient performance in arresting the frequency dips and the deviation in the tie-lines
- ESSs with suitably designed converter/inverter can effectively be used as sources of active and reactive power support in case of LFC requirements
- Incorporating ESSs in AGC loop improves dynamic efficiency against frequency oscillations and other external disturbances
- Other storage solutions used for improving performance of LFC:
  - double-layer capacitor (DLC)
  - supercapacitor and Li-battery
  - Fuel cell

AGC with ESS



Ultra capacitor
DLC bank
DC-AC converter
P_{UC}
Wind speed
P_{WTG}
Wind turbine generator
$P_{WTG} + P_{PV}$
P_{Net}
Load
Load
Load
Load
Solar irradiation
P_{PV}
DC-AC converter
P_{FC}
Photovoltaic system
FC
FC
FC
FC
Fuel Cell system
DC-AC converter
Fuel cell array

AGC with ESS



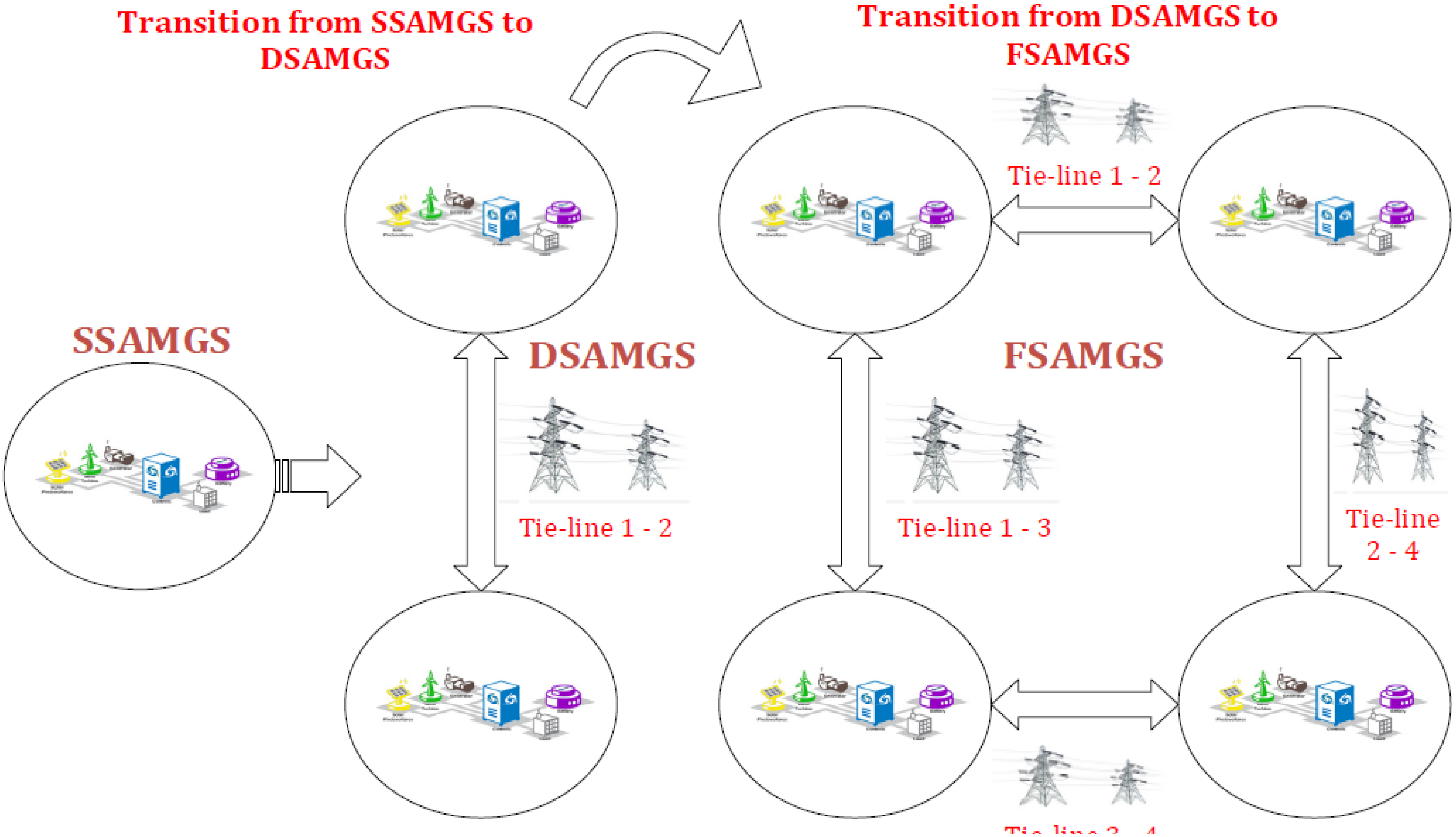
UC
HPF
1
1 + sT_UC
PI
s
1 + s
WTG
P_Wind
1
1+ sT_WTG
P_WTG
P_UC
+
+
P_Net
-
ΔP
1
D + Ms
Δf
+
+
+
PV
P_PV
P_FC
P_Load
φ
1
1+ sT_PV
FC system
1
1+ sT_FC
PI

AGC in Micro Grid

AGC in Microgrids

- A microgrid (MG) is a fairly recent phenomenon in the contemporary electricity sector, comprising small power systems with the ability to work in isolation from the main grid and is known for its resilience and reliability
- MG is capable of handling traditional and non-conventional generation units like micro-turbine generators (MTG), diesel engine generators (DEG), fuel cells, wind turbine generators (WTG), solar photovoltaic generators, solar thermal power generators, and energy storage units like, flywheel storage system, ultra-capacitor, and Superconducting Magnetic Energy Storage (SMES)
- MG supports these units as a single entity and offers essential control capabilities

AGC in Micro Grid



SSAMGS: Single Area Stand-Alone Microgrid System

DSAMGS: Dual Areas Stand-Alone Microgrid System,

FSAMGS: Four Areas Stand-Alone Microgrid System

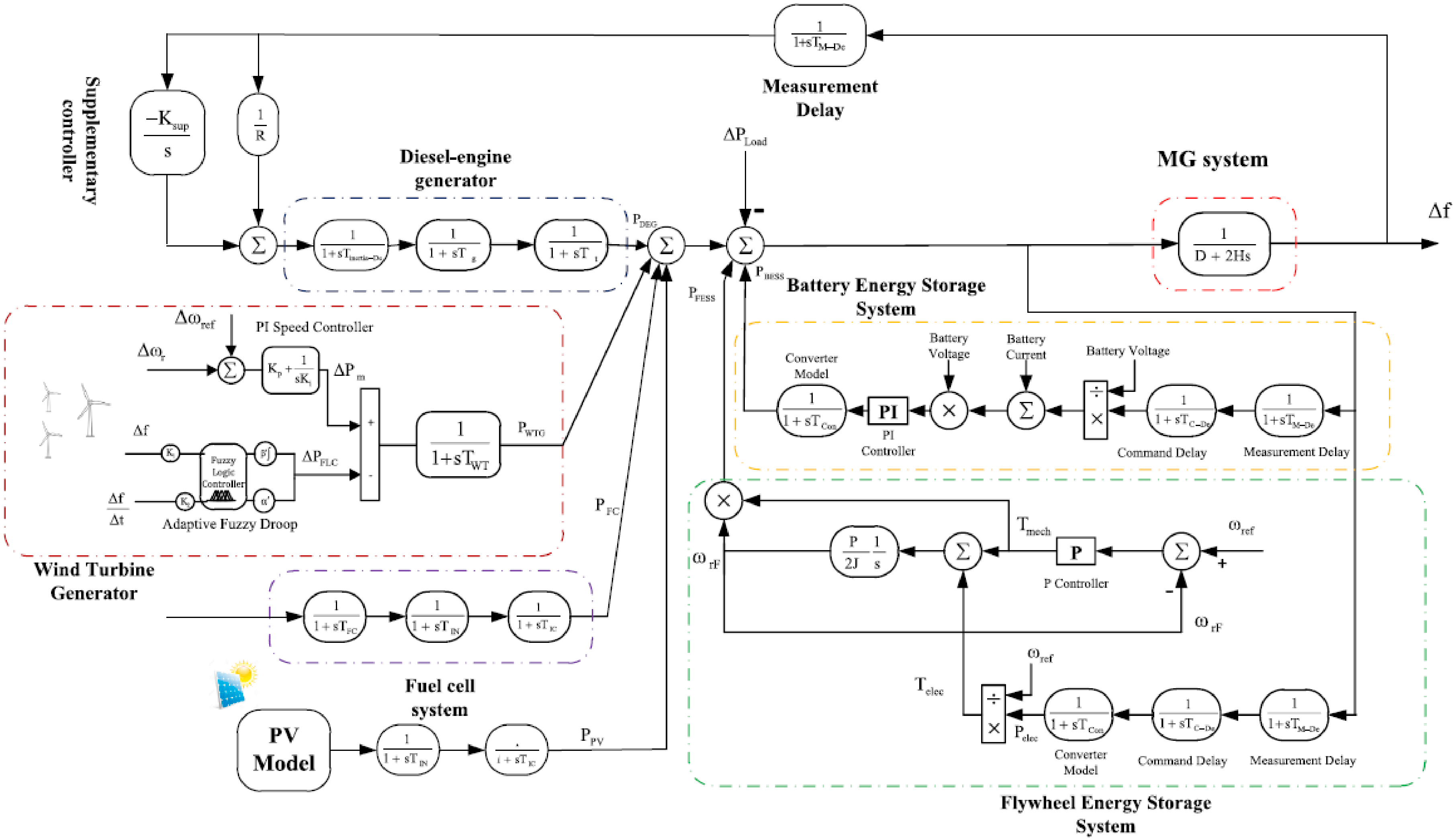
AGC in Micro Grid

AGC in SSAMGS

- MG in stand-alone mode is mostly used in areas that are inaccessible to the central grid
- Here the purpose of the AGC is to control the frequency and hold the value of each generation unit within the optimum range
- However, due to low inertia and unpredictable nature of RESs, microgrids are highly exposed to unstable oscillations in frequency
- To encourage the reliable participation of wind power and photovoltaic power into the LFC of a stand-alone microgrid system, it is necessary to study the accurate prediction model of solar and wind sources
- The forecasted power from both solar and wind need to be utilized in the LFC control algorithm of the SSAMGS

