NUST
Defining Futures

U.S.-PAKISTAN CENTER
FOR ADVANCED STUDIES
IN ENERGY (USPCAS-E)

Smart Grid Architecture
ESE-909 (Core)
Lecture 3

By
Dr. Syed Ali Abbas Kazmi

Performance analysis tools for smart grid design

1. *Challenges to load flow in smart grid*
2. *Load Flow Techniques Comparison*
3. *Traditional load flow techniques*
4. *Classical Load flow analysis*
5. *Distribution Load Flow Methods*
6. *Congestion Management Effect*
7. *Load flow for smart grid design*
8. *Cases for the DSOPF*
9. *Static Security Assessment (SSA) and Contingencies*
10. *Steady-State Contingency Analysis*
11. *Contingency Studies for the Smart Grid*

Challenges to load flow in smart grid

Challenges to load flow in smart grid

Current legacy methods have weaknesses that need to be addressed prior to their use in analyzing SG performance and operations.

Four fundamental questions should be answered:

1. What are the special features of the SG compared to the legacy system?
2. What computations are needed in the case of smart grid?
3. What specific directions are needed for developing a new power flow?
4. What new features of the load flow make it suitable for smart grid performance and evaluation?

Challenges to load flow in smart grid: Contd.

Other features to be considered in the development of the new load flow include:

1. **Condition adaption** of T&D grid systems **to accommodate load flows comprising renewable generation**

2. **Self-adaptiveness** to ensure **proper coordination**

3. **High impedance topology matching** for **distribution network** with **randomness** and **uncertainty** and requires **intelligent analytical tools**

4. Since **reverse power flow** technique is **possible**, the use of FACTs devices to power electronics; will be building blocks and will be essential.

Challenges to load flow in smart grid: Contd.

- Existing load flow performance tools are mostly offline.
- To enhance load flow capabilities, SG load flow process consists of the following steps:

1. **Data acquisition** for radial or mesh network
2. Existence of **connection of data** to assure **network feasibility**
3. **Formulation of Y - bus for representing the interconnection** of the system under study and **determination of initial conditions**
4. Solution of mismatch real and reactive powers and checking of mismatch by **adjusting the initial conditions typically called the hot state**.
5. With the **snapshot power demand** (real power and reactive power demand), determining a **feasible static voltage and angle** to minimize mismatch

Load Flow Techniques Comparison

Old Load Flow Technique	Desired Load Flow Technique
Central generation and Simple control	Central and distributed generation control and distributed intelligence
Load flow by Kirchhoff’s laws	Load flow by power electronics
Power generation according to demand	Controllable generation, fluctuating / random sources and demand in dynamic conditions
Manual switching and manual trouble shooting response	Automatic response and predictive avoidance
Simulation and response tracking	Monitoring overload against bottlenecks

Traditional load flow techniques

1. Distribution systems are **radial network** structures
2. **High X/R ratios** in the line impedances
3. Single phase loads handled by the distribution load flow programs (**for unbalanced systems**)
4. DG, renewable generation and cogeneration power supplies **installed in relative proximity to some load centers**
5. Distribution systems with **many short line segments, most of which have low impedance values**

Classical Load flow analysis

The classical methods of studying load flow include:

1. **Gauss – Seidal**: Uses KCL nodal Equations.

- Worse in RDN due to lack of branch connections between a large set of surrounding buses

2. **Newton – Raphson**: Vi for computing Power mismatches.

- Excellent for large systems, however computationally inefficient.
- Fails when J-matrix is singular or system is ill-conditioned system with a high X/R ratio

3. **Fast Decouple:** Simplify J-matrix using small angle approx. to eliminate relatively small elements of the Jacobian.

- Poor convergence with a high R/X ratio system .
- Interaction of V and ϑ magnitudes with P&Q power flows cause poor convergence as well.

Distribution Load Flow (DLF) Methods

Due to the limitation of the methods in solving an ill - conditioned system with a high X/R ratio DLF techniques (in last slide) require alternative methods

1. **Forward/backward sweep** methods **solves branch current** or load flow by **using the forward sweeping** method

2. **Compute the nodal voltages** using **backward sweep** approach

3. **Newton method** uses **power mismatches** at the **end of feeders and laterals** to iteratively solve the nodal voltage

4. **Gauss method** on the **bus impedance matrix** equation solves **iteratively for the branch currents**.

DLF Methods, Contd.

Forward/backward sweep methods:

- This method models the distribution system as a tree network, with the slack bus denoted as the root of the tree and the branch networks as the layers which are far away from the root nodal.
- Weakly meshed networks are converted to a radial network by breaking the loops and injection currents computation.

Load Flow Based on Sensitivity Matrix for Mismatch Calculation:

- This DLF is an improved forward/backward method
- By utilizing a sensitivity matrix scheme to compensate the mismatch between slack bus power injection and the load flow at the feeder and lateral ends. This results in the N– R method for DLF.

Bus Impedance Network.

- This method uses the bus impedance matrix and equivalent current injection to solve the network equation in a distribution system.
- It employs a simple superposition to find the bus voltage through the system.