AGC in Micro Grid

AGC in SSAMGS



AGC in Micro Grid

AGC in MSAMGS

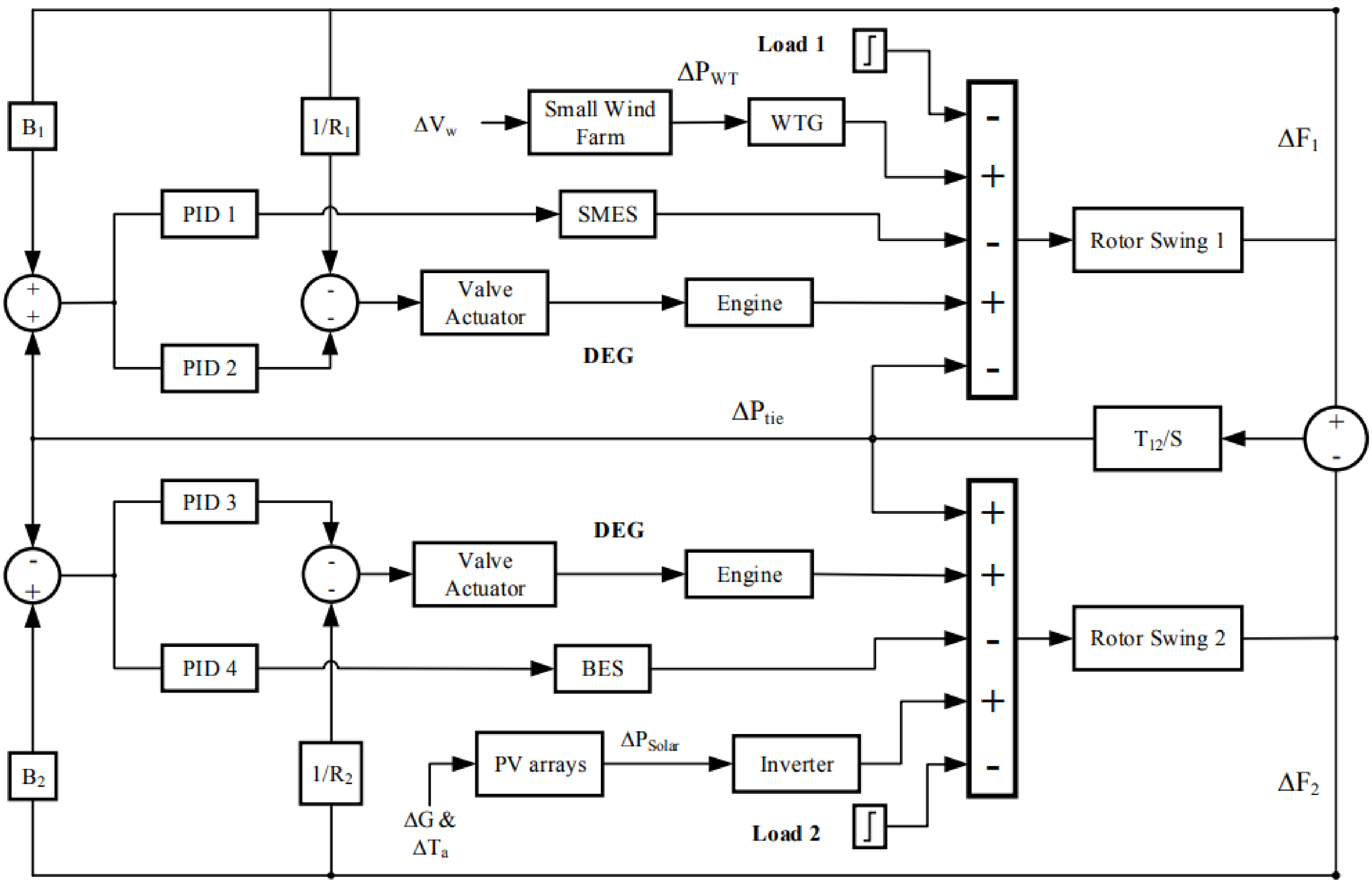
- To meet the consistently increasing daily load demands and to supply reliable power, the idea of the multiple areas stand-alone microgrid system (MSAMGS) is another promising Solution

- Villages far away from the main grid can develop MSAMGS to meet their daily load demands

- But microgrids with multiple areas are still susceptible to the frequency oscillations due to many factors such as a low moment of inertia and the volatile nature of renewable energy sources

AGC in Micro Grid

AGC in MSAMGS



AGC in Micro Grid

AGC in Microgrids - Comparison of AGC schemes in microgrids networks

Type of Power System	Areas	Energy Generation Sources	Additional Devices	Controller Approach
SSAMGS	1	DEG, WTG	FESS, FC	ABC based fuzzy-PID
SSAMGS & MSAMGS	1,2	Wind, MH, and BG,	-	NQOSO based PID
SSAMGS	1	WTG, PV	DLC, FC	GA based PID
SSAMGS	1	DEG, WT, PV,	FC, BESS, FESS	ABC based TSMC
SSAMGS	1	PV, WTG, DEG,	AE, FC, BESS	PI control
SSAMGS	1	WTG, DEG, PV	BESS, FESS	LADR control
SSAMGS	1	Wind, PV, DEG	BESS, SMES	PSO based ANN
MSAMGS	2	WTG and PV	SMES, BES	SSO based PID
MSAMGS	2	MT, PV DEG	FC, BESS	I-SSO based type-II fuzzy PID
MSAMGS	3	WTG, PV, PTC	ESS	MBA based 2DOF-PID

Abbreviations: FESS - Flywheel energy storage systems, FC – Fuel cell, DLC – Double layer capacitor, BESS - Battery Energy Storage System, AE – Air Energy storage, SMES - Superconducting Magnetic Energy Storage

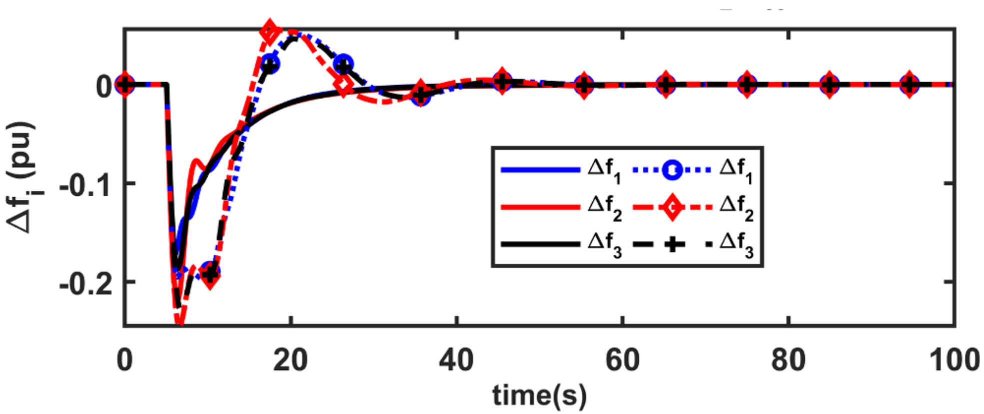
Abbreviations: NQOSO: novel quasi-oppositional selfish-herd optimization algorithm, SSO: Social-spider optimizer; I-SSO: improved-salp swarm optimization; DSTS: Dish-Stirling solar thermal systems, MBA: mine blast algorithm, FISCA: Fuzzy improved sine cosine algorithm, AWEC: Archimedes wave energy conversion, VIC: Virtual Inertial Controller: LADR: Linear Active Disturbance Rejection.

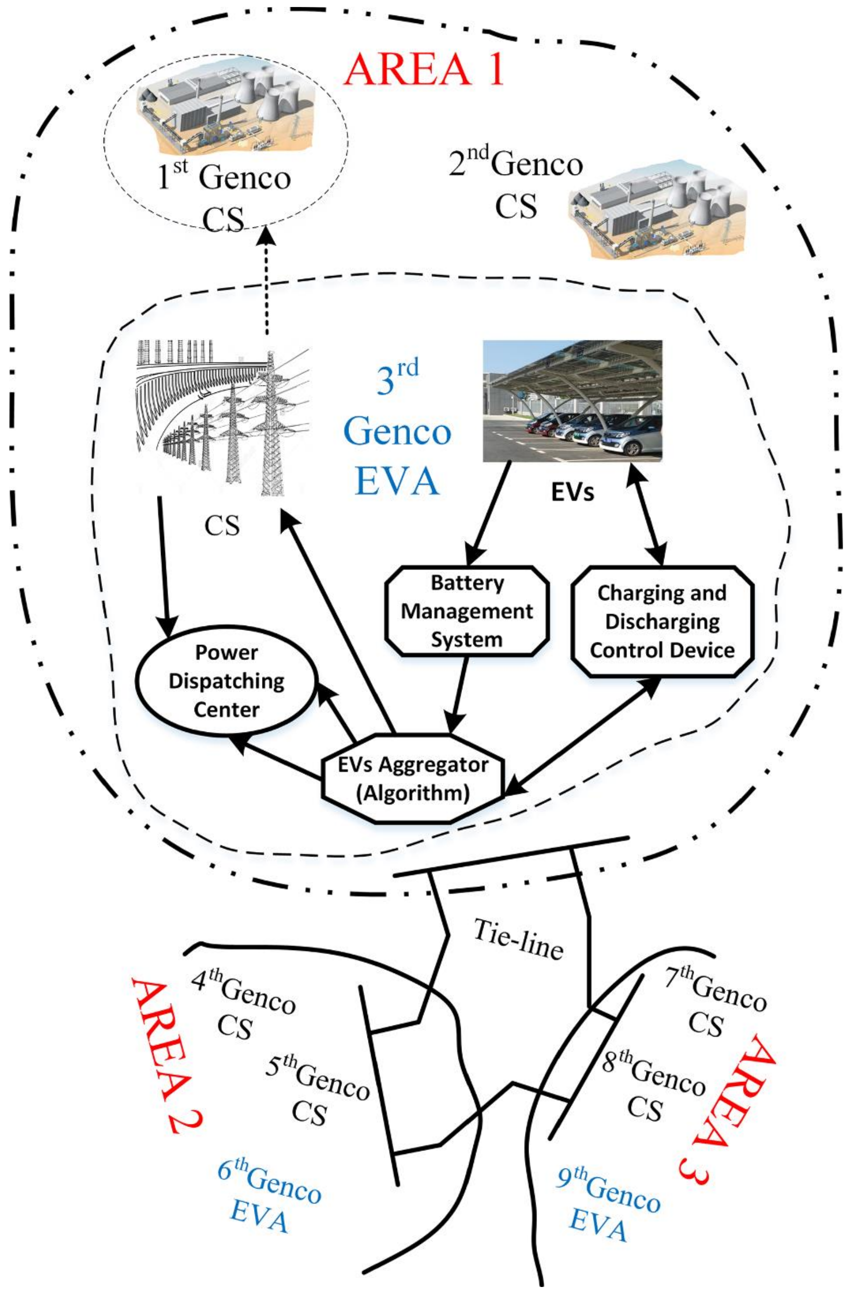
AGC in Smart Grids

AGC in Smart Grids

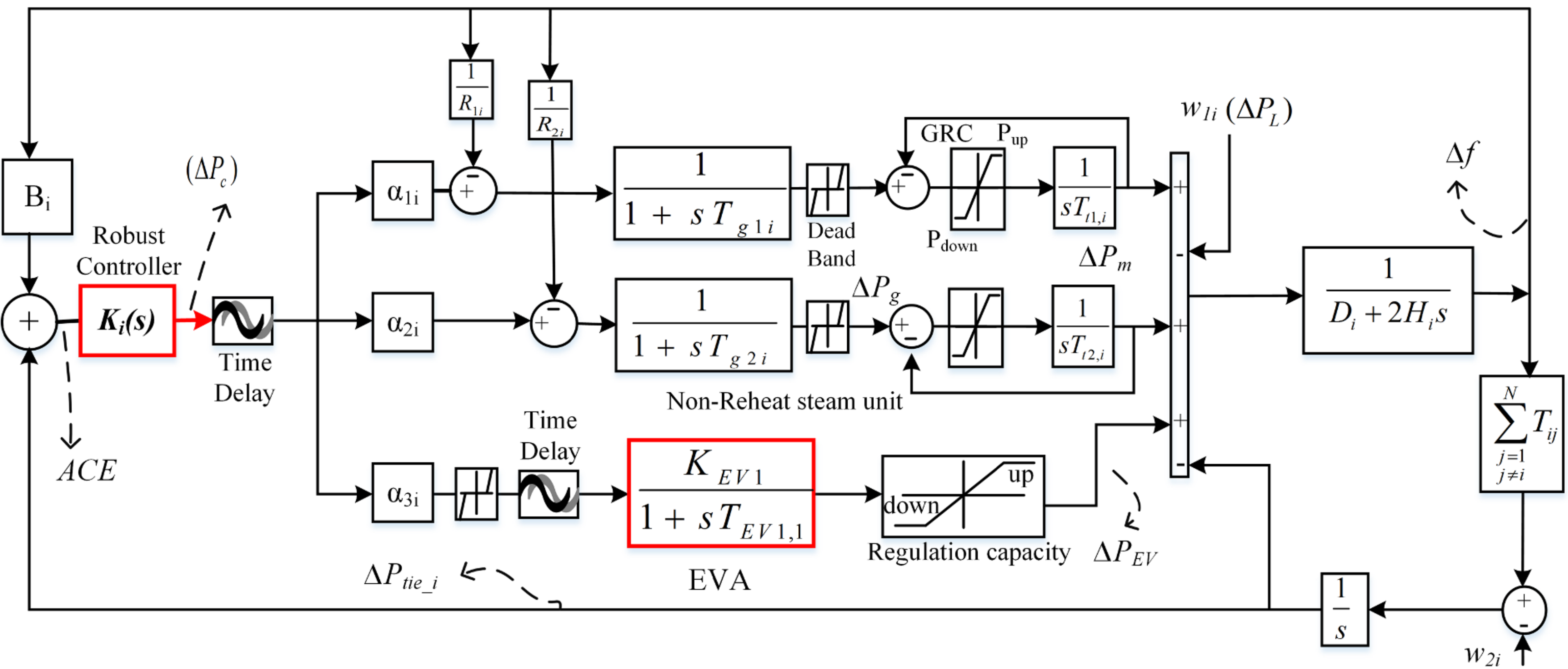
- Designing an AGC system for the smart grid (SG) is another prominent issue
- The smart management of EVs power provides the best opportunity to use it as a vehicle-to-grid (V2G) source for AGC regulators in an integrated power system
- Challenges related to the integration of EVs include uncertainty in capacity and time delay problems due to charging and discharging
- A static output feedback-based regulator can be designed for the AGC system to provide better reference tracking to both EVs and other conventional sources for ensuring the system frequency and tie-line interchange at their minimal value.
- The controller and EVs should respond intelligently in different scenarios such as load perturbation, parameters variations, dead band effects, and time delay problems

AGC in Smart Grids





AGC in Smart Grids

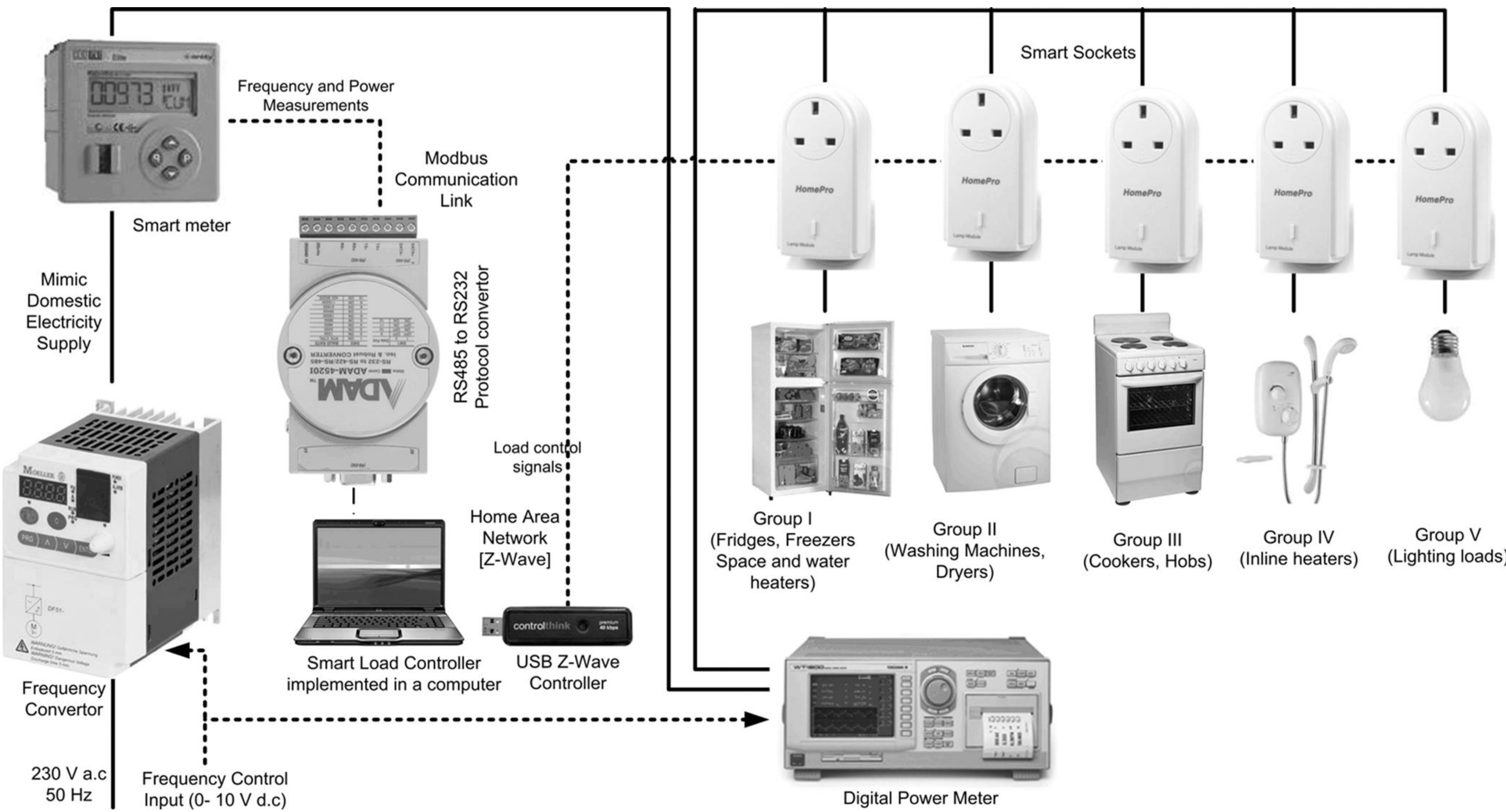


AGC in Smart Grids

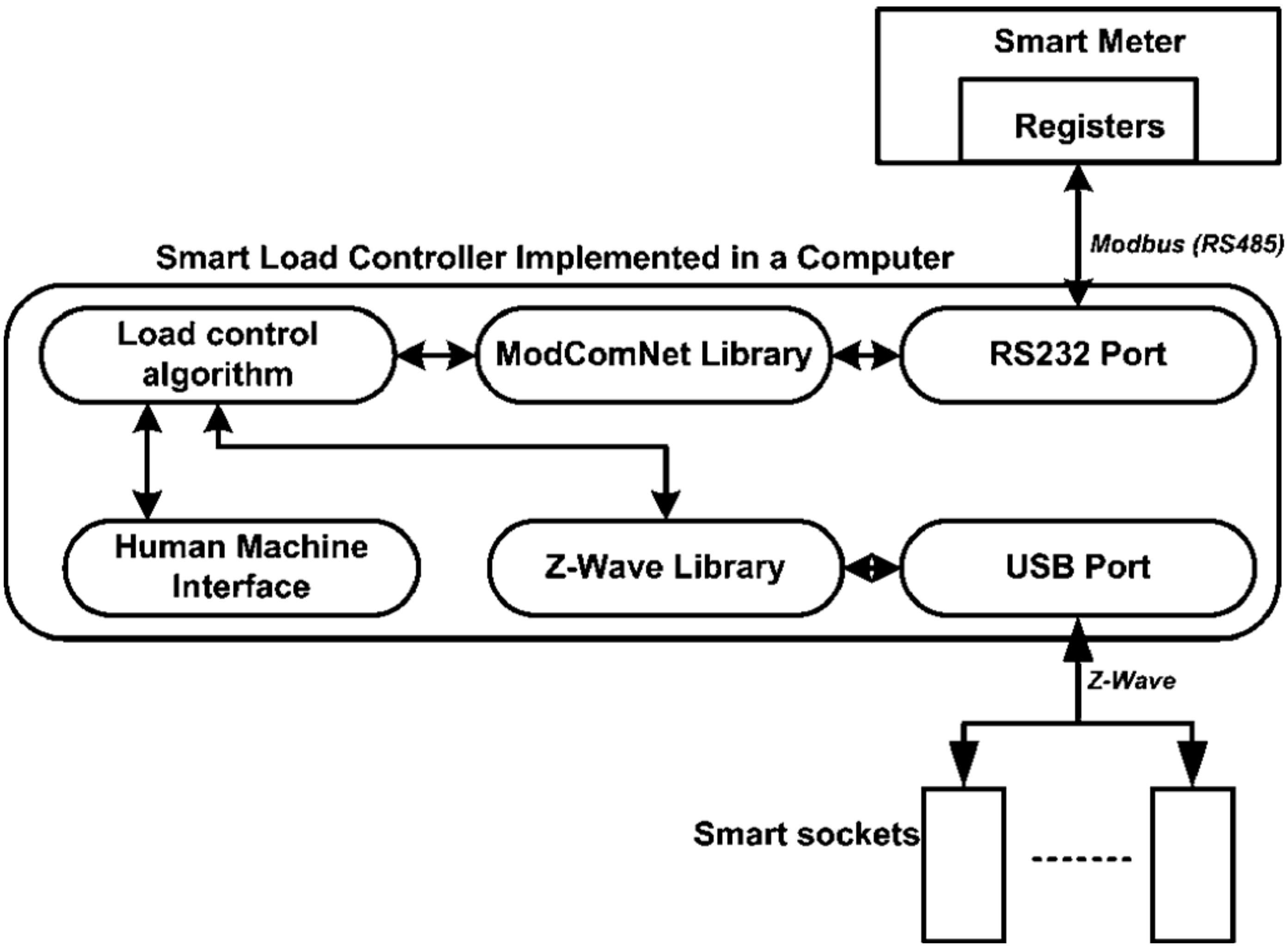
AGC in Smart Grids

- Dynamic demand response is another main aspect of the SG and has to be incorporated for AGC models
- Controlling the domestic demands directly from the smart meters
- LFC schemes should be designed to measure the load frequency using the smart meters
- An active power balance control strategy can also be adopted that considers the integration of flexible loads and RES in AGC
- Incorporation of flexible loads and RES into the AGC system can eradicate the fluctuations via provisioning of active power support to the real-time imbalances