Congestion Management Effect

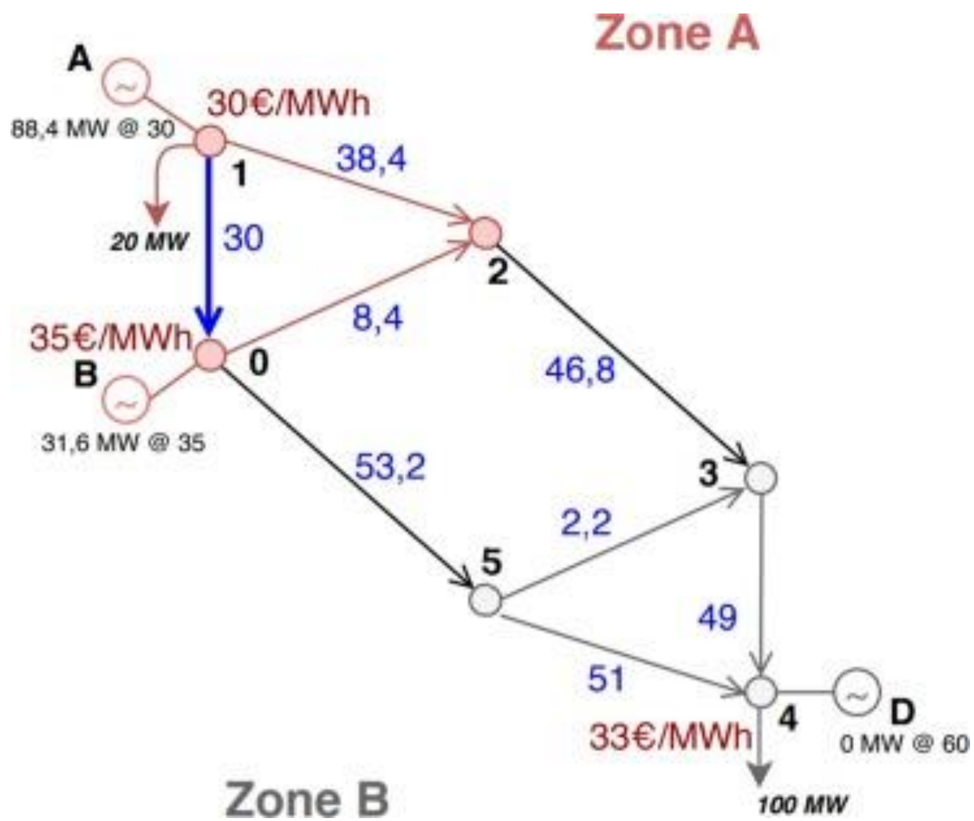
Congestion is defined as “**A situation where load flows lead to a violation of operational limits, that is, maximal thermal loading, voltage stability, etc.**”.

- In a meshed network, intra-zonal injection variations will influence cross – border load flows and are an important factor in the determination of transmission capacities.

- These **variations are a superposition of load flows** on a given scenario of injections.

- Accounting for **the injection variations allows for a better estimation of the transfer capacities**, indifferent to the base case variations and creating thus more accurate long - term capacity index.

intra-zonal injection variations with respect to Congestion management



Congestion Management Effect. Contd.

- Due to **large number of linked equations** that describe an actual electricity network, **numerical methods are used** to determine load flows and node voltages.

- The **base load flow calculation** method uses Newton–Raphson **(NR)** iterations, also called AC load flow.

- The computational efforts can be relieved by using **decoupled load flow equations**.
  - This **assumes** line **impedances to be particularly inductive**, which is an acceptable assumption in the case of **high voltage transmission lines**.

- One step ahead, DC load flow can be used. In this method ohmic losses are ignored by stating that lines are purely inductive.
  - The injection of reactive power is assumed to be sufficient to keep the voltage profile in the network at a constant and nominal level.

Congestion Management Effect. Contd.

- The <u>injection in node *i*</u> is generated power minus load at node *i*.
- Injection Shift Factor **(ISF)** represents the proportion of the power injected in node k which flows in transmission line n.

$$\begin{bmatrix} ISF_{1,1} & \cdots & ISF_{1,k} \\ \vdots & \ddots & \vdots \\ ISF_{n,1} & \cdots & ISF_{n,k} \end{bmatrix} \begin{bmatrix} I_{nj_1} \\ \vdots \\ I_{nj_k} \end{bmatrix} = \begin{bmatrix} flow_1 \\ \vdots \\ flow_n \end{bmatrix}$$

- The load flows to a certain reference node which is not of importance for the global system solution, is however **used in the calculation of the ISFs and is necessary for a proper understanding of these factors**.

Congestion Management Effect. Contd.

- The difference between two ISFs gives a Power Transfer Distribution Factors (PTDF).
- A PTDF indicates the **proportion of a transaction between two nodes that flows across a certain line**.
- PTDFs **measure the sensitivity of line MW flows to a MW transfer**.
- The line flows, from network theory, are simply functions of the voltages and angles at its terminal buses — sending and receiving.
- Using the chain rule, the PTDFs are represented as a function of these voltage and angle sensitivities (Weakest link of chain shows its strength).

Load Flow for Smart Grid Design.

- Load flow tools that incorporate the stochastic and random study of the SG could be modeled with the improved algorithm.
- Conditioning the load flow topology will require a new methodology and algorithm that will include feeders and the evolution of a time- dependent load flow.
- This method has been proven in terms of characteristics and usage in power system planning and operation.
- Hence, the interoperability of RER with SG specifications could account for adequate use of current methodology to perform analysis in both usual and alert states.

Load Flow for Smart Grid Design. Contd.

- The anticipated SG algorithm proposed for implementation may extend to the following capability:

1. Model input of RER (REG) and load will be changed to account for variability;
   - ❑ The input will have to include some power distribution flow so as to advance the congested value of new estimate of Pg, Qg, and Pd , Qd.
   - ❑ These attributes also have a unique load appropriate effectiveness in the performance study.
2. Sparsity (Spreading) may be affected because the loads of RER may be widely distributed, that is, load and size of RER has to be considered.
3. Computational challenges in new load flow with RER for smart grid that includes
   - Stochastic model may affect the independent computation.
   - (See Load flow used for distribution network as in Slide 5/Section 3.2)

Load Flow for Smart Grid Design. Contd.