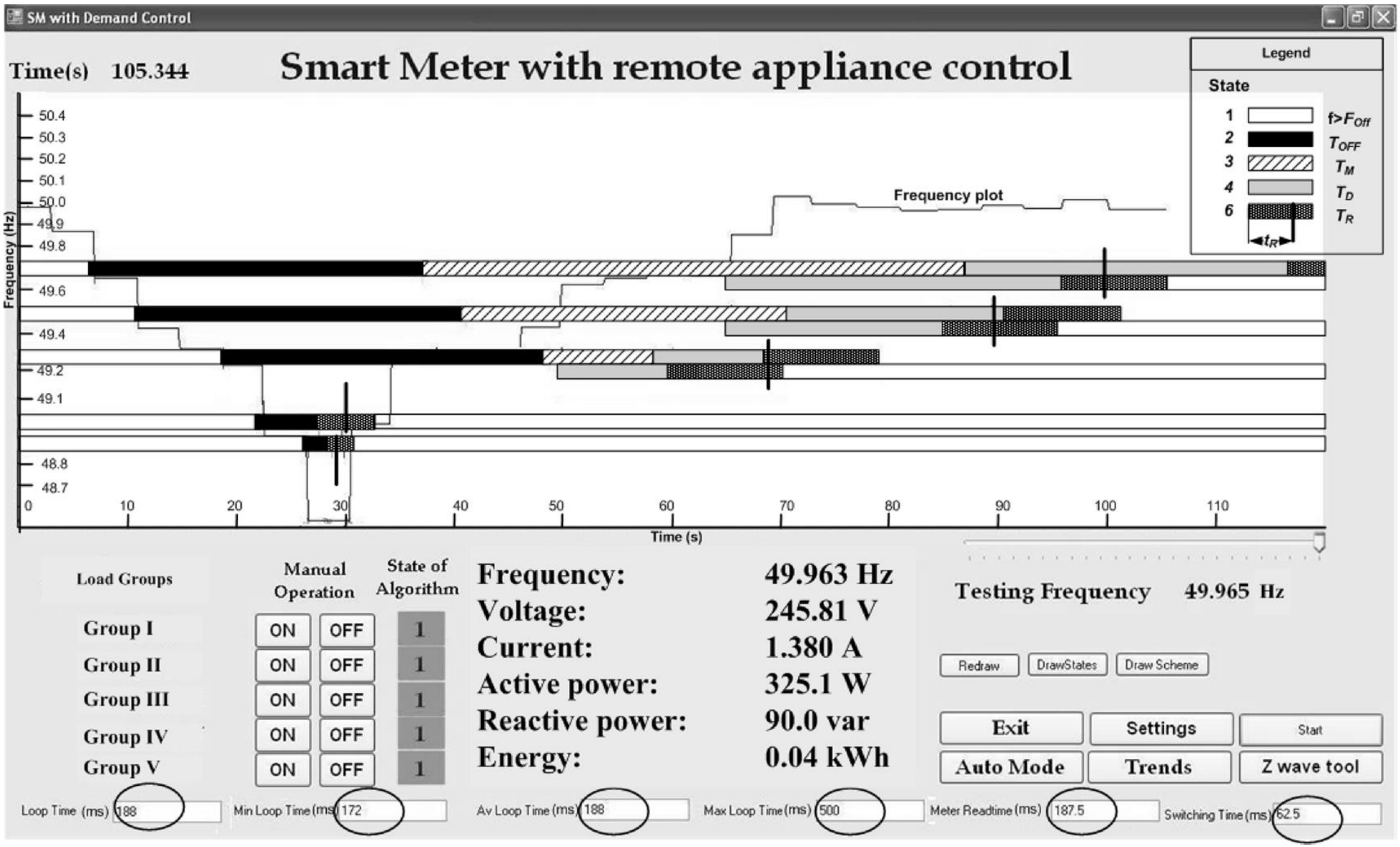
AGC in Smart Grids



AGC in Smart Grids



AGC in Smart Grids



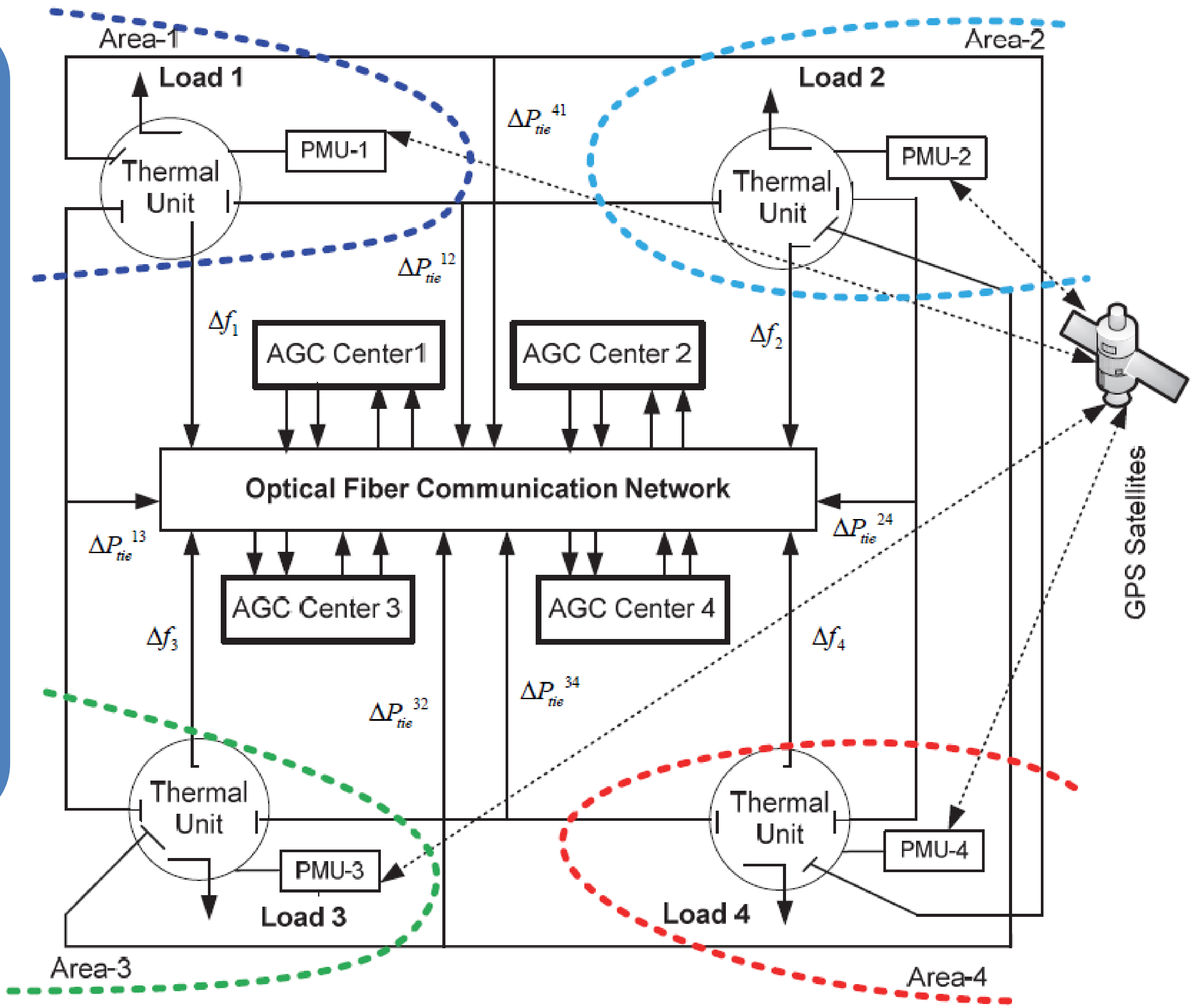
AGC in Smart Grids

AGC in Smart Grids – effect of communication network

- The betterment of the connectivity networks in a multi-area interrelated power grid for AGC problems mediated effects like:
  - time delay
  - packet loss
  - Bandwidth
  - Quantization
  - change in communication topology

AGC in Smart Grids

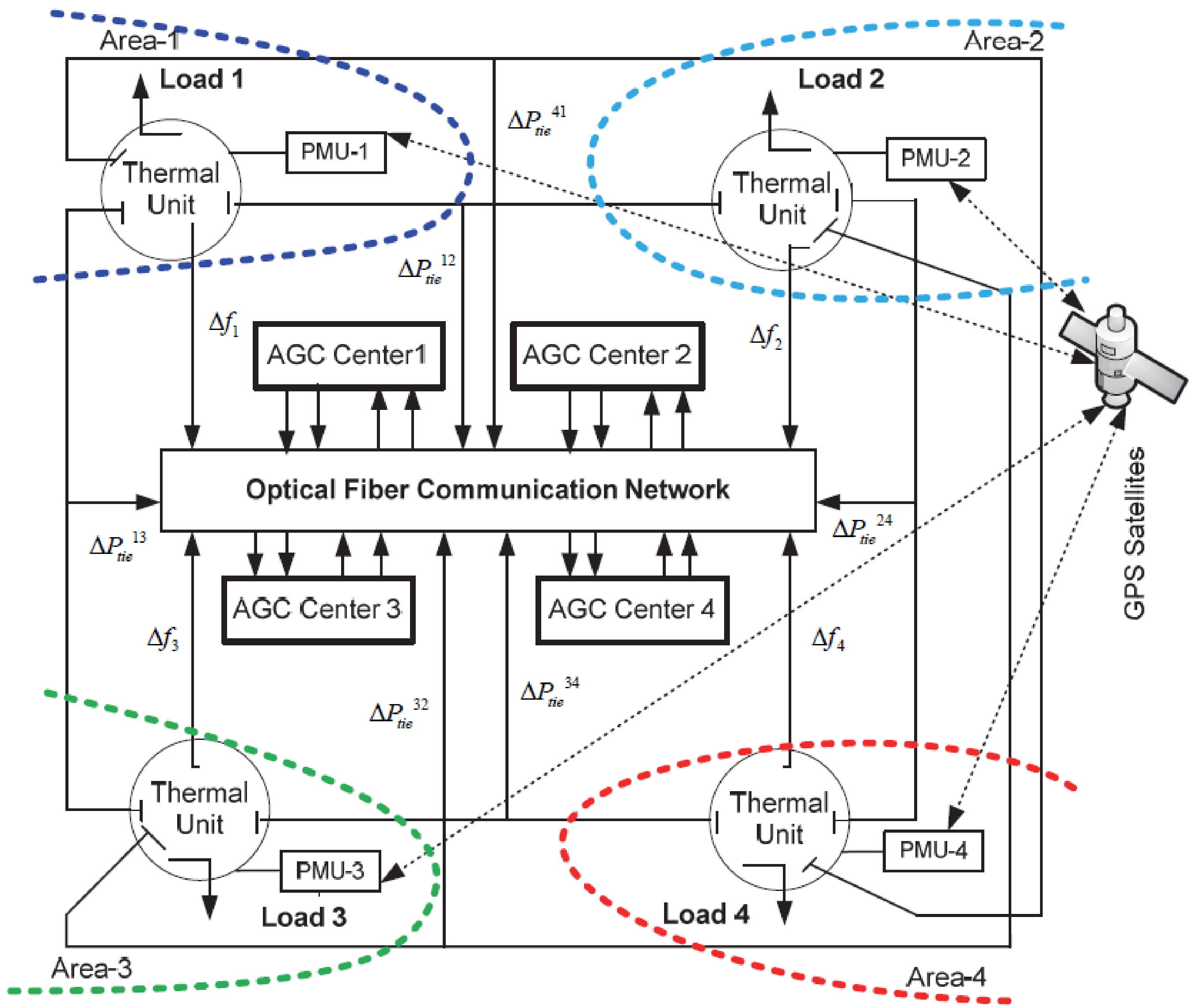
Each generation unit is associated with PMU which is responsible for tie-line power measurements between two areas



AGC in Smart Grids

The tie-line power signal is sampled at PMU and transmitted to the local/control center through communication network

All the PMUs are time-synchronized with GPS satellites



AGC in Smart Grids

AGC in Smart Grids – Cyber threat

- The reliability of the LFC schemes is highly vulnerable to cyber-attacks, which can amend the critical variables data of LFC system and make received data unreliable leading to system frequency oscillations and even collapse
- The two main types of cyber attacks against power systems are:
  - false data injection (FDI) attacks, and
  - denial of service (DoS) attacks
- A detection scheme for the detection of cyber-attacks on actual data of compromised variables need to be put in place
- Secured phasor measurement unit (PMU) measurement is used to detect malicious attacks on power grids
- Adopting appropriate communication protocol and event-triggered control scheme can effectively mitigate the impacts of DoS attacks