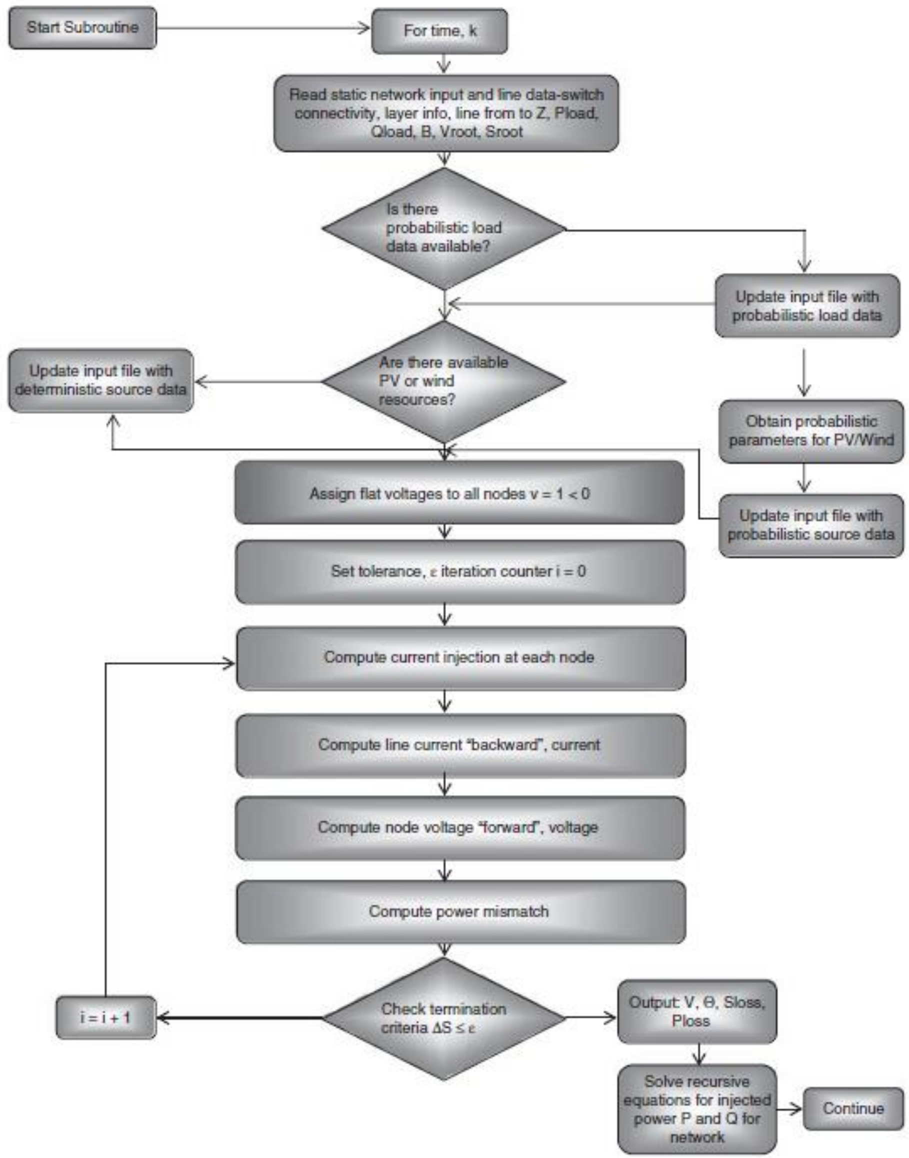


Fig: Proposed SG based load flow methodology

Cases for the Development of Dynamic Stochastic Optimal Power Flow (DSOPF)

- DSOPF computational algorithm has following performance (built-in) measures that are defined for general purpose tools:

- **Controllability and interoperability:**
  - This is important for enabling different devices, systems, and subsystems to provide greater observability when different devices interact as agents for cooperation and benefits.

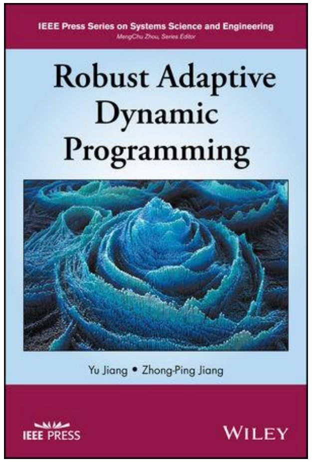
- **Reliability:**
  - Quality measure of electricity delivered to achieve adequacy and performance using intelligence tools, support devices, and software;
  - Ability to achieve power quality and improve voltage profile is one of the attributes of SG

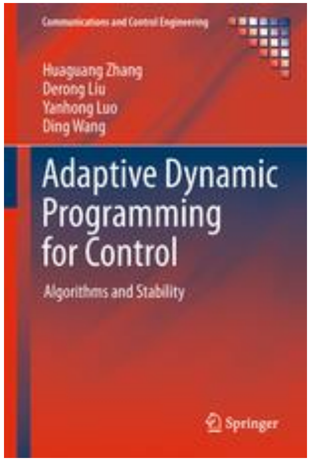
- **Adaptability and sustainability:**
  - Ability of the grid to adapt to changes;
  - Meeting energy needs in a way that can sustain life and civilization

- **Anticipatory behavior and affirmation of security:**
  - Ability of the grid to anticipate different scenarios
  - Prepare to handle the dynamic changes while guaranteeing system security.

DSOPF Application to the Smart Grid

- Adaptive Dynamic Programming (ADP)
  - It is a computational intelligence technique that incorporates time Framework for Implementation of DSOPF:
- There is a need for a generalized framework for solving the many classes of power system problems where programmers, domain experts, and so on, can submit their challenge problem.
- The collective knowledge will published and posted on the Web for dissemination.





DSOPF Application to the Smart Grid

The general framework for the application of ADP to develop a new class of OPF problems called DSOPF; it is divided into three modules.

Module 1:

1. **Read PS parameters** and **obtain distribution function for**
   - **State estimation** of **measurement errors inherent in data**;
   - **Determine** and **improve accuracy of data**.

2. Infer relationships b/w past data and future of unknown period using:
   - **Time series** and **dynamical systems**;
   - **Determine** the **time-dependent model approximation** behavior of the generation data.

3. Define the model with:
   - **Uncertainties**
   - **Problem objective** (Must be properly defined)
   - **Constraint functions** (Must be given for each problem).

DSOPF Application to the Smart Grid

Module 2:

1. **Determine** the **feasibility region** of **operation** of the power system:
   – Also the **emergency state** with **corresponding violations** under **different contingencies**.
2. **Enumerate** and **schedule different control options** over time **for the different contingency scenarios**.
3. **Coordinate the controls** & **perform post optimizations** of additional changes.
4. **Evaluate results** and perform **sensitivity analysis** studies.

Module 3:

1. Address the **post-optimization process** through **cost benefit analysis** to evaluate the various controls (**cost effectiveness and efficiency**).

2. The **critic network** from **ADP techniques** will help realize the **dual goals** of **cost effectiveness** and **efficiency of the solution** via **optimization process**.

DSOPF Application to the Smart Grid. Contd.

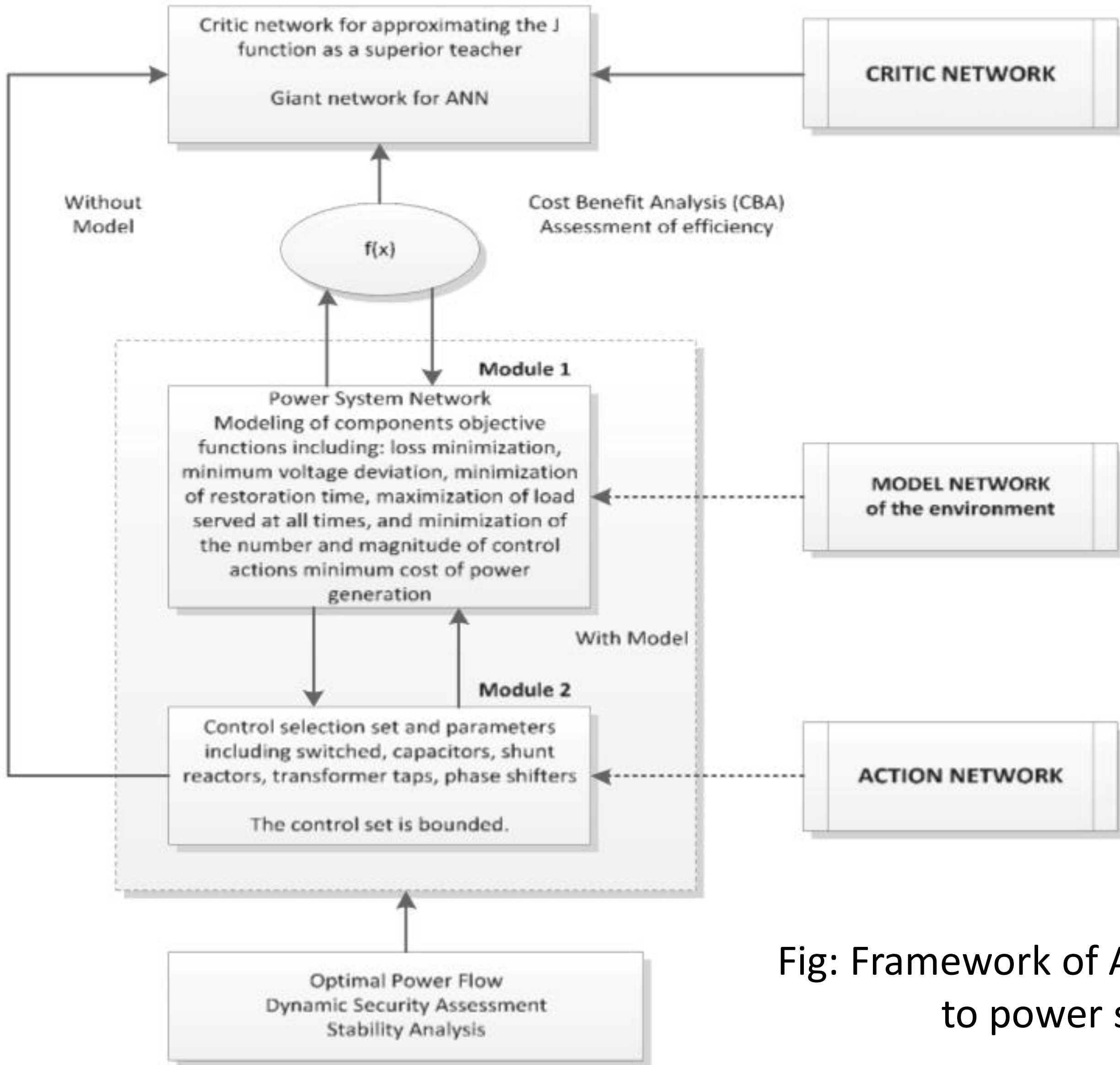


Fig: Framework of ADP applications to power systems

Static Security Assessment (SSA) and Contingencies

- **System security** refers to the **ability of power system** to **withstand probable disturbance** with **minimal disruption of service**.
  - In an operational environment, security assessment involves **predicting the vulnerability** of the system to **possible disruptive events** in **real time**.
- **Steady-state security** involves situations where the transients following a disturbance have decayed, but where some limit violations could not be tolerated for long.
- Actual operating conditions change constantly due to maintenance requirements, forced outages, load patterns.
- The concept of DyLiacco’s security- state diagram, shown in Figure, shows the principal operating states.