Smart AGC

Smart AGC

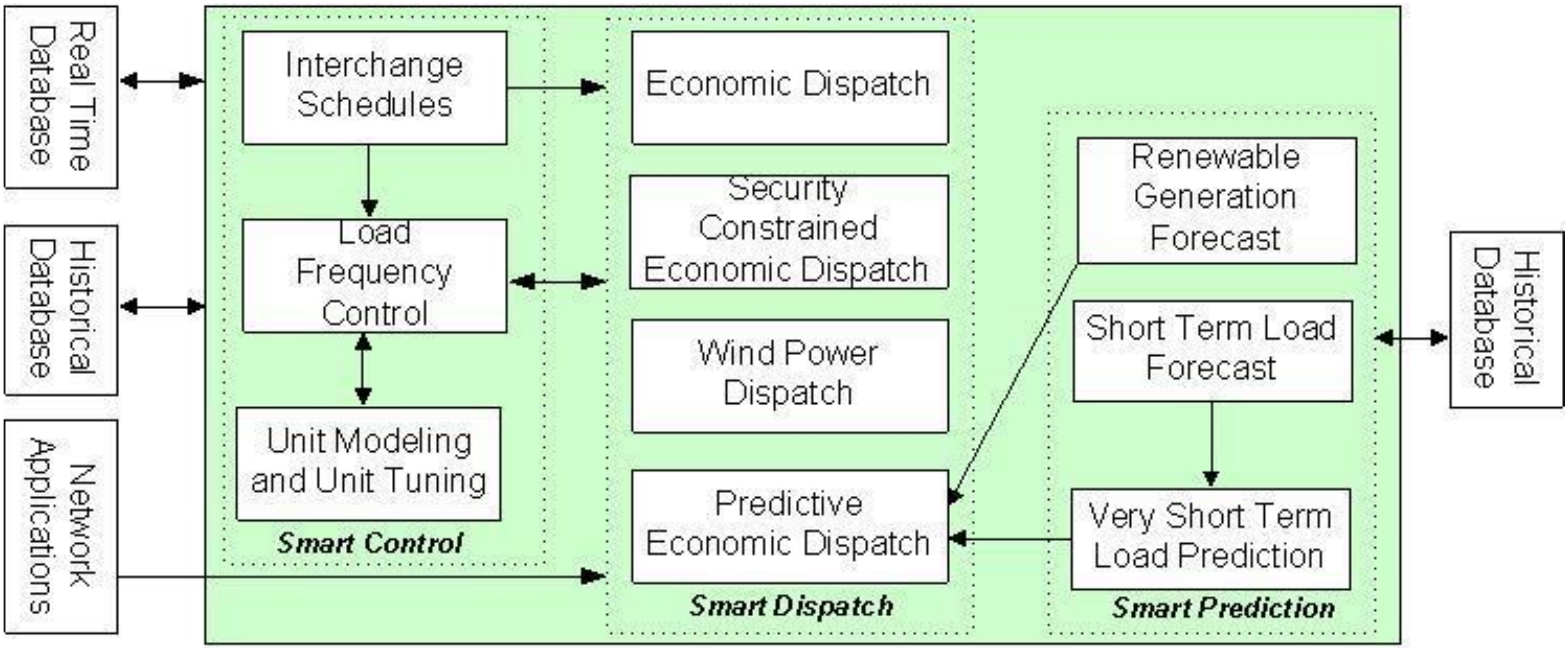
Smart AGC

- Smart AGC is composed of three core functional groups:
  - applications for smart prediction
  - applications for smart dispatch
  - applications for smart control

Smart AGC

Smart AGC - smart prediction

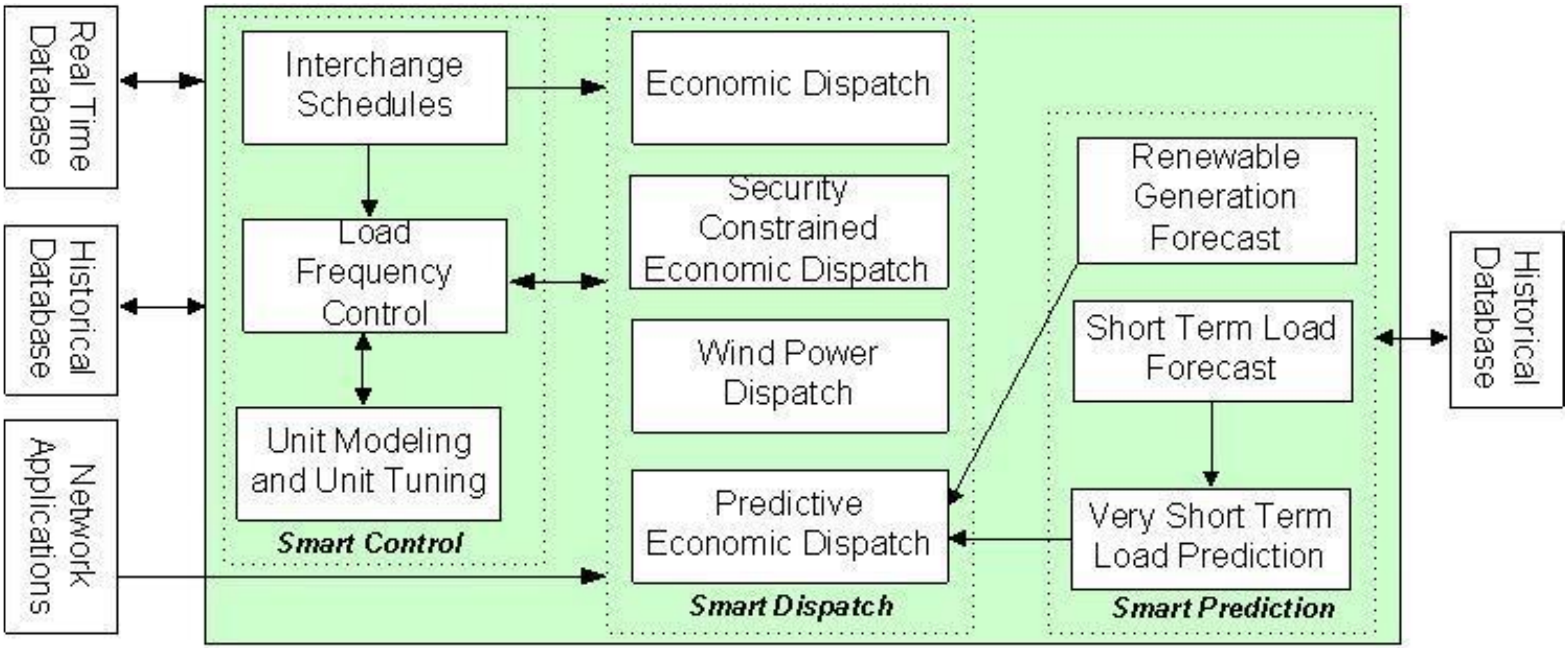
- Load forecast required for generation scheduling and dispatch
- Balancing conventional generation and renewable generation with predicted load requires accurate short-term (minute ahead or half an hour ahead) forecast for RES



Smart AGC

Smart AGC - smart prediction

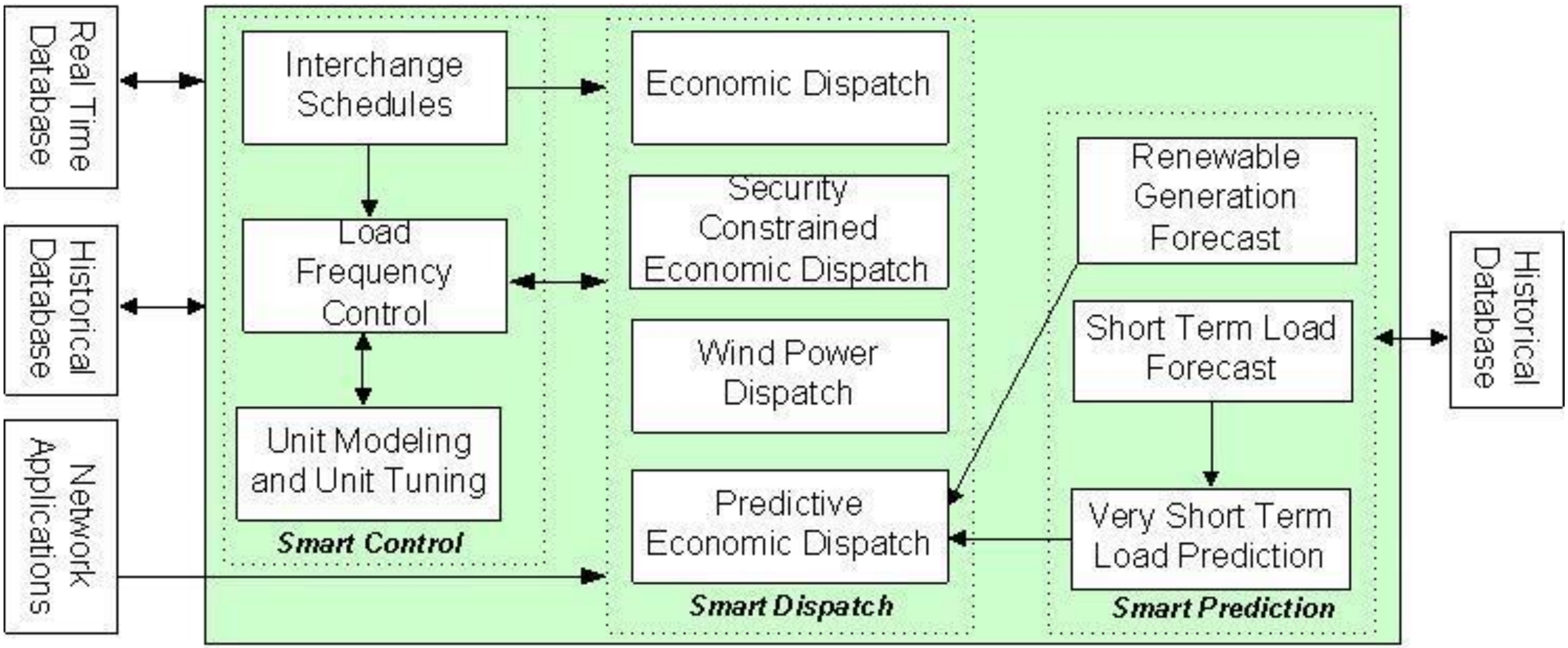
- Smart prediction is such an application group, responsible for providing very short term load predictions
- Such forecasting can be performed by employing neural network technologies