Static Security Assessment (SSA) and Contingencies. Contd.

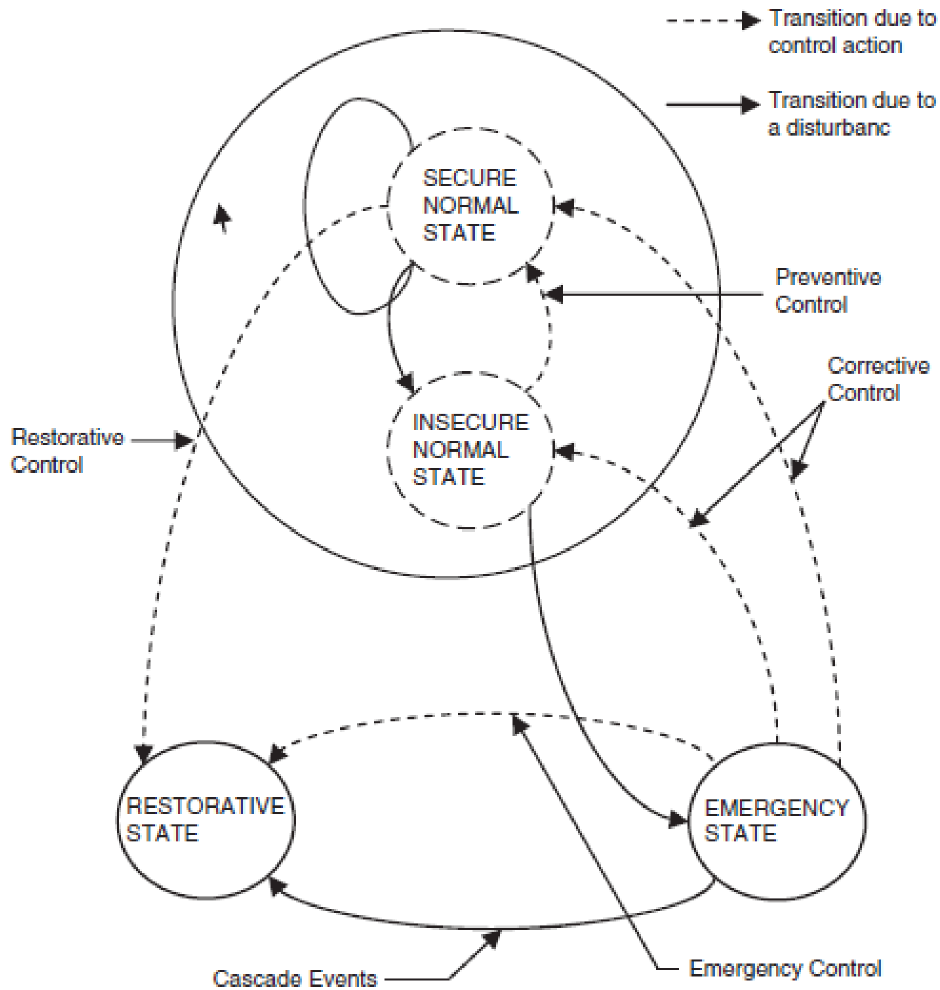


Fig: DyLiacco’s security-state diagram.

Static Security Assessment (SSA) and Contingencies. Contd.

3 States in SSA related DyLiacco's security-state diagram

- **Secure or normal state**: All system loads are satisfied at the specified voltage levels.

- **Emergency state**: Some operating limits are violated, for example, overloaded lines.

- **Restorative state**: Some loads are not met, that is, partial or total blackout, but the operating portion of the system is in a normal state.

Static Security Assessment (SSA) and Contingencies. Contd.

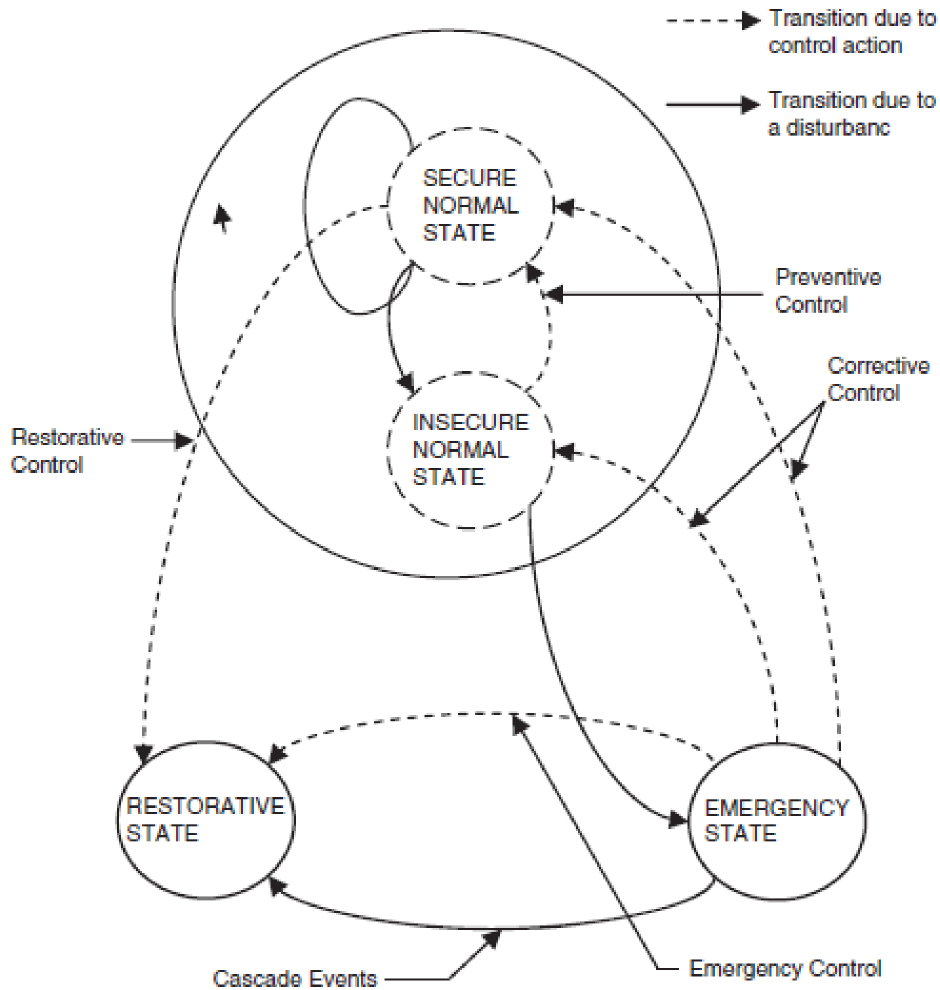


Fig: DyLiacco’s security-state diagram.

Static Security Assessment (SSA) and Contingencies. Contd.

- **Secure or normal state**: Assume that a transmission line sustains a fault, which causes an outage.
  - This will result in a redistribution of power flows and changes in all voltages in the system.
  - If this redistribution results in a normal system condition then the pre-disturbance state was both normal and secure relative to this event.

- **Emergency state**: If an emergency condition occurred, then the pre-disturbance state was normal, but insecure.
  - Similarly, a system in the emergency state can be forced to return to normal following some corrective control measures.

Alleviate: كم كرنا

- **Restorative state**: Depending on the severity of the emergency, loads may be shed to alleviate a more catastrophic situation leading to a partially normal system (i.e., restorative state).
  - System restoration involves activities to restore service to all interrupted loads.

Static Security Assessment (SSA) and Contingencies. Contd.

- **SSA involves situations** where **transients after a disturbance have decayed & violations could not be tolerated for long**.
- The **loss of a transmission link**, for example, after the transients have died out, may result in an **overloaded line**, or an **over - voltage condition**.
- The system may tolerate such limit violations for a short period. During such a period corrective action should be taken.
- If corrective action is not possible, then the pre-disturbance state is seriously insecure and some preventive measures should be **carried out**.
- Analysis tools required to address **steady-state operation**, that is, load flow and related analysis methods.

Static Security Assessment (SSA) and Contingencies. Contd.

- The output of state estimator can be used directly to determine the security state (normal or emergency).
- **For an emergency state**, next step is to specify the required corrective action and apply it before it is too late.
- **For a normal state**, it is not usually known if a postulated disturbance will or will not cause an emergency.
- As a result, **contingency analysis** is **carried out** using three data sources:
  - The pre-contingency state (state estimator output)
  - A model of the external system
  - A specified list of contingencies

Contingency Approach definition
The contingency approach is a management theory that suggests the most appropriate style of management is dependent on the context of the situation and that adopting a single, rigid style is inefficient in the long term.

- **Security analysis**: The results of contingency analysis are reevaluated further to examine the level of system security.

Static Security Assessment (SSA) and Contingencies. Contd.

- Security analysis will yield information, what to do next
- **If the system is deemed secure,** then nothing is done till the next cycle of analysis (30 min or 1 hour later).
- **If the system is deemed insecure,** then preventive measures are evaluated but not necessarily carried out.

NTDC or Regional departments of NTDC

- At this stage the system operator will exercise some judgment over the desirability of preventive action since, invariably, it **may lead to less favorable operational economics**.

Static Security Assessment (SSA) and Contingencies. Contd.