Smart AGC

Smart AGC - smart prediction

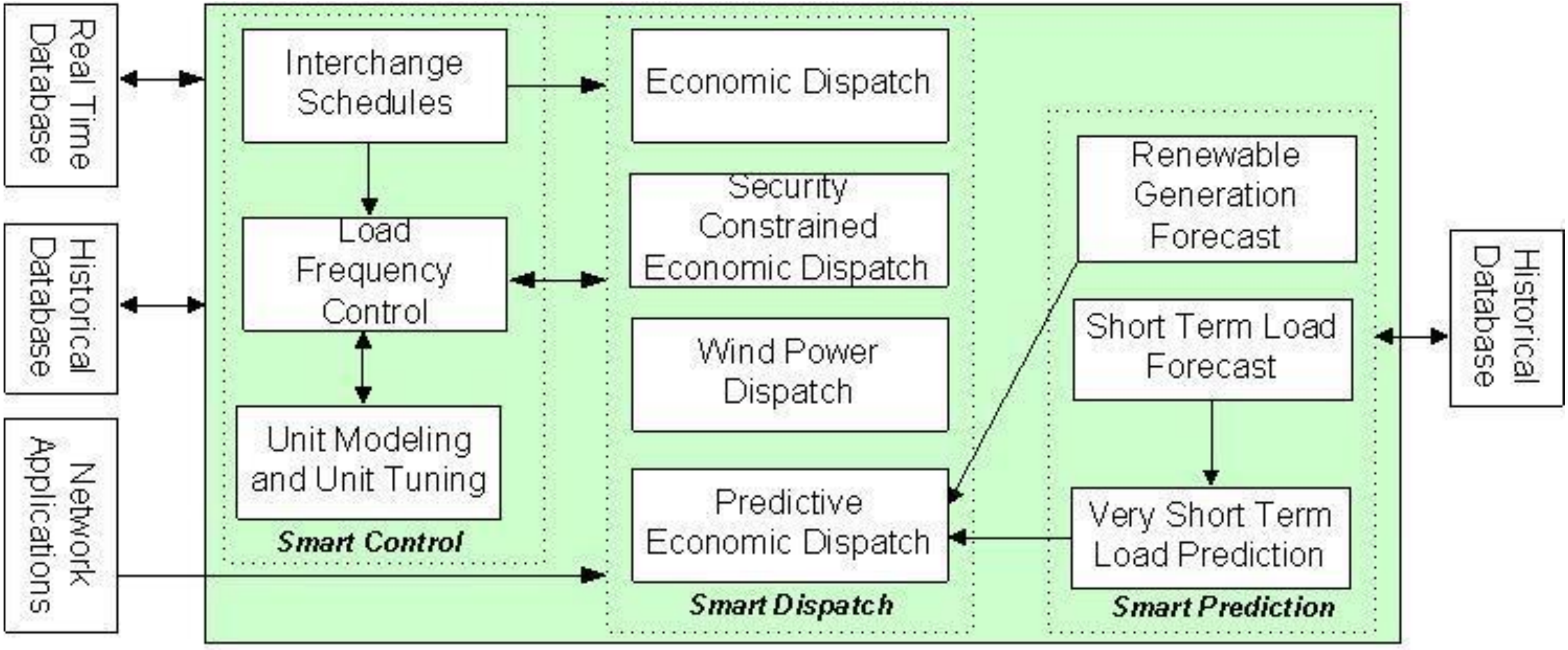
- In addition, the PV and wind generation forecast for each wind farm or groups of wind farms would give the system operators the information about the total wind generation that can be expected for both planning and real time operation purposes



Smart AGC

Smart AGC - smart dispatch

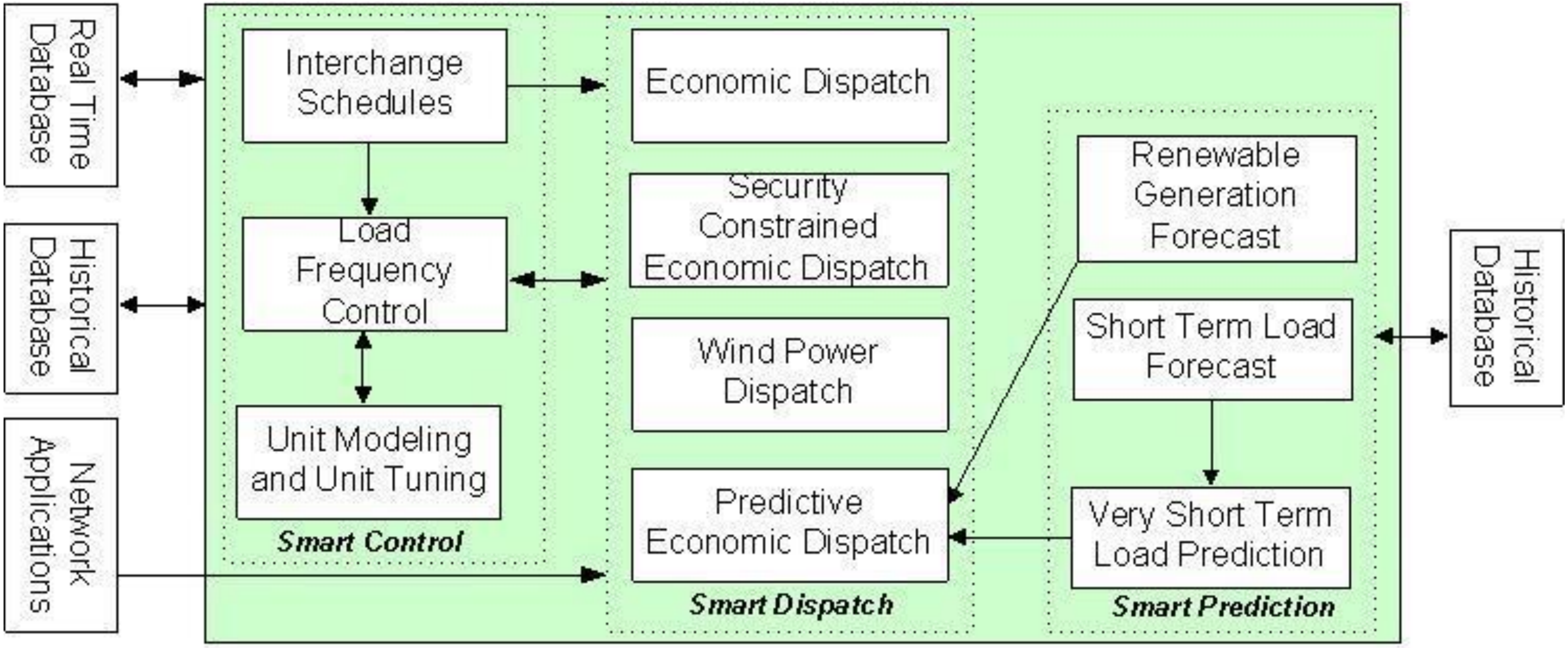
- Dispatch means coordinating all generating units in an area to deliver scheduled quality power (specified voltage, frequency) matching load demand in the area with due consideration to operational efficiency and economics



Smart AGC

Smart AGC - smart dispatch

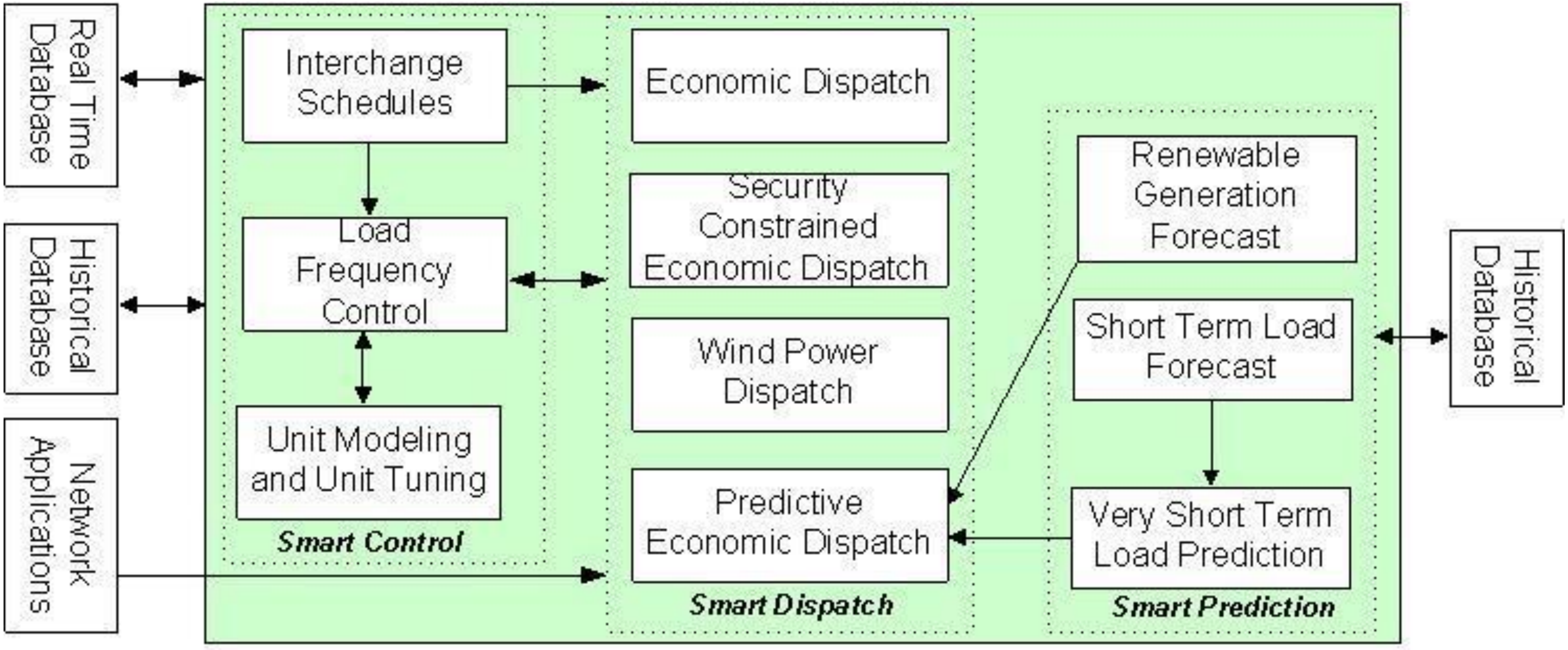
- Constraints of dispatch:
  - Regulation
  - Unit life span
  - Unit efficiency
  - Economics



Smart AGC

Smart AGC - smart dispatch

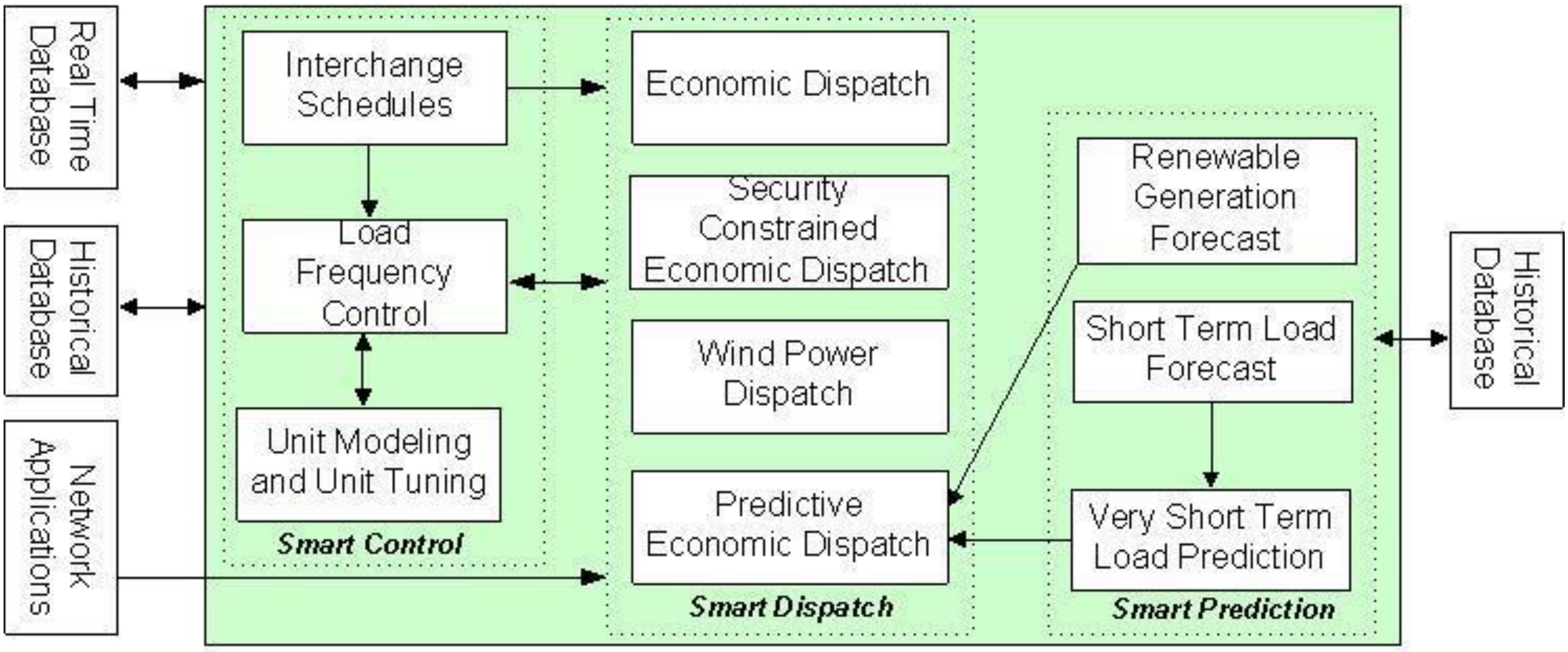
- Not all generating units are capable of regulation
- In addition, participation in regulation causes the generating unit to move up and down frequently, shortening the generating unit's life span