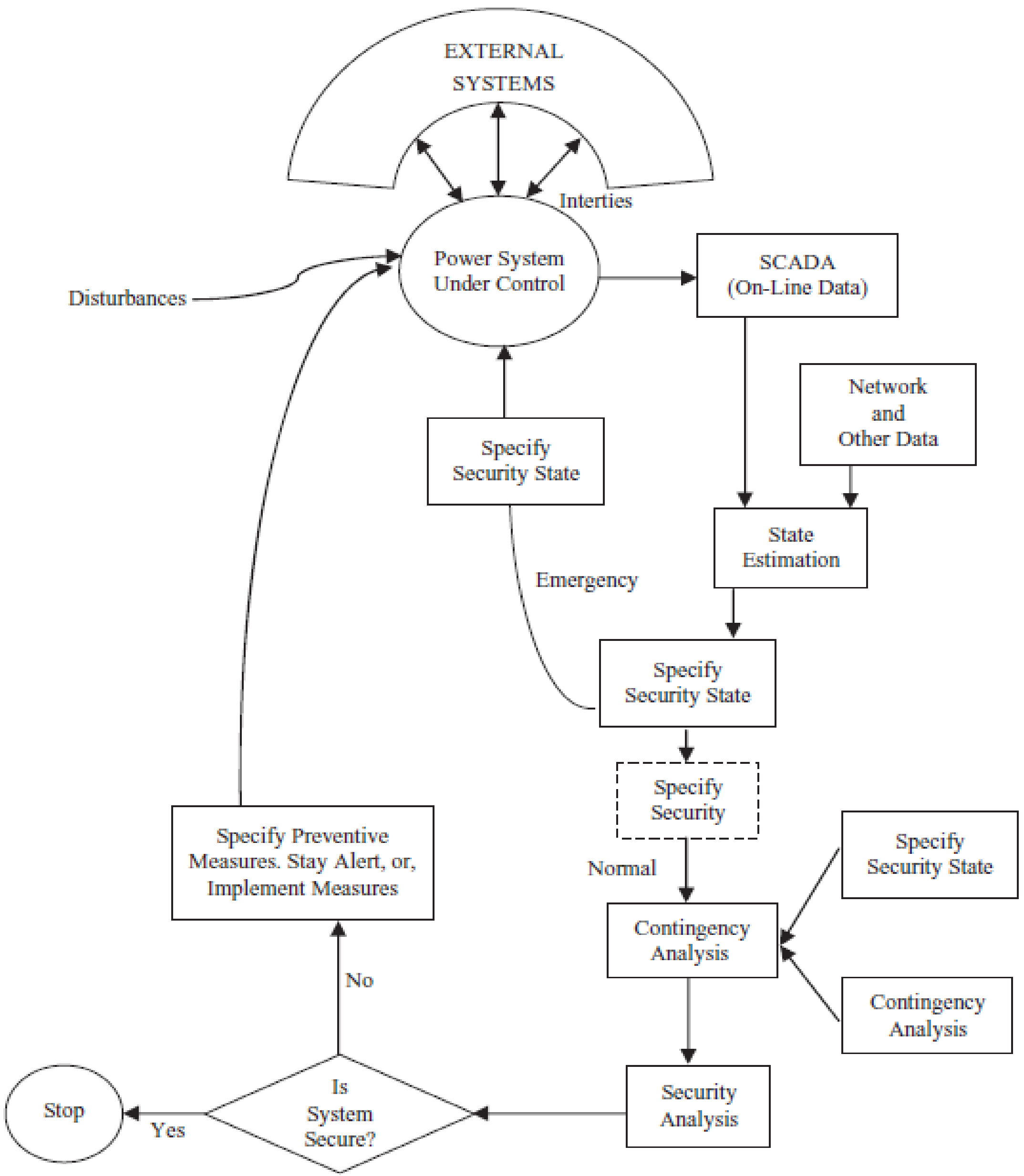


Figure: A block diagram illustrates the functions associated with on-line system security analysis.

Contingencies and their classification

- Steady-state contingency analysis (SSCA) **predicts** power flows and bus voltage conditions following events such as line outages, transformer outages, and generator outages.
- There are many reasons for transmission line and transformer outages. (1) Normal; (2) Forced.
- **Normal**: Planned maintenance, switching operations to control power flows in network and/or to overcome voltage problems.
  - In either case, the outages are caused by operators performing daily dispatching and maintenance functions.
- **Forced**: A line that has experienced a permanent fault is automatically de-energized by circuit breakers, or an overloaded line or transformer is de-energized to protect it from damage.

Contingencies and their classification

- In both normal and forced case, the **operator needs to know the effects of the outage** on power flows and voltage conditions throughout the system
  - In order to take preventive measures before outages occur.

- **In case of planned maintenance**, the operator will require a forecasted load flow case at the time of planned outage.

- **In the case of switching operations** for flow and voltage control, the operator will require a load flow solution for the present pre-outage condition.

- Forced outage cases are more complicated since they occur with very low probabilities that are time - and weather - dependent.

Contingencies and their classification. Contd.

Single line to ground fault

- Usually, **single-line outages are more probable** than double or multiple outages, However, **double and multiple outages occasionally occur during severe weather**.
- As a result of the **large amount of computations involved**, only single - line contingencies are considered.
- Generator outages occur for **reasons similar** to those of line and transformer outages.
- Power plants are taken **off-line** for operational and maintenance requirements.
- There are also **forced generator outages caused by equipment failures,** line faults near the generator, and so on.

Steady-State Contingency Analysis (SSCA)

- SSCA **predicts** power flows and bus voltage conditions following TL outages, TF & generator outages.
- **Assumption:** In TL & TF contingency, it is assumed that input/ demand load flow variables will not change due to the outage.
  - This line- outage model is only approximate
  - P_L, Q_L, P_G And V_G will be constant before and after the outage
- **Practically:** The loss of a major transmission line will cause changes in voltage and power flow conditions.
  - The first consequence is that power system losses will change.
  - These losses will be accounted for by a changed slack-bus generation level.
- Changes in voltage conditions at load busses normally mean changes in load itself, especially when it is **represented as an impedance load**.
  - **Only with an adequate load model** for each bus can **the accuracy of contingency analysis be improved**.
  - For most purposes, the **errors introduced by** the above **modeling assumption are fewer than** those resulting from **inaccuracies in the input data**.

Steady-State Contingency Analysis. Contd.

The **case of generator outage is more complicated** for a no. of reasons.

1. Immediately following the outage (first few seconds), remainder of generating system will be unable to respond to the resulting generation/load unbalance by increasing its generation level.