Smart AGC

Smart AGC - smart dispatch

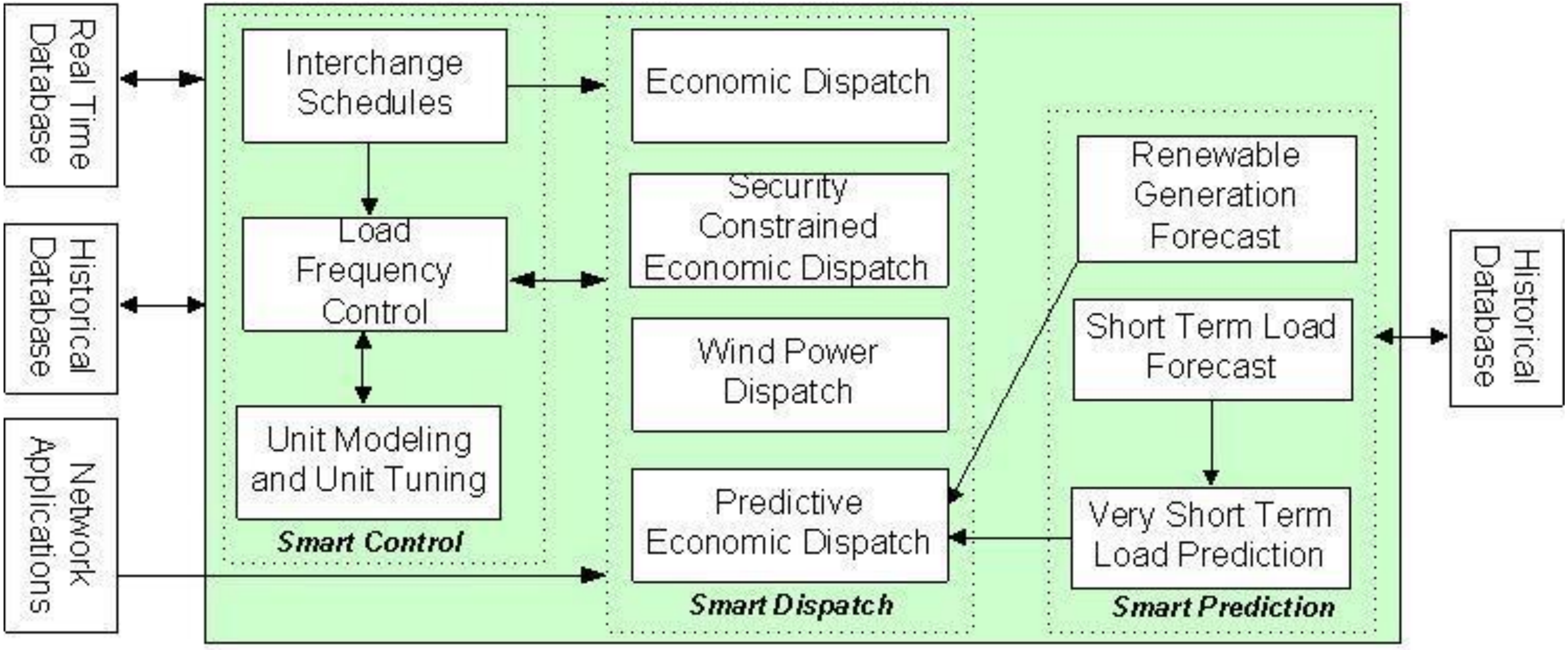
- There is a need to place generating units at sustained generation levels whenever possible and minimize the amount of regulation
- This not only reduce generation production cost and also prolong the unit's life span



Smart AGC

Smart AGC - smart dispatch

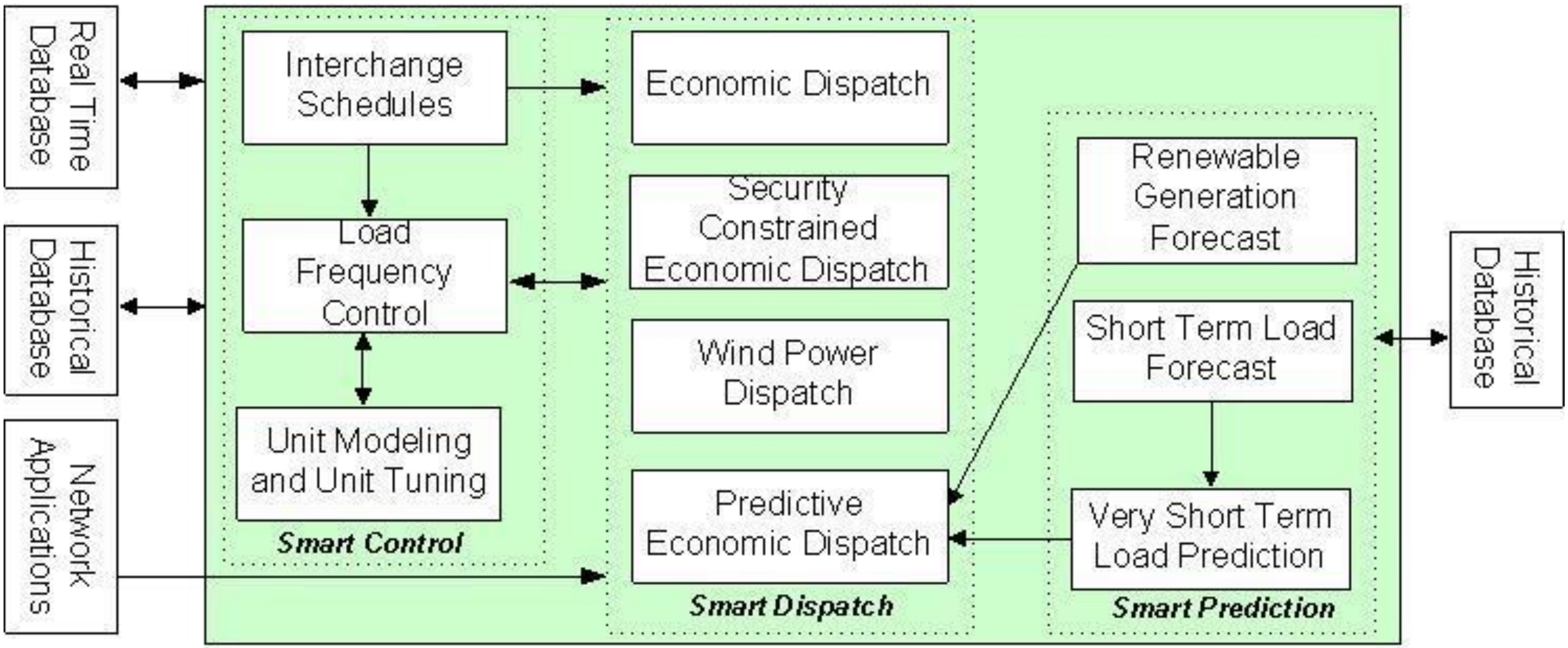
- Smart dispatch is such an application group, responsible for cyclically optimizing total generation, load, and regulation requirements
- It assigns an economic base-point to each generating unit to minimize the overall system production cost



Smart AGC

Smart AGC - smart dispatch

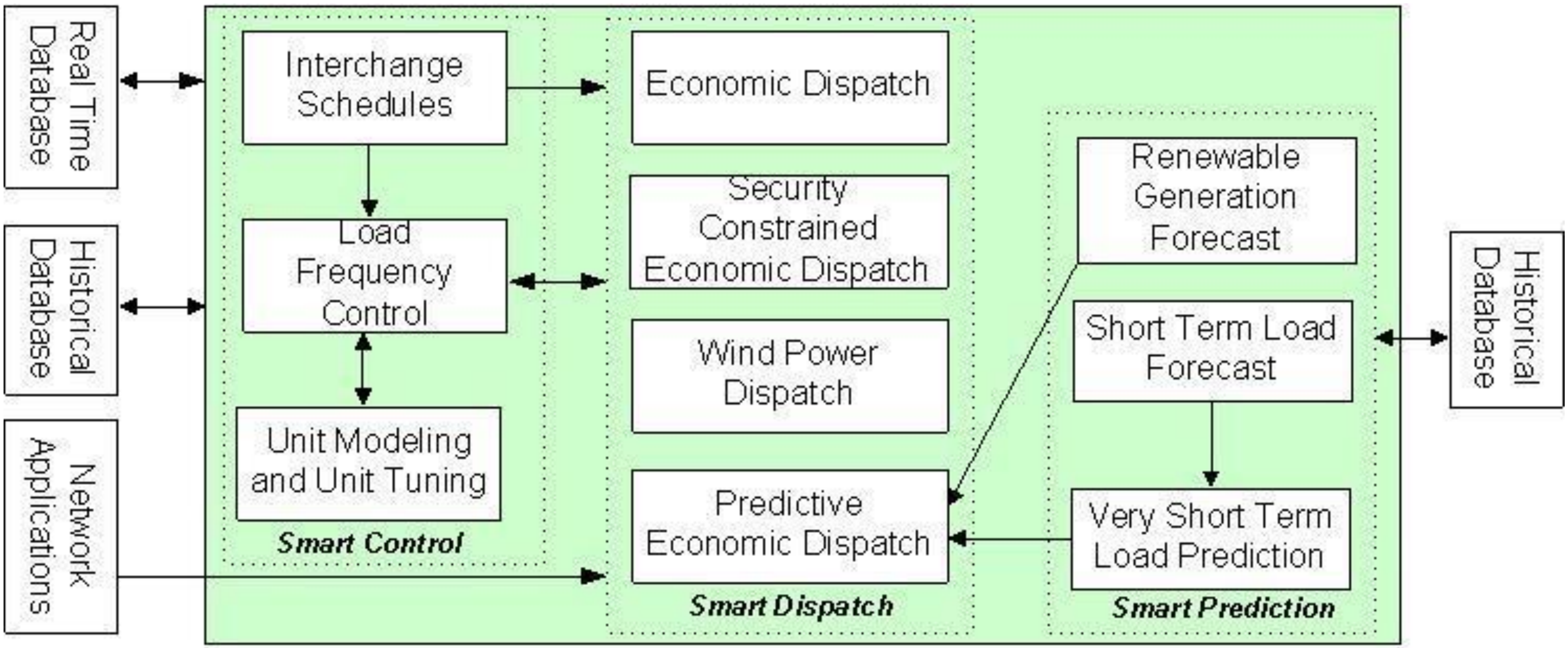
- System reserve (standby) requirements may also be well incorporated into the smart optimization process