2. System frequency will drop, with the net effect being an overall and fairly uniform reduction in system load

   Frequecny: Global parameter

   – Because loads are frequency-dependent and tending to decrease or increase with corresponding decreases and increases in frequency.

3. Because of this drop in frequency, as well as the serious violation of the requirements on scheduled net power flow interchanges with neighboring systems,

   – Generation levels of various generators will be automatically controlled to restore normal system frequency

   – Net interchanges with neighboring systems through automatic generation control (AGC) within a few minutes.

Steady-State Contingency Analysis. Contd.

- The **use of economic dispatch** allows the desired optimal generation levels to be accomplished, although they may not be economically and/or environmentally optimal.
  - This final steady-state condition is reached in several minutes after the disturbance.

- **In practice**, many smart grid contingencies will require the same number of fast load flow techniques for **performing contingency analysis**.
  - In such techniques, starting point is that of pre-outage solution.

- Some of these techniques includes:
  - Performance Indices.
  - Sensitivity-Based Approaches

Performance Indices.

- Security- type performance index **ranks the severity of various contingencies**. The following index is an illustration.

$$J = \frac{1}{2}\sum_{k}(V_k - V_{k-ref})^2 W_k$$

- A similar performance index can be formulated for **line power flow limit violations**.

$$J' = \frac{1}{2}\sum_{k} W_k \left(\frac{T_k}{T_{k\max}}\right)^2$$

External System Equivalents.

- In the **online control and operational context**, the system being controlled is usually interconnected to other systems.
- A contingency in one system is strongly felt in another, for example, the **loss of a major generating unit may cause power flow limit violations elsewhere**.
- The difficulty in predicting the impact of a contingency arises from the fact that the **external network is not monitored as carefully as the internal network**.
- **Through state estimation, all internal system** voltage magnitudes and angles, power flows, generations, load, and network topology **are known online**.
- **As for the external system, online information is normally restricted** to items such as **inter-tie power flows**, **status of major lines and generators**, and **possibly individual unit outputs**.

External System Equivalents. Contd.

متوقع

- Anticipated power flow solution to a postulated contingency
  - The state of the entire network (internal and external) should be known to establish the pre-contingency base case.
- The state of the external network is not fully known, two types of approximations are considered.
  - 1st is based on sensitivity approaches
  - 2nd on network reduction approaches
- The starting point is base case load flow solution. In a planning study this can be a complete network solution for a given set of loads, generation, and network configuration.
  - In the case of online operations, it can be a solution of the internal plus the boundary system obtained from on-line state estimation using live measurement data.

External System Equivalents. Contd.

- In fact, some operators have reclassified all boundary load busses as generation busses, claiming higher accuracy of solutions.

Network Reduction approach

- **The steps in the utilization of network equivalents are**:

1. Perform **network reduction** using an appropriate techniques
2. **Given the base case** (pre-outage) solution, **compute boundary bus injections**
3. **Reclassify some boundary busses** as generation busses if necessary
4. **Postulate a contingency list**
5. For each contingency in the list, **solve the load flow problem using a fast contingency evaluation technique** that is initiated by the base case solution

Sensitivity-Based Approaches.

- After a line outage or generator contingency, the **external voltages, and possibly some injections will be different**.
  - This means that a post-outage equivalent is required.
  - Obviously, it defeats entire purpose of network reduction.

- A **more crucial problem** is that external system injections & voltages are actually unknown in an online environment.

- **There are two possible solution paths.**
  - **1st path, during offline studies**, obtain equivalent networks that are insensitive to external conditions and to internal outages.
  - If this objective is achieved, the **next step uses online measurements to calibrate the parametric values** of equivalent lines and power injections.

Contingency Studies for the Smart Grid.

- Contingency studies are proposed planning/operation tool for assessing the impact of unit or line outage in an integrated smart grid environment.
- This could be a single or multiple line outages called N−1, N−2, N−3,. . contingency. **There are two types of contingency.**
  1. AC automatic contingency **screening/filtering**
  2. AC automatic contingency **control**
- **Use of the contingency set includes:**

  Static Security Assessment

  – **These contingencies sets are used in SSA as well as in Dynamic security analysis (DSA). The SSA consists of the following elements.**
    a. Load flow base case
    b. Schedule contingency
    c. Develop and model a Performance index (PI) for each contingency
  – **Provide the studies for violation check against a given threshold**, PI ≤ Threshold for violated contingency case in ascending order.
  – **Develop security measure to aid improvement** in recommendation and display.

Contingency Studies for the Smart Grid.

- SSA is well known for **classical** power system.
  - The **weak points** includes are:

1. Selection of **weighting measure**
2. **Exponent factors**
3. The probability of **selecting a contingency**
4. **Lack of human intelligence**
   - Relative information on knowledge - base for decision - making by non-experts.

     Artificial Neural Networks
   - Work has been planned using ES, ANN, and fuzzy sets.
   - These schemes do not include time against sources, variability in selecting parameters for contingency studies.

Contingency Studies for the Smart Grid.

- An **Advance contingency studies (ACS)** is **capable of including**:

1. RER with variability in output power **as contingency**
2. Loss of measured unit needed for **performance study**
3. Probabilistic measure of contingency to be **added to the input**
4. Resulting PI index needs to be replaced **with time stamp measurements**
   – To predict, analyze, and view recommendations by classified behavior
   – And impact of contingency under study in real time, hence creating a new opportunity in research.

- **Future:** There are many opportunities for designing new computational algorithms to support the deployment of a smart grid equipped with advanced tools for system security, reliability, sustainability, and affordability.