Smart AGC

Smart AGC - smart dispatch

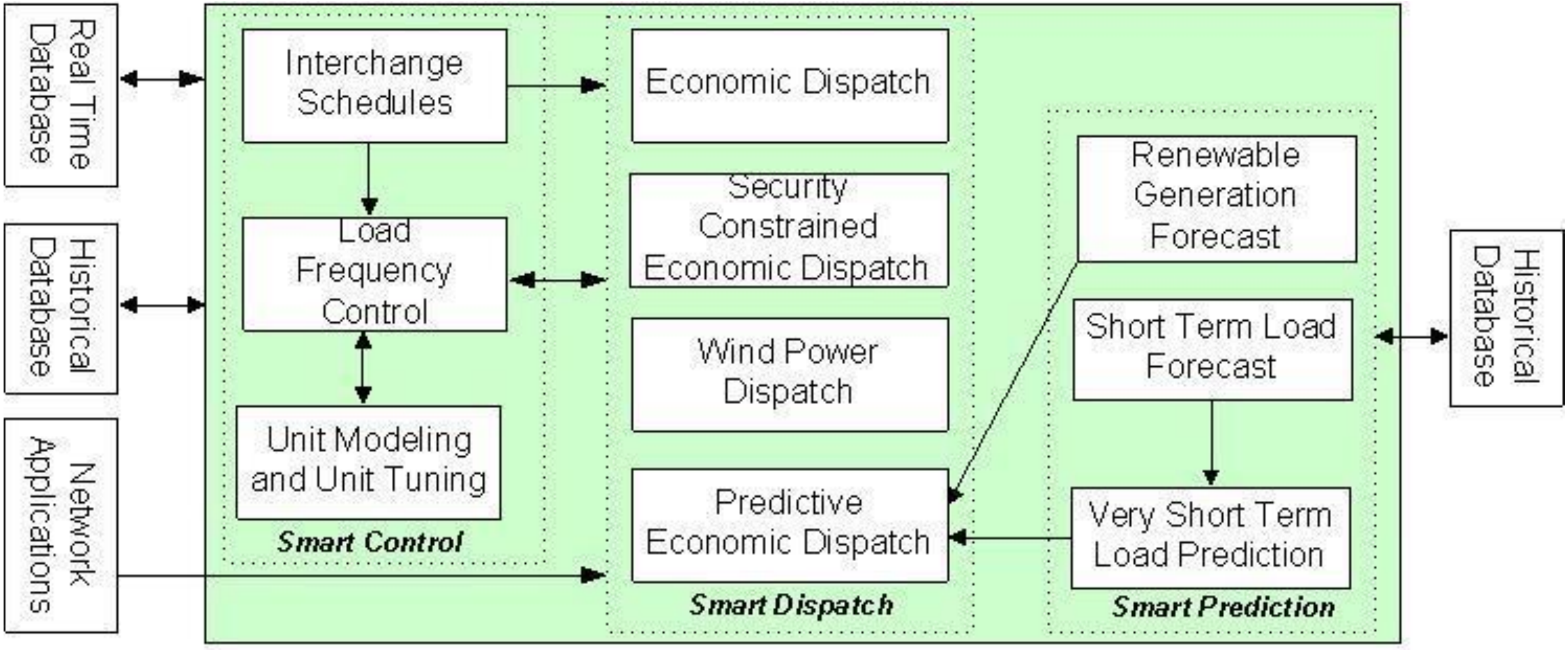
- When there is a need to consider network flow constraints, security constrained economic dispatch (SCED) is tool to derive the best economically sound base-points to also reduce or remove the overloading of transmission branches and/or corridors



Smart AGC

Smart AGC - smart dispatch

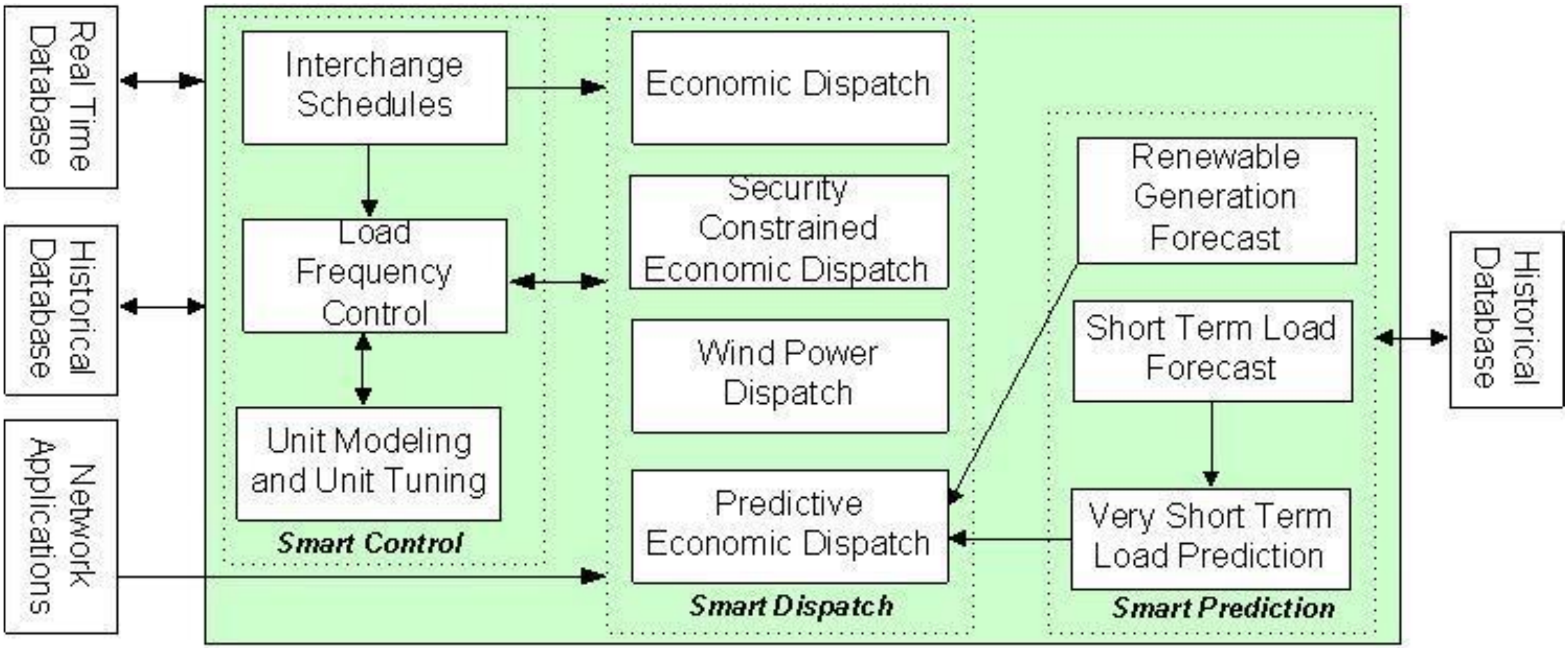
- Smart Dispatch also oversees that slow units are move up well ahead of time to provide sufficient generation for system peak load
  - Similarly slow units need to be moved down well ahead of time to provide minimum generation when the system load reaches its minimum around midnight



Smart AGC

Smart AGC - smart dispatch

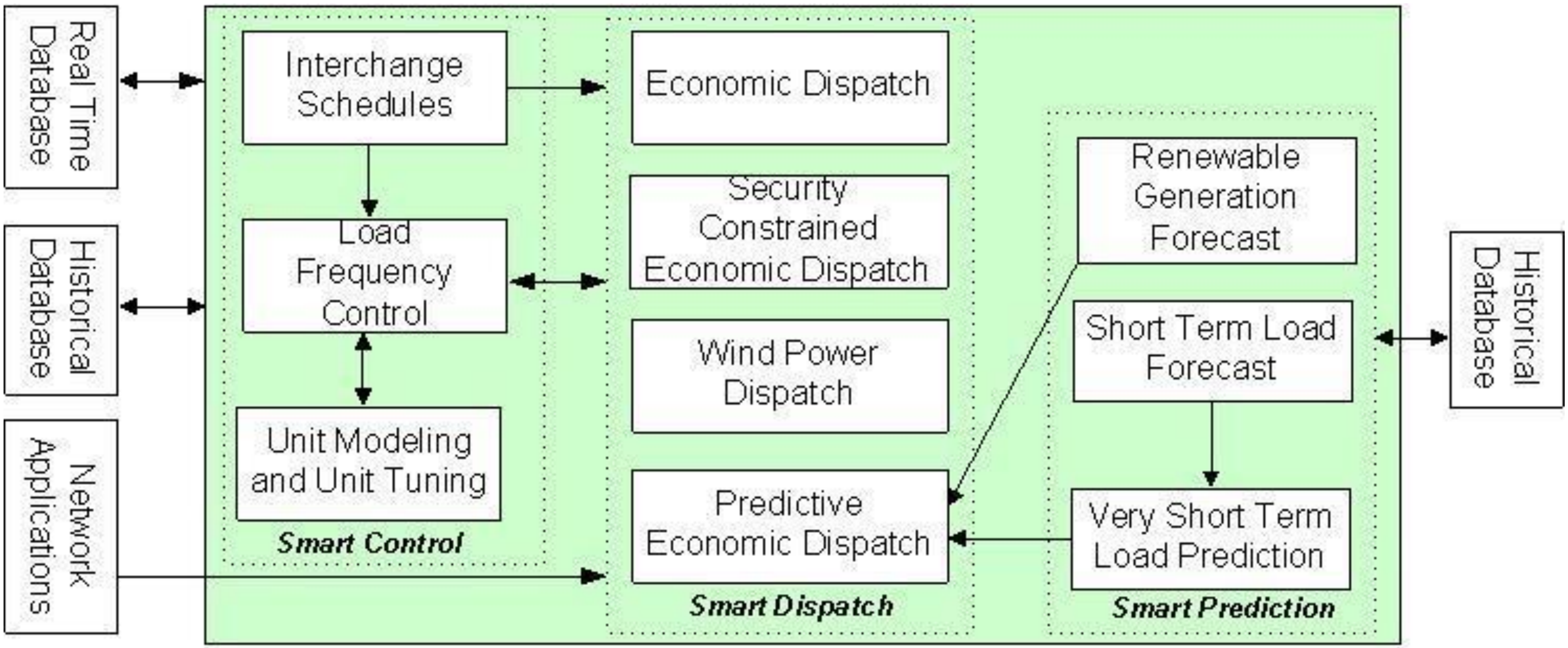
- Smart Renewable Power Dispatch is another component that optimizes the maximum RES generation level that can be integrated to grid with due consideration to network security and economics



Smart AGC

Smart AGC - smart control

- Smart control is responsible for cyclically computing total desired generation based on targets, determining the regulation obligation, and allocating the regulation to regulating units



Smart AGC

Smart AGC - smart control

- These control targets are typically updated every 1-miute and every 10-minute intervals
- Quick control response can be achieved when renewables are integrated with conventional units